THE DEPTHS OF THE OCEAN

John Murray

Frontispiece.

THE DEPTHS OF THE OCEAN

MACMILLAN AND CO., LIMITED
LONDON · BOMBAY · CALCUTTA
MELBOURNE

THE MACMILLAN COMPANY
NEW YORK · BOSTON · CHICAGO
DALLAS · SAN FRANCISCO

THE MACMILLAN CO. OF CANADA, LTD.
TORONTO

THE

DEPTHS OF THE OCEAN

A GENERAL ACCOUNT
OF THE MODERN SCIENCE OF OCEANOGRAPHY
BASED LARGELY ON THE SCIENTIFIC RESEARCHES
OF THE NORWEGIAN STEAMER
MICHAEL SARS
IN THE NORTH ATLANTIC

BY

SIR JOHN MURRAY, K.C.B., F.R.S., ETC.
OF THE 'CHALLENGER' EXPEDITION

AND

DR. JOHAN HJORT
DIRECTOR OF NORWEGIAN FISHERIES

WITH CONTRIBUTIONS FROM

PROFESSOR A. APPELLÖF, PROFESSOR H. H. GRAN
AND DR. B. HELLAND-HANSEN

MACMILLAN AND CO., LIMITED
ST. MARTIN'S STREET, LONDON

1912

PREFACE

At the International Congress for the Exploration of the Sea held on the invitation of the Swedish Government in Stockholm in 1899, Sir John Murray was the chief British delegate, and acted as president of the physical and chemical section, which drew up a programme of work for the proposed investigations in the North Sea and in the Norwegian Sea. Although his official connection with these marine researches came to an end with the close of the first Congress, it is well known that he has followed with great interest all the proceedings of the International Council during the past ten or twelve years.

In the year 1909 he chanced to visit Copenhagen at a time when one of the annual meetings of the Council was going on, and was invited by the members to take part in some of their deliberations. In the course of the conversations which followed he expressed the opinion that systematic observations in the Atlantic might throw much light on some of the problems then being studied in our more northern seas.

Subsequently Sir John Murray wrote to me that if the Norwegian Government would lend the "Michael Sars" and her scientific staff for a four months' summer cruise in the North Atlantic, he would pay all the other expenses.

When this proposal was laid before the Norwegian Government it was favourably received, and within a few weeks a satisfactory financial agreement was drawn up and adopted. My scientific colleagues, Professor Gran, Dr. Helland-Hansen, Mr. E. Koefoed, and Captain Thor Iversen, who had long been associated with me in oceanographical investigations in the Norwegian Sea, likewise received the proposal with enthusiasm. A large part of the winter of 1909–10 was spent in making the necessary rearrangements on board the ship, in the selection and installation of new apparatus and instruments, and in choosing the routes where we might expect to get the most interesting results.

By the 1st of April 1910 the ship was fully equipped and ready for sea. The first port of call was Plymouth, where Sir John Murray embarked, and the last piece of apparatus—a large centrifuge—was installed on board. After being hospitably entertained by scientific men in London and Plymouth, we sailed on the 7th of April for the south-west of Ireland, where it was arranged that we should occupy our first observing station. The ship worked down the western coasts of Europe as far as the Canaries, then proceeded across the Atlantic, by way of the Azores, to Newfoundland, afterwards re-crossing from Newfoundland to the coast of Ireland, and returned to Bergen by way of the Faroe Channel. About 120 observing stations were established, and the expedition was in all respects successful.

It was agreed that the zoological and all other collections and observations made during the cruise should be sent to Bergen, Sir John Murray generously agreeing to provide £500 to enable the collections to be sorted out and arranged for study by specialists.

It was further arranged that a general account of the cruise and of the results of the observations should be published as soon as possible after the return of the expedition, and this volume has accordingly been prepared. Its main object is to indicate the most important results of the voyage in so far as these can be stated at the present time, although the biological collections and the physical observations have as yet only been examined in a preliminary way. In preparing the various chapters the previous investigations of the "Michael Sars" in the North Sea and in the Norwegian Sea generally have been taken into consideration, in order to compare the physical and biological conditions prevailing in northern waters with those in the Atlantic. In this way it is hoped that the book as a whole will present the student with a fairly complete epitome of recent advances in the modern science of oceanography, even though it has proved impossible to give a complete review of the literature of the subject.

The historical chapter and the chapter on the Depths and Deposits of the Ocean have been prepared by Sir John Murray; that on Physical Oceanography by Dr. Helland-Hansen; that on Phytoplankton by Professor Gran; and that on the Bottom Fauna by Professor Appellöf, while the chapters dealing with the equipment of the ship, the working of the gear, the narrative of the cruise, the fishes from the sea-bottom, the pelagic animals, and general biology have been written by myself.

In the examination of the zoological collections I have received most valuable assistance from Mr. James Grieg, Mr. Einar Koefoed (who took part in the expedition and also in the special examination of the fishes), Mr. Einar Lea, and Mr. Oscar Sund. All the original drawings have been made by Mr. Thorolv Rasmussen, who also took part in the cruise, and was continually engaged in making drawings and sketches on board ship. To all these gentlemen I acknowledge my indebtedness.

The biological collections have been distributed to specialists in different parts of the world, and the following have sent me preliminary reports on their results, which I have been able to use in this book :—

Mr. Paul Bjerkan, Bergen;
Dr. Kristine Bonnevie, Christiania;
Dr. August Brinkmann, Bergen;
Dr. Hjalmar Broch, Trondhjem;

Professor Carl Chun, Leipzig;
Mr. C. Dons, Tromsö;
Dr. P. P. C. Hoek, Haarlem;
Dr. O. Nordgaard, Trondhjem;
Professor G. O. Sars, Christiania;
Professor R. Woltereck, Leipzig.

Sir John Murray's secretary, Mr. James Chumley, has given us most valuable assistance by correcting the English manuscript and taking care of all printing arrangements. Sir John Murray wishes also to acknowledge the co-operation of Dr. Caspari and the other assistants in the "Challenger" office in correcting proofs and preparing the indexes of this book.

The authorities of the Bergen Museum have undertaken to publish a detailed account of the voyage and of the physical and biological observations, in a series of quarto volumes which will be issued from the press at intervals during the next few years. These more detailed reports will undoubtedly form valuable contributions to the science of oceanography. I hope also that this general account will be of use to those engaged in the study of oceanography, and that it may lead to further investigations in the North Atlantic—that wonderful ocean bordered by nearly all the seafaring countries. As will be seen from several of the following chapters, Sir John Murray's well-known scientific views and his original ideas have been of great value to this expedition. I wish therefore to express my indebtedness to Sir John Murray, not only for the opportunity of engaging in this interesting Atlantic cruise, but also for his kindness in giving the benefit of his great experience to the advancement of the undertaking.

JOHAN HJORT.

BERGEN, *February* 1912.

CONTENTS

PAGE

Table I. for converting Metres into Fathoms . . . xiii

„ II. for converting Degrees Fahrenheit into Degrees Centigrade xiv

„ III. showing Mean Temperature at Various Depths for the Whole Ocean xvi

„ IV. showing Positions of "Michael Sars" Stations . xvii

CHAPTER I

A Brief Historical Review of Oceanographical Investigations 1

CHAPTER II

The Ship and its Equipment 22

CHAPTER III

The Work and Cruises of the "Michael Sars" . . 52

CHAPTER IV

The Depths and Deposits of the Ocean 129

CHAPTER V

Physical Oceanography 210

CHAPTER VI

PAGE

Pelagic Plant Life 307

CHAPTER VII

Fishes from the Sea-Bottom 387

CHAPTER VIII

Invertebrate Bottom Fauna of the Norwegian Sea and North Atlantic 457

CHAPTER IX

Pelagic Animal Life 561

CHAPTER X

General Biology 660

INDEXES

Index of Proper Names 787

Index of Genera and Species 791

General Index 809

MAPS AND PLATES

			CHAP.
Map	I.	Reproduction of Lieut. Maury's Map of the North Atlantic, 1854	I
,,	II.	Bathymetrical Chart of the Oceans showing the "Deeps," according to Sir John Murray	IV
,,	III.	Depths of the North Atlantic compiled from the latest sources, 1911	IV
,,	IV.	Deposits of the North Atlantic, after Sir John Murray	IV
Plate	I.	Cyclothone	X
,,	II.	Argyropelecus and Gonostoma	X
,,	III.	Red-coloured Shrimps	X
,,	IV.	Flying-Fish and Pilot-Fish	X
,,	V.	Sargasso Fish	X
,,	VI.	Sargasso Crabs	X
,,	VII.	Coast Fishes from the bottom	X
,,	VIII.	Deep-Sea Fishes from the bottom	X
,,	IX.	Bathytroctes	X

I. Table for Converting Metres into Fathoms

Metres.	Fathoms.	Metres.	Fathoms.
1	0.55	200	109.36
2	1.09	300	164.04
3	1.64	400	218.73
4	2.19	500	273.41
5	2.73	600	328.09
6	3.28	700	382.77
7	3.83	800	437.45
8	4.37	900	492.13
9	4.92	1,000	546.82
10	5.47	2,000	1,093.63
20	10.94	3,000	1,640.45
30	16.40	4,000	2,187.27
40	21.87	5,000	2,734.08
50	27.34	6,000	3,280.90
60	32.81	7,000	3,827.72
70	38.28	8,000	4,374.53
80	43.75	9,000	4,921.35
90	49.21	10,000	5,468.16
100	54.68		

II. Table for Converting Degrees of Fahrenheit into Degrees of Centigrade

° F.	° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.	° C.
80.0	26.67	75.5	24.17	71.0	21.67	66.5	19.17	62.0	16.67
79.9	26.61	75.4	24.11	70.9	21.61	66.4	19.11	61.9	16.61
79.8	26.56	75.3	24.05	70.8	21.56	66.3	19.05	61.8	16.56
79.7	26.50	75.2	24.00	70.7	21.50	66.2	19.00	61.7	16.50
79.6	26.44	75.1	23.95	70.6	21.44	66.1	18.95	61.6	16.44
79.5	26.39	75.0	23.89	70.5	21.39	66.0	18.89	61.5	16.39
79.4	26.33	74.9	23.83	70.4	21.33	65.9	18.83	61.4	16.33
79.3	26.28	74.8	23.78	70.3	21.28	65.8	18.78	61.3	16.28
79.2	26.22	74.7	23.72	70.2	21.22	65.7	18.72	61.2	16.22
79.1	26.17	74.6	23.67	70.1	21.17	65.6	18.67	61.1	16.17
79.0	26.11	74.5	23.61	70.0	21.11	65.5	18.61	61.0	16.11
78.9	26.05	74.4	23.56	69.9	21.05	65.4	18.56	60.9	16.05
78.8	26.00	74.3	23.50	69.8	21.00	65.3	18.50	60.8	16.00
78.7	25.95	74.2	23.44	69.7	20.95	65.2	18.44	60.7	15.95
78.6	25.89	74.1	23.39	69.6	20.89	65.1	18.39	60.6	15.89
78.5	25.83	74.0	23.33	69.5	20.83	65.0	18.33	60.5	15.83
78.4	25.78	73.9	23.28	69.4	20.78	64.9	18.28	60.4	15.78
78.3	25.72	73.8	23.22	69.3	20.72	64.8	18.22	60.3	15.72
78.2	25.67	73.7	23.17	69.2	20.67	64.7	18.17	60.2	15.67
78.1	25.61	73.6	23.11	69.1	20.61	64.6	18.11	60.1	15.61
78.0	25.56	73.5	23.05	69.0	20.56	64.5	18.05	60.0	15.56
77.9	25.50	73.4	23.00	68.9	20.50	64.4	18.00	59.9	15.50
77.8	25.44	73.3	22.95	68.8	20.44	64.3	17.95	59.8	15.44
77.7	25.39	73.2	22.89	68.7	20.39	64.2	17.89	59.7	15.39
77.6	25.33	73.1	22.83	68.6	20.33	64.1	17.83	59.6	15.33
77.5	25.28	73.0	22.78	68.5	20.28	64.0	17.78	59.5	15.28
77.4	25.22	72.9	22.72	68.4	20.22	63.9	17.72	59.4	15.22
77.3	25.17	72.8	22.67	68.3	20.17	63.8	17.67	59.3	15.17
77.2	25.11	72.7	22.61	68.2	20.11	63.7	17.61	59.2	15.11
77.1	25.05	72.6	22.56	68.1	20.05	63.6	17.56	59.1	15.05
77.0	25.00	72.5	22.50	68.0	20.00	63.5	17.50	59.0	15.00
76.9	24.95	72.4	22.44	67.9	19.95	63.4	17.44	58.9	14.95
76.8	24.89	72.3	22.39	67.8	19.89	63.3	17.39	58.8	14.89
76.7	24.83	72.2	22.33	67.7	19.83	63.2	17.33	58.7	14.83
76.6	24.78	72.1	22.28	67.6	19.78	63.1	17.28	58.6	14.78
76.5	24.72	72.0	22.22	67.5	19.72	63.0	17.22	58.5	14.72
76.4	24.67	71.9	22.17	67.4	19.67	62.9	17.17	58.4	14.67
76.3	24.61	71.8	22.11	67.3	19.61	62.8	17.11	58.3	14.61
76.2	24.56	71.7	22.05	67.2	19.56	62.7	17.05	58.2	14.56
76.1	24.50	71.6	22.00	67.1	19.50	62.6	17.00	58.1	14.50
76.0	24.44	71.5	21.95	67.0	19.44	62.5	16.95	58.0	14.44
75.9	24.39	71.4	21.89	66.9	19.39	62.4	16.89	57.9	14.39
75.8	24.33	71.3	21.83	66.8	19.33	62.3	16.83	57.8	14.33
75.7	24.28	71.2	21.78	66.7	19.28	62.2	16.78	57.7	14.28
75.6	24.22	71.1	21.72	66.6	19.22	62.1	16.72	57.6	14.22

II. TABLE FOR CONVERTING DEGREES OF FAHRENHEIT INTO DEGREES OF CENTIGRADE—*Continued*

° F.	° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.	° C.
57.5	14.17	52.9	11.61	48.3	9.05	43.7	6.50	39.1	3.95
57.4	14.11	52.8	11.56	48.2	9.00	43.6	6.44	39.0	3.89
57.3	14.05	52.7	11.50	48.1	8.95	43.5	6.39	38.9	3.83
57.2	14.00	52.6	11.44	48.0	8.89	43.4	6.33	38.8	3.78
57.1	13.95	52.5	11.39	47.9	8.83	43.3	6.28	38.7	3.72
57.0	13.89	52.4	11.33	47.8	8.78	43.2	6.22	38.6	3.67
56.9	13.83	52.3	11.28	47.7	8.72	43.1	6.17	38.5	3.61
56.8	13.78	52.2	11.22	47.6	8.67	43.0	6.11	38.4	3.56
56.7	13.72	52.1	11.17	47.5	8.61	42.9	6.05	38.3	3.50
56.6	13.67	52.0	11.11	47.4	8.56	42.8	6.00	38.2	3.44
56.5	13.61	51.9	11.05	47.3	8.50	42.7	5.95	38.1	3.39
56.4	13.56	51.8	11.00	47.2	8.44	42.6	5.89	38.0	3.33
56.3	13.50	51.7	10.95	47.1	8.39	42.5	5.83	37.9	3.28
56.2	13.44	51.6	10.89	47.0	8.33	42.4	5.78	37.8	3.22
56.1	13.39	51.5	10.83	46.9	8.28	42.3	5.72	37.7	3.17
56.0	13.33	51.4	10.78	46.8	8.22	42.2	5.67	37.6	3.11
55.9	13.28	51.3	10.72	46.7	8.17	42.1	5.61	37.5	3.05
55.8	13.22	51.2	10.67	46.6	8.11	42.0	5.56	37.4	3.00
55.7	13.17	51.1	10.61	46.5	8.05	41.9	5.50	37.3	2.95
55.6	13.11	51.0	10.56	46.4	8.00	41.8	5.44	37.2	2.89
55.5	13.05	50.9	10.50	46.3	7.95	41.7	5.39	37.1	2.83
55.4	13.00	50.8	10.44	46.2	7.89	41.6	5.33	37.0	2.78
55.3	12.95	50.7	10.39	46.1	7.83	41.5	5.28	36.9	2.72
55.2	12.89	50.6	10.33	46.0	7.78	41.4	5.22	36.8	2.67
55.1	12.83	50.5	10.28	45.9	7.72	41.3	5.17	36.7	2.61
55.0	12.78	50.4	10.22	45.8	7.67	41.2	5.11	36.6	2.56
54.9	12.72	50.3	10.17	45.7	7.61	41.1	5.05	36.5	2.50
54.8	12.67	50.2	10.11	45.6	7.56	41.0	5.00	36.4	2.44
54.7	12.61	50.1	10.05	45.5	7.50	40.9	4.95	36.3	2.39
54.6	12.56	50.0	10.00	45.4	7.44	40.8	4.89	36.2	2.33
54.5	12.50	49.9	9.95	45.3	7.39	40.7	4.83	36.1	2.28
54.4	12.44	49.8	9.89	45.2	7.33	40.6	4.78	36.0	2.22
54.3	12.39	49.7	9.83	45.1	7.28	40.5	4.72	35.9	2.17
54.2	12.33	49.6	9.78	45.0	7.22	40.4	4.67	35.8	2.11
54.1	12.28	49.5	9.72	44.9	7.17	40.3	4.61	35.7	2.05
54.0	12.22	49.4	9.67	44.8	7.11	40.2	4.56	35.6	2.00
53.9	12.17	49.3	9.61	44.7	7.05	40.1	4.50	35.5	1.95
53.8	12.11	49.2	9.56	44.6	7.00	40.0	4.44	35.4	1.89
53.7	12.05	49.1	9.50	44.5	6.95	39.9	4.39	35.3	1.83
53.6	12.00	49.0	9.44	44.4	6.89	39.8	4.33	35.2	1.78
53.5	11.95	48.9	9.39	44.3	6.83	39.7	4.28	35.1	1.72
53.4	11.89	48.8	9.33	44.2	6.78	39.6	4.22	35.0	1.67
53.3	11.83	48.7	9.28	44.1	6.72	39.5	4.17	34.9	1.61
53.2	11.78	48.6	9.22	44.0	6.67	39.4	4.11	34.8	1.56
53.1	11.72	48.5	9.17	43.9	6.61	39.3	4.05	34.7	1.50
53.0	11.67	48.4	9.11	43.8	6.56	39.2	4.00	34.6	1.44

II. Table for Converting Degrees of Fahrenheit into Degrees of Centigrade—*Continued*

° F.	° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.	° C.
34.5	1.39	33.1	0.61	31.8	− 0.11	30.5	− 0.83	29.2	− 1.56
34.4	1.33	33.0	0.56	31.7	− 0.17	30.4	− 0.89	29.1	− 1.61
34.3	1.28	32.9	0.50	31.6	− 0.22	30.3	− 0.95	29.0	− 1.67
34.2	1.22	32.8	0.44	31.5	− 0.28	30.2	− 1.00	28.9	− 1.72
34.1	1.17	32.7	0.39	31.4	− 0.33	30.1	− 1.05	28.8	− 1.78
34.0	1.11	32.6	0.33	31.3	− 0.39	30.0	− 1.11	28.7	− 1.83
33.9	1.05	32.5	0.28	31.2	− 0.44	29.9	− 1.17	28.6	− 1.89
33.8	1.00	32.4	0.22	31.1	− 0.50	29.8	− 1.22	28.5	− 1.95
33.7	0.95	32.3	0.17	31.0	− 0.56	29.7	− 1.28	28.4	− 2.00
33.6	0.89	32.2	0.11	30.9	− 0.61	29.6	− 1.33	28.3	− 2.05
33.5	0.83	32.1	0.05	30.8	− 0.67	29.5	− 1.39	28.2	− 2.11
33.4	0.78	32.0	0.00	30.7	− 0.72	29.4	− 1.44	28.1	− 2.17
33.3	0.72	31.9	− 0.05	30.6	− 0.78	29.3	− 1.50	28.0	− 2.22
33.2	0.67								

III. Table showing Decrease of Mean Temperature with Increase of Depth for the whole Ocean

Calculated from the "Challenger" and all other observations available up to the year 1895.

Depth.		Temperature.	
Fathoms.	Metres.	° F.	° C.
100	183	60°.7	15°.95
200	366	50°.1	10°.05
300	549	44°.7	7°.05
400	732	41°.8	5°.44
500	914	40°.1	4°.50
600	1097	39°.0	3°.89
700	1280	38°.1	3°.39
800	1463	37°.3	2°.95
900	1646	36°.8	2°.67
1000	1829	36°.5	2°.50
1100	2012	36°.1	2°.28
1200	2195	35°.8	2°.11
1300	2377	35°.6	2°.00
1400	2560	35°.4	1°.89
1500	2743	35°.3	1°.83
2200	4023	35°.2	1°.78

Except in the Norwegian Sea and in the North-West Atlantic to the south-east of Greenland, the temperatures in the North Atlantic at all depths down to the bottom are above the means for the whole ocean as given in this table. On the other hand, the temperatures in the North Pacific in the same latitudes and depths are, for the most part, below these means.

IV. Table showing the Positions of the "Michael Sars" Observing Stations, 1910

Night Stations where the nets were towed between midnight and dawn are distinguished by asterisks.

Station.	Date.	Position. N.	Position. W.	Depth in Metres.	Depth in Fathoms.
From Plymouth to Gibraltar.					
1	April 9	49° 27′	8° 36′	146	80
2	" 10	49° 30′	9° 42′	149	82
3	" 10	49° 32′	10° 49′	184	101
4	" 10–11	49° 38′	11° 35′	923	504
5	" 16	51° 24′	9° 27′	68	37
6	" 16–17	50° 33′	10° 42′	168	92
7	" 17	49° 54′	12° 10′	1813	991
8	" 18	48° 53′	11° 31′	...	...
9	" 18	47° 49′	10° 52′	...	...
10	" 19–21	45° 26′	9° 20′	4700	2570
11	" 21	44° 25′	9° 18′	...	...
12	" 21	43° 11′	9° 26′	166	91
13	" 22	41° 32′	9° 05′	78	42
14	" 22	41° 15′	8° 54′	69	38
15	" 22–23	40° 56′	9° 28′	...	...
16	" 23	40° 15′	9° 23′	154	84
17	" 23	38° 20′	9° 43′	1860	1017
18	" 29–30	35° 56′	5° 43′	About 400	219
From Gibraltar to Gran Canaria.					
19	May 2–3	36° 5′	4° 42′	...	...
20	" 5	35° 25′	6° 25′	141	77
21	" 5	35° 31′	6° 35′	535	292
22	" 5	35° 42′	6° 51′	835	456
*23	" 5–6	35° 32′	7° 7′	1215	664
*24	" 6–7	35° 34′	7° 35′	1615	883
25 A	" 7	35° 36′	8° 25′	2300	1258
*25 B	" 8	35° 46′	8° 16′	2055	1124
26	" 8	36° 53′	6° 48′	50	27
27	" 9	36° 31′	7° 1′	...	...
28	" 9	36° 0′	7° 19′	...	...
29	" 9–10	35° 10′	7° 55′	...	...
30	" 10	34° 38′	8° 22′	...	...
31	" 10	33° 47′	8° 27′	184	101
32	" 10	33° 27′	8° 32′	105	57
33	" 11	31° 17′	10° 6′	100	55
*34	" 13–14	28° 52′	14° 16′	2170	1187

IV. Table showing the Positions of the "Michael Sars" Observing Stations, 1910—*Continued*

Station.	Date.	Position.		Depth in Metres.	Depth in Fathoms.
Between Gran Canaria and Cape Bojador (Africa).					
		N.	W.		
35	May 18–19	27° 27′	14° 52′	2603	1424
36	„ 19–20	26° 12′	14° 26′	10	5
37	„ 20	26° 6′	14° 33′	39	21
38	„ 20	26° 3′	14° 36′	77	42
39 A	„ 20–21	26° 3′	15° 0′	214	116
*39 B	„ 21	26° 3′	15° 0′	267–280	146–153
40	„ 22–23	28° 15′	13° 29′	1197	655
41	„ 23	28° 8′	13° 35′	1365	747
*42	„ 23–24	28° 2′	14° 17′	...	...
From Gran Canaria to Fayal (the Azores).					
43	May 27	28° 2′	17° 18′	...	...
44	„ 28	28° 37′	19° 8′	...	...
*45	„ 28–29	28° 42′	20° 0′	...	...
46	„ 29	28° 56′	21° 45′	...	...
47	„ 30	29° 2′	22° 53′	5160	2822
48	„ 31	28° 54′	24° 14′	...	...
49 A	June 1	29° 6′	25° 2′	...	...
49 B	„ 1	29° 8′	25° 16′	...	...
*49 C	„ 1–2	29° 7′	25° 32′	...	...
50	„ 4	30° 8′	31° 19′	...	...
*51	„ 5–6	31° 20′	35° 7′	3886	2124
52	„ 6–7	31° 24′	34° 47′	...	...
*53	„ 8–9	34° 59′	33° 1′	2615–2865	1430–1567
54	„ 10	35° 37′	30° 15′	3185	1742
55	„ 10	36° 24′	29° 52′	3239	1770
*56	„ 10–11	36° 53′	29° 47′	3239	1770
57	„ 11	37° 20′	29° 33′	...	...
		37° 11′	29° 31′	1700	930
		37° 33′	29° 29′	1510	825
		37° 33′	29° 20′	1735	949
*58	„ 11–13	37° 37′	29° 25′	1235	675
		37° 38′	29° 20′	948	518
		37° 42′	29° 18′	990	541

IV. TABLE SHOWING THE POSITIONS OF THE "MICHAEL SARS" OBSERVING STATIONS, 1910—*Continued*

Station.	Date.	Position.		Depth in Metres.	Depth in Fathoms.
		From the Azores to Newfoundland.			
		N.	W.		
59	June 17	38° 30′	28° 37′	225	123
60	,, 20	37° 9′	38° 5′	...	...
61	,, 20	37° 7′	38° 34′	...	...
*62	,, 20–21	36° 52′	39° 55′	...	...
63	,, 22	36° 5′	43° 58′	5035	2753
64	,, 24	34° 44′	47° 52′	...	...
65	,, 25	37° 12′	48° 30′	...	...
66	,, 26	39° 30′	49° 42′	...	...
67	,, 27	40° 17′	50° 39′	...	...
68	,, 28	39° 20′	50° 50′	...	...
69	,, 29	41° 39′	51° 4′	...	...
70	,, 30	42° 59′	51° 15′	1100	602
70 A	,, 30	...	...	...	...
71	,, 30	43° 18′	51° 17′	147–138	80–75
72	July 1	44° 35′	51° 15′	75	41
73	,, 1	45° 58′	51° 25′	70	38
74	,, 2	47° 25′	52° 20′	156	85
		From Newfoundland to Glasgow.			
75	July 9	47° 22′	49° 16′	120	66
76	,, 9	47° 11′	47° 6′	380	208
77	,, 10	47° 18′	44° 54′	171	93
78	,, 10	47° 17′	44° 32′	202	110
79	,, 10	47° 16′	44° 17′	271	147
80	,, 11	47° 34′	43° 11′	2000	1094
81	,, 12	48° 2′	39° 55′	...	...
81 A	,, 12	...	...	...	...
82	,, 13	48° 24′	36° 53′	...	...
83	,, 14	48° 30′	33° 35′	...	...
84	,, 15	48° 4′	32° 25′	...	...
*85	,, 15–16	47° 58′	31° 41′	...	...
86	,, 16	47° 29′	30° 20′	...	...
87	,, 17	46° 48′	27° 46′	2157	1180
88	,, 18	45° 26′	25° 45′	3120	1706
88 A	,, 18	...	...	...	...
88 B	,, 19	...	...	...	...

IV. TABLE SHOWING THE POSITIONS OF THE "MICHAEL SARS" OBSERVING STATIONS, 1910—*Continued.*

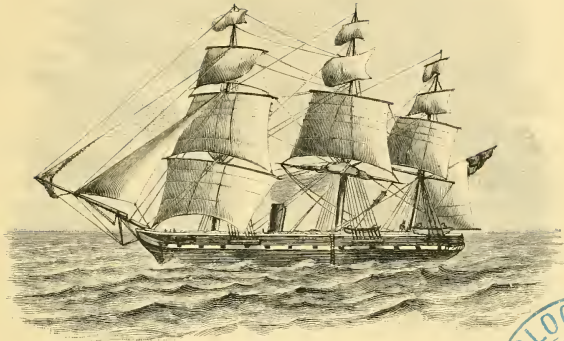
Station.	Date.	Position. N.	Position. W.	Depth in Metres.	Depth in Fathoms.
89	July 20	45° 55′	22° 24′	...	...
90	" 21	46° 58′	19° 6′	...	...
91	" 22	47° 32′	16° 38′	4922	2691
*92	" 23-24	48° 29′	13° 55′	...	...
93	" 25	50° 13′	11° 23′	1257	687
94	" 26	50° 13′	11° 23′	1565	856
*95	" 26-27	50° 22′	11° 44′	1797	983
96	" 27	50° 57′	10° 46′	184	101

From Glasgow to Bergen.

Station.	Date.	Position. N.	Position. W.	Depth in Metres.	Depth in Fathoms.
97	August 4	56° 15′	8° 28′	139	76
98	" 5	56° 33′	9° 30′	1000-1360	547-744
99	" 6	57° 45′	13° 40′	149	82
100	" 6	57° 48′	12° 43′	1530	836
101	" 6-7	57° 41′	11° 48′	1853	1013
*102	" 9-10	60° 57′	4° 38′	1098	600
103	" 10	60° 26′	2° 34′	159	87
104	" 10	60° 35′	3° 20′	234	127
105	" 10	60° 45′	3° 50′	670	366
106	" 10-11	60° 54′	4° 28′	1140	624
107	" 11	61° 4′	5° 5′	730	399
108	" 11	61° 13′	5° 47′	249	136
109	" 11	61° 22′	6° 24′	228	124
110	" 11-12	61° 39′	5° 57′	170	93
111	" 12	61° 32′	5° 15′	300	164
112	" 12	61° 24′	4° 34′	560	306
113	" 12	61° 16′	3° 50′	1080	591
114	" 12-13	61° 8′	3° 16′	1047	573
115	" 13-14	61° 0′	2° 40′	580	317
116	" 14	60° 52′	2° 1′	125	69

Johan Hjort.

To face page 1.



H.M.S. "CHALLENGER"
Shortening sail to sound.

CHAPTER I

A BRIEF HISTORICAL REVIEW OF OCEANOGRAPHICAL INVESTIGATIONS

THE phenomena displayed at the surface of the ocean have been the object of observation from the earliest ages,—waves, currents, winds, tides, and the temperature of the water were matters of very great importance and concern to the earliest navigators. It was not, however, till about the time of the famous "Challenger" Expedition, nearly forty years ago, that any systematic attempts were made to examine the deeper and more remote regions, or to explore the physical and biological conditions of the ocean as a whole.

Development of the modern science of oceanography.

It seems desirable to commence this book by indicating, as briefly as possible, the various steps by which the present development of the modern science of oceanography has been reached. This can best be accomplished by (1) pointing out some of the scientific observations made previous to the "Challenger" Expedition, (2) referring to the expeditions contemporaneous with and subsequent to that expedition, and (3) referring to the work carried out at marine biological laboratories, and in connection with international and other fishery investigations.

Early soundings.

From time immemorial soundings were taken by hand with a plummet, always in shallow water near land, but attempts have not been wanting to sound the ocean without the aid of a line. Thus about the middle of the fifteenth century Cardinal Nicolaus Cusanus invented a bathometer, consisting of a hollow sphere with a heavy weight attached by means of a hook; on touching the bottom the weight was detached, and the sphere returned to the surface, the interval of time from the launching of the apparatus to the re-appearance of the sphere at the surface indicating the depth. A century later Puehler improved on Cusanus' bathometer by adding a piece of apparatus (clepsydra) to measure the time from the disappearance to the re-appearance of the float, using for this purpose a clay vase with a small orifice at the bottom, through which water was made to enter during the period of the experiment, the amount of water in the vase indicating the depth. Alberti subsequently replaced the sphere by a light, bent metal tube. In 1667 Robert Hooke described in the *Philosophical Transactions* a similar apparatus, shown in the tailpiece to Chapter IV., with which experiments were made in the Indian Ocean, but there was always doubt as to the moment when the float returned to the surface, and to remedy this Hooke introduced first a clockwork odometer to register the descent, and then two odometers—one for the descent and the other for the ascent. These various forms of bathometers, though interesting historically, proved of little practical value.

Cusanus' bathometer.

Puehler's apparatus.

Alberti's apparatus.

Hooke's apparatus.

First soundings laid down on maps.

Soundings in shallow water first appeared on a map by Juan de la Cosa in 1504, and soundings were laid down on maps by Gerard Mercator in 1585 and by Lucas Janszon Waghenaer in 1586.

First attempt at deep-sea sounding.

Probably the first attempt at oceanographical research to which the term "scientific" may be applied is Magellan's unsuccessful effort to determine the depth of the Pacific Ocean during the first circumnavigation of the globe. In 1521, we are told, Magellan tried to sound the ocean between the two coral islands, St. Paul and Los Tiburones in the Low Archipelago, making use of the sounding lines carried by explorers at that period, which were only 100 to 200 fathoms in length. He failed to touch bottom, and therefore concluded that he had reached the deepest part of the ocean. This first authentic attempt at deep-sea sounding ever made in the open sea is historically extremely interesting, though scientifically the result was negative.

Magellan.

The expedition of Edmund Halley, Astronomer-Royal, in 1699, to improve our knowledge concerning longitude and the variation of the compass, was a purely scientific voyage, though it may be said that scientific voyages were really initiated at the time of James Cook in the second half of the eighteenth century. Halley's expedition.

Cruquius introduced bathymetrical contours on a chart of the River Merwede published in 1728. Thus contour lines were first used on maps to show the depths of the sea and not the heights of the land. Bathymetrical contours laid down on maps. Cruquius.

In a map published by Philippe Buache in 1737 we find the bottom of the sea again represented by isobathic curves, intended to show that certain elevations of the sea-floor correspond to the orography of the neighbouring land. He develops these ideas in his Essay on Physical Geography, published in 1752, maintaining that the globe is sustained by chains of mountains crossing the sea as well as the land, forming as it were the framework of the globe—a view previously expressed by Father Athanasius Kircher. His conception of submarine mountains was a first step towards founding geography on the real form and relief of each region. Buache. Kircher.

The dredge seems to have been first used by two Italians, Marsigli and Donati, about the year 1750, for obtaining marine organisms from shallow water, and a modification of this form was introduced by O. F. Müller in 1799, which was known as the naturalist's dredge. First use of dredge. Marsigli and Donati. O. F. Müller.

In the middle of the eighteenth century Dalrymple and Davy made observations on the temperature of the equatorial currents during a voyage to the East Indies. Temperature observations. Dalrymple and Davy.

In 1770 Benjamin Franklin published the first map of the Gulf Stream (see figure in Chapter V.), and in 1776 Charles Blagden was engaged in the study of temperature distribution on the North American coasts, reporting on his results to the Royal Society of London in 1781. Benjamin Franklin. Blagden.

During Cook's voyages (1772–73), temperature observations beneath the surface were taken by the Forsters, father and son, but the first use of self-registering thermometers for determining the temperature beneath the surface of the sea was during Lord Mulgraves' expedition to the Arctic in 1773 by Dr. Irvine, who seems also to have constructed a water-bottle for bringing up water-samples from various depths, one sample giving a reading of 40° Fahr., while the surface temperature was 55° Fahr. James Cook. The Forsters. Irvine.

Phipps' deep-sea soundings.

During this expedition also some of the earliest attempts at deep-sea sounding were made by Captain Phipps, the deepest sounding being 683 fathoms, from which depth he brought up a sample of Blue mud.

Saussure.

In 1780 Saussure determined the temperature of the Mediterranean at depths of 300 and 600 fathoms by protected thermometers, and in 1782 Six's maximum and minimum thermometer was invented, and subsequently made use of by Krusenstern in 1803, by Kotzebue in 1815, by Sir John Ross accompanied by Sir Edward Sabine in 1818, by Parry in 1819, and by Dumont d'Urville in 1826. Slow-conducting water-bottles were used by Péron in 1800, by Scoresby in 1811, who recorded warmer water beneath the colder surface layers in the Arctic regions, and by Kotzebue accompanied by Lenz in 1823. Protected thermometers were used for deep-sea temperatures by Thouars in 1832, by Martins and Bravais in 1839, and by Sir James Clark Ross during his Antarctic expedition from 1839 to 1843, the last-mentioned making also many observations on the density of the water at various depths. In 1843 Aimé introduced reversible outflow thermometers, and about 1851 Maury used cylinders of non-conducting material for taking temperatures in deep water. But it was only when thermometers with bulbs properly protected from pressure came into use that oceanic temperatures could be recorded with precision. The first thermometer of this kind seems to have been used in 1857 by Captain Pullen of H.M.S. "Cyclops," and shortly thereafter improved forms of the Six pattern (Miller-Casella) and of Negretti and Zambra's reversing pattern were introduced, and have been largely used ever since, improvements and modifications being incorporated from time to time.

Krusenstern. Kotzebue. John Ross and Sabine. Parry. d'Urville. Péron. Scoresby. Lenz. Thouars. Martins and Bravais. James Clark Ross. Aimé. Maury. Pullen.

CAPTAIN JAMES COOK.

Scoresby in 1811 recorded some soundings off the coast of Greenland, and Sir John Ross during his voyage to Baffin's Bay in 1817–18 took some deep soundings by means of an apparatus, designed by him and made on board, called "deep-sea clamms," in depths of 450, 650, 1000, and 1050 fathoms, bringing up from the last-mentioned depth several pounds of greenish mud. With the deposit-samples worms and other animals were brought up, and when sounding in 1000 fathoms a star-fish was found entangled in the line a little distance above the mud, thus proving that animal life was present in deep water.

Deep soundings. Scoresby. John Ross.

Deep-sea animals.

In 1817 Romme published in Paris a work on winds, tides, and currents, and Risso in 1826, Lowe from 1843 to 1860, Johnson from 1862 to 1866, and Günther from 1860 to 1870, published important papers dealing with deep-sea and pelagic fishes. In 1832 James Rennell published an investigation of the currents of the Atlantic Ocean, based upon the observations recorded by sailors up to that time.

Romme. Risso. Lowe. Johnson. Günther. Rennell.

During the United States Exploring Expedition in 1839–1842 under Captain Wilkes, accompanied by Dana, several deep soundings were taken with the aid of a copper wire, and a few dredgings in shallow water were also made.

Wilkes and Dana.

Important sounding and dredging work was carried out by Sir James Clark Ross, accompanied by Hooker, during the British Antarctic Expedition in 1839 to 1843, the first truly oceanic soundings in depths exceeding 2000 fathoms being taken. After many unsuccessful attempts to sound in deep water, due to the want of a proper line, Ross had a line 3600 fathoms in length specially constructed on board. It was fitted with swivels here and there, strong enough to carry a weight of 76 lbs., and was allowed to run out from an enormous reel in one of the ship's boats. With this line the first abysmal sounding on record was taken in 2425 fathoms on the 3rd January 1840, in lat. 27° 26′ S., long. 17° 29′ W., and frequently during the cruise similar and greater depths were sounded. Such deep soundings could only be attempted in calm weather, and a note was kept of the time each 100-fathoms mark left the reel, a lengthening of the time-interval indicating when the weight had reached the bottom. The dredge also was successfully used during this expedition in depths down to 400 fathoms, abundant evidence of animal life being forthcoming, though unfortunately the deep-sea zoological collections were

British Antarctic Expedition. James Clark Ross and Hooker.

Soundings in very deep water

Introduction of time intervals in sounding.

Dredgings in deep water.

subsequently lost to science. In April 1840 the dredge came up full of coral from a depth of 95 fathoms, and in the following January dredgings in 270 and 300 fathoms gave abundance of marine invertebrates in great variety, the deepest dredging in 400 fathoms in August 1841 bringing up some beautiful specimens of coral, corallines, flustræ, and a few crustaceous animals.

Hooker on Antarctic diatoms.

Hooker made known some of Ross's results, and drew attention to the great rôle played by diatoms in the seas of the far south.

Sir James Clark Ross.

British Association Dredging Committee.

Edward Forbes.

Audouin and Milne-Edwards.

Michael Sars.

In 1839 the British Association appointed a Committee to investigate the marine zoology of Great Britain by means of the dredge, the ruling spirit of this Committee being Edward Forbes, who made many observations on the bathymetrical distribution of life in various seas. Before this time, it is true, Audouin and Milne-Edwards in 1830, and Michael Sars in 1835, had published the results of dredgings in comparatively shallow waters within limited areas along the coasts of Europe.

In 1840–41 Forbes studied the fauna of the Ægean Sea, taking a great many dredgings at different depths, and came to the conclusion that marine animals were distributed in zones of depth, each characterised by a special assemblage of species. He divided the area occupied by marine animals into eight zones, in which animal life gradually diminished with increase of depth, until a zero was reached at about 300 fathoms. He supposed that plants, like animals, disappeared at a certain depth, the zero of vegetable life being at a less depth than that of animal life. In his Report on the Investigation of British Marine Zoology by means of the Dredge (1850), Forbes suggested that dredgings off the Hebrides and the Shetlands, and between the Shetland and Faroe Islands, would throw much light on marine zoology, thus pointing to the scene of the subsequent important work carried on by Carpenter and Wyville Thomson, and Murray and Tizard.

Forbes' observations in Ægean Sea.

Marine animals distributed in zones of depth.

Zero of life in the sea.

Professor Michael Sars.

Lovèn.

In 1844 Lovèn carried on researches on the distribution of marine organisms along the Scandinavian coasts, confirming and extending the observations recorded by Forbes, and in 1845 Johannes Müller commenced to study the pelagic life of the sea by examining samples of sea-water and by means of the tow-net, thus giving a great impetus to the study of marine biology.

John Franklin and Goodsir.

In 1845 Sir John Franklin set sail on his ill-fated North Polar Expedition, accompanied by Harry Goodsir, who recorded the results of dredging in depths of 300 fathoms.

Spratt.

In 1846 Spratt took dredgings in the Mediterranean down to a depth of 310 fathoms; he afterwards brought up shell-fragments from a depth of 1620 fathoms in the Mediterranean.

Michael Sars and G. O. Sars.

In 1850 Michael Sars published the results of his dredgings off the coast of Norway, giving a list of 19 species living at depths greater than 300 fathoms. He was afterwards assisted by his son, G. O. Sars, in carrying on this work, and in 1864 they gave a list of 92 species living in depths between 200 and 300 fathoms, and showed a few years later that marine life was abundant down to depths of 450 fathoms.

MacAndrew.

In 1856 MacAndrew published the results of his observations on the marine Mollusca of the Atlantic coasts of Europe and northern Africa, giving a list of 750 species obtained in his dredgings, which covered 43 degrees of latitude.

United States Coast Survey.

The oceanographical researches of the United States Coast Survey may be said to date back to 1844, when the Director, Bache, issued instructions to his officers to preserve the deposit-samples brought up by the sounding-machine. J. W. Bailey studied these deposit-samples, and published the result of his examination in 1851, followed in 1856 by other papers on deposits and on the formation of greensand in modern seas.

Bailey.

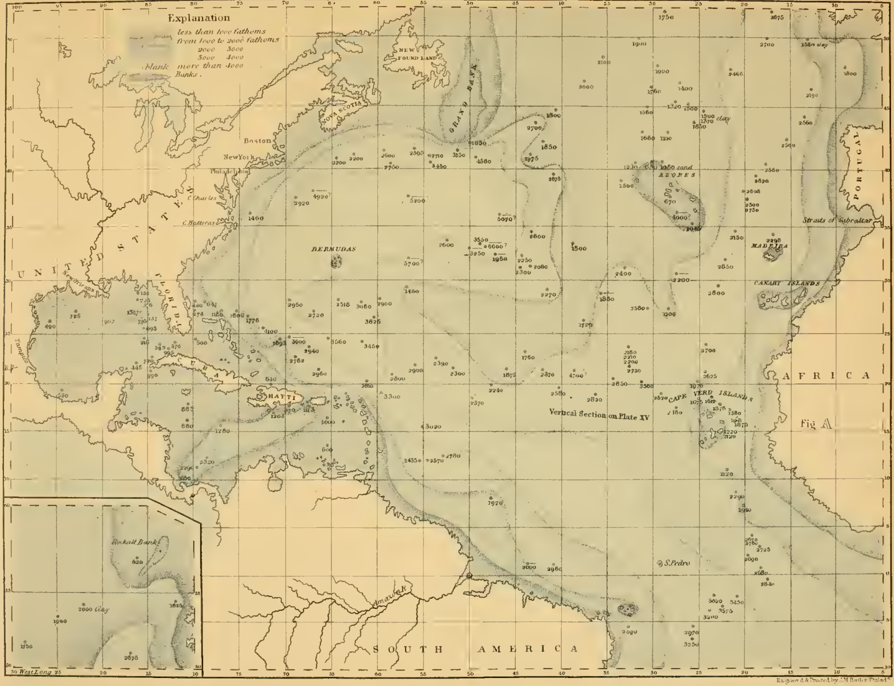
Maury.

The name of M. F. Maury, of the United States Navy, was for a long period associated with the hydrographical work of the United States. He issued several editions of his Sailing Directions to accompany the wind and current charts published by the U.S. Hydrographic Office, the last edition appearing in 1859. About this time the need was felt for an improved and more trustworthy method of sounding in deep water, and various attempts were made to devise forms of apparatus to replace the heavy weight attached to a line which had to be let down and then drawn up to the surface again, the difficulty being to know when the weight touched the bottom. This problem was finally solved by Midshipman Brooke, who conceived the idea of detaching the weight used to carry down the sounding lead upon striking the bottom, the sounding tube, enclosing its deposit-sample, being alone drawn to the surface. He used a spherical weight (a bullet), with a hole passing through the centre to receive the sounding tube, suspended by a cord to the upper part of the sounding tube; on touching the bottom the cord was thrown off its support and remained at the bottom along with the weight. With the aid of Brooke's sounding apparatus, the records of deep-sea soundings rapidly accumulated, and enabled Maury to prepare the first bathymetrical map of the North Atlantic Ocean, with contour-lines drawn in at 1000, 2000, 3000, and 4000 fathoms, which was published in 1854 and is reproduced in Map I. The deposit-

Brooke's sounding apparatus.

Maury's map of North Atlantic.

REPRODUCTION OF LIEUT. MAURY'S MAP OF NORTH ATLANTIC, 1854



Engraved & Printed by J. M. Butler Philad.

samples procured were examined and described by Bailey and by Pourtalès, the results being of great importance and interest. Pourtalès.

Systematic soundings in the North Atlantic were commenced by Lee in the U.S.S. "Dolphin" in 1851–52, and continued in the same vessel by Berryman in 1852–53. In 1856 Berryman on the U.S.S. "Arctic" sounded across the North Atlantic from Newfoundland to Ireland, with the object of verifying the existence of a submarine ridge, along which it was proposed to lay a telegraph cable; his deposit-samples were described by Bailey. Systematic soundings. Lee. Berryman.

In 1857 Pullen and Dayman in H.M.S. "Cyclops" ran a line of soundings along the great circle from Ireland to Newfoundland, a little to the north of Berryman's line. A modification of Brooke's sounding-machine was used, in which the spherical weight was replaced by a cylindrical one suspended by wire instead of cord, and with a different valve for collecting the deposit. The deposit-samples were examined and described by Huxley, who found in the bottles a viscous substance, described by him as *Bathybius*, which was subsequently shown by the "Challenger" observers to be a chemical precipitate thrown down from the sea-water associated with the deposits by the alcohol used in their preservation. Pullen and Dayman. Huxley. *Bathybius*.

In 1858 Dayman in H.M.S. "Gorgon" sounded across the North Atlantic from Newfoundland to the Azores, and thence to the south-west of England. Dayman.

In 1860 Sir Leopold M'Clintock on board H.M.S. "Bulldog" surveyed the route for the telegraph cable between England and America, in the region previously sounded by Berryman and Dayman. He was accompanied by G. C. Wallich, who published in 1862 an interesting account of the very important observations he made during the cruise on life in deep water and on the deposits covering the floor of the North Atlantic. M'Clintock and Wallich.

In 1860 a telegraph cable laid along the bed of the Mediterranean gave way at a depth of 1200 fathoms, and was raised for repair by Fleeming Jenkin, who brought up to the surface portions of the cable about forty miles in length, to which living organisms were found attached. Corals were growing on the cable at the place where it broke in 1200 fathoms, and other forms were adhering to the cable where it had lain in lesser depths, including molluscs, worms, bryozoa, alcyonarians, and hydroids, thus establishing beyond all doubt Animals attached to submarine cable.

the fact that members of the higher groups of animals really lived at great depths in the sea.

Since 1861 Swedish and Norwegian expeditions to the Arctic regions and the North Atlantic have been numerous, and during one of these in 1864 many animals were dredged from depths of 1000 to 1400 fathoms by Otto Torell. In the same year Bocage published a paper on the occurrence of the glass-rope sponge (*Hyalonema*) at depths of 500 fathoms off the coast of Portugal, which was confirmed in 1868 by Perceval Wright, who went there for the purpose and dredged up specimens from 480 fathoms.

Torell.

Bocage.

Perceval Wright.

From the year 1867 dredgings as well as soundings were carried out under the auspices of the United States Coast Survey by Pourtalès and Louis Agassiz off the coast of Florida, and between Cuba and Florida. Pourtalès took up the examination of the deposit-samples after the death of Bailey, the number of samples collected up to 1870 being nine thousand. Louis Agassiz reported on the results of the dredgings, and compared some of the dredged forms with fossil types; he concluded by stating his conviction that the continental areas and the oceanic areas have occupied from the earliest times much the same positions as at the present day.

Pourtalès.

Louis Agassiz.

Permanence of oceanic and continental areas.

Sir C. Wyville Thomson.

In 1868 were commenced a series of short cruises in the North Atlantic and Mediterranean, under the direction of British naturalists, which may be regarded as preliminary and leading up to the great "Challenger" Expedition. Thus in 1868 Wyville Thomson and W. B. Carpenter carried out oceanographical work on board H.M.S. "Lightning," taking dredgings in depths down to 650 fathoms, and showing beyond question that animal life is there varied and abundant, represented by all the invertebrate groups, a large proportion of the forms belonging to species hitherto unknown, others being specifically identical with tertiary fossils hitherto believed to be extinct, or illustrating extinct groups of the fauna of more remote periods. The temperature observations seemed to

H.M.S. "Lightning."

Wyville Thomson and W. B. Carpenter.

disclose two adjacent regions in which the bottom temperatures differed as much as 15° Fahr. (30° Fahr. in the one region and 45° Fahr. in the other), and it was concluded that great masses of water at different temperatures were moving about, each in its particular course, maintaining a remarkable system of oceanic circulation, and yet keeping so distinct from one another that one hour's sail might be sufficient to pass from the extreme of heat to the extreme of cold.

Peculiar temperature conditions in the Faroe Channel.

In 1869 Gwyn Jeffreys was associated with Carpenter and Wyville Thomson in carrying on the work on board H.M.S. "Porcupine," which made three cruises: (1) to the west of Ireland, where dredgings down to 1470 fathoms were taken; (2) to the Bay of Biscay, where dredgings were taken in depths exceeding 2000 fathoms; and (3) to the Faroe Channel to confirm and extend the "Lightning" observations. In 1870 the "Porcupine" carried on work in the Mediterranean and the Strait of Gibraltar, which was continued in 1871 on board H.M.S. "Shearwater."

H.M.S. "Porcupine." Jeffreys, Carpenter, and Thomson.

About the same time Leigh Smith made several voyages to the Arctic regions, and, like Scoresby, recorded warmer layers of water beneath the colder surface waters of the Arctic Ocean.[1]

Leigh Smith.

The researches briefly noticed in the preceding paragraphs paved the way for the special investigation of the physical, chemical, and biological conditions of the great ocean basins of the world carried out on board H.M.S. "Challenger" from December 1872 to May 1876 by a staff of scientific observers. During this period she circumnavigated the world, traversed the great oceans in many directions, made observations in nearly all departments of the physical and biological sciences, and laid down the broad general foundations of the recent science of oceanography. The results of the "Challenger" Expedition were published by the British Government in fifty quarto volumes, and became the starting-point for all subsequent observations.

The "Challenger" Expedition.

Contemporaneous with the "Challenger" Expedition was that of the U.S.S. "Tuscarora," under Belknap, in the Pacific Ocean, which contributed greatly to our knowledge of the

The "Tuscarora." Belknap.

[1] Leigh Smith's temperature observations were published in *Proc. Roy. Soc. Lond.*, vol. xxi. pp. 94 and 97, 1873, and in *Natural Science*, vol. xi. p. 48, 1897. In the former paper Wells quotes a reading of 64° F. in 600 fathoms and a reading of 42° F. at 300 fathoms near Spitzbergen, and argues that they indicate the southward flow of a vast body of warm water from the circumpolar region, while in the latter paper Leigh Smith refers to a warm undercurrent running into the Arctic basin between Greenland and Spitzbergen.

distribution of temperature in that ocean and of the deep-sea deposits covering its floor. Piano wire was first used for oceanic sounding work on board the "Tuscarora," though for some years previously Sir William Thomson (Lord Kelvin) had been experimenting with it on board his yacht.

Piano wire used for sounding.

Lord Kelvin.

Also contemporaneous with the "Challenger" Expedition was the circumnavigating cruise of the German ship "Gazelle," during which many valuable oceanographical observations were recorded.

The "Gazelle."

In 1876 the U.S.S. "Gettysburg" took a series of deep-sea soundings in the North Atlantic, and in the years 1876 to 1878 the Norwegian North Atlantic Expedition on board the S.S. "Vöringen" made important physical and biological observations in the seas between Norway and Greenland, making thus the first survey of the Norwegian Sea; the scientific results were published in English and Norwegian.

The "Gettysburg."

The "Vöringen."

Dr. Alexander Agassiz.

From 1877 to 1880 the United States Coast Survey steamer "Blake" explored the Caribbean Sea, the Gulf of Mexico, and the coasts of Florida, under the direction of Alexander Agassiz, who published in 1888 a general account of the results. At the same time the U.S. Fish Commission steamer "Albatross" was engaged in making observations along the Atlantic coast of the United States, and later, in 1891, explored the Panamic region of the Pacific under the direction of Alexander Agassiz.

Alexander Agassiz.

The "Blake."

The "Albatross."

During the "Challenger" Expedition the naturalists became convinced, as a result of their observations in different parts of the world, that a ridge must separate the bodies of cold and warm water found by the "Lightning" and "Porcupine"

Expeditions to occupy the Faroe Channel. On the representations of Murray and Tizard, H.M.S. "Knight Errant" in 1880, and H.M.S. "Triton" in 1882, were engaged in re-examining the Faroe Channel. The result was the discovery of the Wyville Thomson Ridge, which separates the warm and cold areas, and accounts for the great difference in the marine faunas in the deep water on either side of this ridge. Detailed lists of the animals obtained by these four expeditions were published in a paper by Murray,[1] who shows that 216 species and varieties were recorded from the warm area, and 217 species and varieties from the cold area, while only 48 species and varieties were found to be common to the two areas.

Murray and Tizard. The "Knight Errant." The "Triton." Wyville Thomson Ridge.

From 1880 to 1883 the French ships "Travailleur" and "Talisman" investigated the eastern Atlantic, while from 1881 to 1885 the Italian ships "Washington" and "Vettor Pisani," the former in the Mediterranean and the latter during a circumnavigating cruise, were engaged in biological and other scientific work.

The "Travailleur." The "Talisman." The "Washington." The "Vettor Pisani."

In 1883 J. Y. Buchanan took part in the sounding expedition of the S.S. "Dacia," belonging to the India-Rubber, Gutta-Percha, and Telegraph Works Company, of Silvertown, when surveying the route for a submarine cable from Cadiz to the Canary Islands, which resulted in the discovery of several oceanic shoals rising steeply from deep water; and again in 1885–86 he joined the same company's S.S. "Buccaneer" while exploring the Gulf of Guinea, accompanied by a trained naturalist, John Rattray, when valuable observations as to the depth, temperature, density, currents, and plankton were made.

J. Y. Buchanan. The "Dacia." The "Buccaneer." John Rattray.

During the years 1883 to 1886 the U.S.S. "Enterprise" brought together a most important collection of deposit-samples taken throughout a cruise embracing all the great oceans.

The "Enterprise."

From 1884 to 1892 Murray investigated the sea-lochs along the west coast of Scotland on board his steam-yacht, the "Medusa," and discovered in the deeper waters of Loch Etive and Upper Loch Fyne remnants of an Arctic fauna. The physical results obtained were used by Mill in his Memoir on the Clyde Sea Area.[2]

John Murray. The "Medusa." H. R. Mill.

Since the year 1885 the Prince of Monaco has carried on oceanographical work in a systematic manner in the Mediter-

Prince of Monaco.

[1] "The Physical and Biological Conditions of the Seas and Estuaries about North Britain," *Proc. Phil. Soc. Glasgow*, vol. xvii. p. 306, 1886.

[2] *Trans. Roy. Soc. Edin.*, vols. xxxvi. and xxxviii., 1891, 1894.

ranean and North Atlantic on board his yachts "Hirondelle," "Hirondelle II," "Princesse Alice," and "Princesse Alice II,"

H.S.H. The Prince of Monaco.

and he has founded and endowed a magnificent oceanographical museum at Monaco and an oceanographical institute in Paris; many important memoirs have been issued from the Monaco press.

From 1886 to 1889 the Russian steamer "Vitiaz," under Makaroff, made a voyage round the world, during which valuable observations on the temperature and specific gravity of the waters of the North Pacific were made, and in 1890 Russian scientists, notably Lebedinzeff and Andrusoff, investigated the physical and biological conditions in the deep water of the Black Sea. The "Vitiaz." Makaroff. Lebedinzeff and Andrusoff. Observations in Black Sea.

In 1889 a German expedition on board the S.S. "National" was despatched to the North Atlantic, with the special object of studying the plankton (hence called the Plankton Expedition) by improved methods, under the direction of Victor Hensen, who was accompanied by several other scientific men. The "National." Plankton Expedition. V. Hensen.

Professor Victor Hensen.

From 1890 till 1898 the Austrian steamer "Pola" made observations in the Mediterranean and the Red Sea, the chemical work being in the hands of Natterer, who published some interesting results. The "Pola." Natterer.

In 1890 systematic observations in the North Sea and adjacent waters were commenced by Swedish investigators under Otto Pettersson and Gustav Ekman, important results as to temperature, salinity, alkalinity, currents, gases, and plankton being achieved, a summary of which was published by Pettersson in English.[1] O. Pettersson and G. Ekman.

During the years 1893 to 1896 Nansen made his remarkable drift on board the "Fram" across the North Polar Sea, during which valuable oceanographical observations were taken, his soundings tending to prove that the position of the North Pole is occupied not by land but by a deep sea, as Murray had Nansen's drift in the "Fram."

[1] *Scott. Geogr. Mag.*, vol. x., 1894.

previously indicated. His scientific results were published in the English language in six handsome volumes.

The "Ingolf." During 1895 and 1896 the Danish ship "Ingolf" was engaged in the investigation of the northerly portions of the Atlantic, the physical and biological results being published in English.

Survey of Scottish lakes. John Murray. F. P. Pullar. Laurence Pullar. From 1897 to 1909 Sir John Murray, associated at first with F. P. Pullar and afterwards with Laurence Pullar, carried out a bathymetrical survey of the Scottish fresh-water lochs, including detailed physical and biological observations, and the report on the scientific results was published in six volumes in 1910. During these investigations very careful observations were made by Chrystal on seiches, as a result of which our knowledge of these oscillations and their causes was widely extended. Another kind of oscillation was also discovered, which has been called the temperature seiche. This occurs at the discontinuity layer, where there is a rapid fall of temperature. This temperature oscillation in Loch Ness had a period of about three days, and a maximum rise and fall of about 200 feet. The period of these oscillations is dependent on the difference in density between the upper warm layer and the lower cold layer: the smaller the difference in density, *i.e.* the smaller the temperature differences in a lake, the longer does the period of the oscillation become. These observations in the Scottish lakes have recently been extended by further systematic work in Loch Earn under E. M. Wedderburn, and have already suggested explanations of phenomena in the ocean, where long-period oscillations are observed in various depths, and the explanation is probably the same as that given for the lakes.

Chrystal's observations on seiches.

Temperature seiche.

Wedderburn.

The "Belgica." In the years 1897 to 1899 the Belgian Antarctic Expedition on board the "Belgica" carried on important work. This was the first vessel to winter in the Antarctic regions, and the scientific results are necessarily of great interest and value.

The "Valdivia." In 1898–99 the German Deep-Sea Expedition on board the "Valdivia" investigated the physical and biological conditions of the Atlantic and Indian Oceans, penetrating into the Antarctic as far as the ice would permit. The extremely valuable scientific results are being issued in a series of magnificent memoirs under the editorship of Chun, the leader of the expedition.

Chun.

The "Nero." In 1899 the U.S.S. "Nero" surveyed the route for a telegraph cable between the Sandwich and Philippine Islands by way of Midway and Ladrone Islands, many of the soundings being in very deep water, including the deepest cast hitherto recorded, viz. 5269 fathoms, in the vicinity of Guam Island in the Ladrone group. The deposit-samples brought home were examined by Flint,[1] who records many distinct patches of Diatom ooze within the tropics, but Murray has examined these samples, and declares them to be identical with what he has called Radiolarian ooze; the frustules of the large *Coscinodiscus rex* are, however, very numerous in these deposits.

Flint.

Professor Carl Chun.

The "Albatross," 1899–1900.

Alexander Agassiz.

In 1899–1900 the U.S.S. "Albatross" carried on oceanographical observations throughout the tropical portions of the Pacific, under the personal direction of Alexander Agassiz, who issued the scientific results in a series of profusely illustrated memoirs, under the auspices of the Museum of Comparative Zoology, Cambridge, Mass.

The "Siboga."

Max Weber.

In 1899–1900 the Dutch steamer "Siboga" investigated the oceanographical conditions in the seas of the Dutch East Indies. Though limited to such a circumscribed area the observations are of great value, and the results are being issued in English, German, or French, under the editorship of the leader of the expedition, Max Weber of Amsterdam.

The "Discovery." Scott.

The "Gauss."

The "Antarctic."

During the years 1901 to 1903 the British National Antarctic Expedition on board the "Discovery" under Scott, the German South Polar Expedition on board the "Gauss" under von Drygalski, and the Swedish South Polar Expedition on board the "Antarctic" under Otto Nordenskjöld, were

[1] "A Contribution to the Oceanography of the Pacific," *Bull. U.S. Nat. Mus.*, No. 55, Washington, 1905.

simultaneously engaged in the exploration of different portions of the Antarctic regions, and in 1902–1904 the Scottish National Antarctic Expedition on board the "Scotia" under Bruce was likewise busy in the far south. The results of all these expeditions have added very largely to our knowledge of the oceanography of the Antarctic.

The "Scotia."
Bruce.

Between 1903 and 1911 the German ships "Edi," "Stephan," and "Planet" took many soundings throughout the different ocean basins, the last-mentioned recording the greatest known depth in the Indian Ocean.

The "Edi." The "Stephan." The "Planet."

In 1904 we find the U.S.S. "Albatross" again carrying on oceanographical work in the eastern Pacific under the personal direction of Alexander Agassiz, the published results constituting a great advance in our knowledge of the Pacific Ocean.

The "Albatross," 1904.
Alexander Agassiz.

Dr. Anton Dohrn.

In 1907–1909 another British Antarctic Expedition on board the "Nimrod," under Shackleton, was engaged in making scientific observations and pushing south beyond anything previously attained. The biological work was under the direction of James Murray, formerly of the Scottish Lake Survey, and the results issued under his editorship are excellent in quality.

The "Nimrod."
Shackleton.
James Murray.

Mention may also be made of the two French Antarctic Expeditions under Charcot, the first from 1903 to 1905 on board the "Français," and the second from 1908 to 1910 on board the "Pourquoi pas?" Still more recently the German Antarctic Expedition of 1911 on board the "Deutschland" has, during the outward voyage, taken valuable serial

The "Français."
The "Pourquoi pas?"
The "Deutschland."

temperatures and salinities off the Atlantic coast of South America.

In addition to the specific expeditions referred to in the foregoing paragraphs, many British surveying and cable ships have been busily engaged during the past thirty years amassing valuable information regarding the depth of the ocean in various parts of the world. Temperature observations were also included in the work carried on by H.M. surveying ships, and by some of the cable ships when accompanied by scientific men like J. Y. Buchanan and R. E. Peake. The principal ships and the oceans investigated by them may be here briefly enumerated :— British surveying ships.

H.M.S. "Egeria"	Atlantic, Indian, and Pacific	1887 to 1899
H.M.S. "Waterwitch"	" "	1894 " 1901
H.M.S. "Rambler"	" "	1888 " 1904
H.M.S. "Penguin"	Indian and Pacific	1890 " 1906
H.M.S. "Stork"	Indian and Atlantic	1888 " 1897
H.M.S. "Investigator"	Indian Ocean	From 1886 to the present time
H.M.S. "Dart"	Pacific Ocean	1888 to 1902

Other ships were engaged in one or other of the great oceans for shorter periods, including H.M.Ss. "Myrmidon," "Marathon," "Flying Fish," "Goldfinch," "Sealark," "Sylvia," "Fantome," and "Mutine."

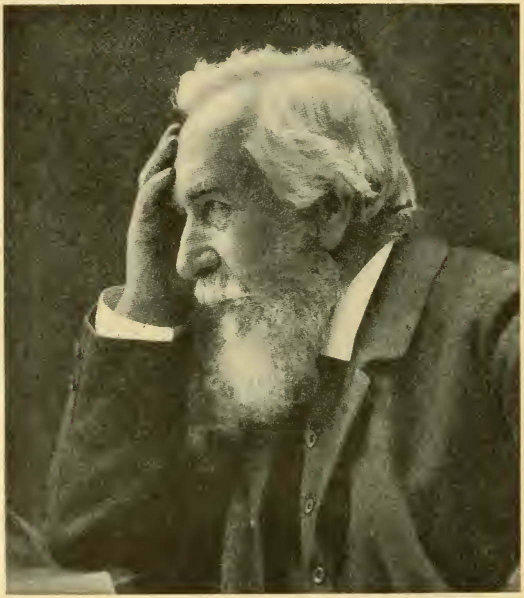
Of British cable ships mention may be made of the following :— British cable ships.

S.S. "Britannia"	Atlantic, Indian, and Pacific	1888 to 1907
S.S. "Great Northern"	Atlantic and Indian	1882 " 1897
S.S. "Chiltern"	" "	1886 " 1897
S.S. "Amber"	" "	1888 " 1906
S.S. "Scotia"	" "	1883 " 1898
S.S. "Seine"	" "	1885 " 1899
S.S. "Electra"	" "	1887 " 1903
S.S. "John Pender"	" "	1878 " 1901
S.S. "Duplex"	" "	1906 " 1907
S.S. "Silvertown"	Atlantic and Pacific	1889 " 1900
S.S. "Retriever"	" "	1880 " 1907
S.S. "Sherard Osborn"	Indian and Pacific	1888 " 1907
S.S. "Recorder"	" "	1888 " 1907
S.S. "Dacia"	Atlantic	1883 " 1905
S.S. "Minia"	"	1885 " 1907
S.S. "Norseman"	"	1893 " 1907
S.S. "Buccaneer"	"	1886 " 1906

Many other ships were engaged for shorter periods, including

S.Ss. "Westmeath," "Roddam," "Volta," "Mirror," "Viking," "Grappler," "Faraday," "Anglia," "Newington," "Henry Holmes," "Cambria," "International," "Clan McNeil," "Patrick Stewart," "Cruiser," "Colonia," "Magnet," etc.

It is quite impossible in this brief review even to mention the names of all the investigators and authors who have during the past thirty years made important original contribu-



Professor Ernst Haeckel.

tions to the science of oceanography. Among those who have not taken an active part in extensive explorations and expeditions, but whose influence on the development of the science has been very great, the names of Ernst Haeckel and Anton Dohrn should be mentioned. Through his voluminous publications on the radiolaria and on other marine groups in the "Challenger" Reports, through his charming Plankton-Studien, and through his more popular writings, Haeckel has created a widespread interest in all marine

Ernst Haeckel.

investigations among the intelligent reading public of the whole world.

Although small and more or less permanent marine laboratories had been established on various parts of the European and American coasts previous to 1880, it must be acknowledged that the foundation of the Zoological Station at Naples in that year by Anton Dohrn marks an era in all that concerns the histology and embryology of marine organisms, and these studies have in turn given a great impetus to the systematic investigation of many purely oceanic problems.

The work of marine biological laboratories and of international and other fishery investigations.

Anton Dohrn.

Similar marine laboratories have since been founded in many parts of the world, some for researches of purely scientific interest and others for the investigation of economic questions connected with the study of the habits and development of the food fishes.

Professor Otto Pettersson.

By far the most important of these organisations was that resulting from an International Hydrographic Congress held in Stockholm in 1899, which was largely brought about by the exertions of Otto Pettersson. An International Commission for the Scientific Investigation of the North Sea was established, the participating countries being Great Britain, Germany, Holland, Belgium, Russia, Denmark, Sweden, and Norway. Many important researches have been undertaken, and many elaborate reports have been issued by the scientific staffs of each of the countries concerned. This international work, which has been carried on for over ten years, and is still in operation, has given a great impulse to nearly all departments of oceanic science, one result among the many others being the organisation of the "Michael Sars" Expedition in the North Atlantic in 1910, to an account of which this volume is chiefly devoted.

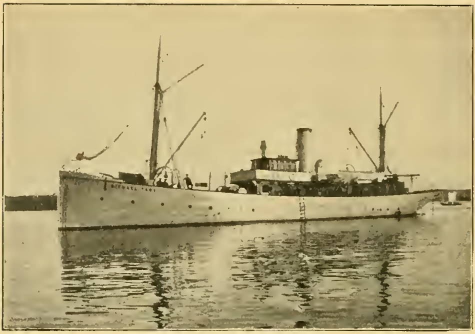
Hydrographic Congress, 1899.

Pettersson.

International North Sea Council.

The "Michael Sars" North Atlantic Expedition, 1910.

J. M.



S.S. "Michael Sars."

CHAPTER II

THE SHIP AND ITS EQUIPMENT

Difficulties experienced in making deep-sea observations.

It has often been said that studying the depths of the sea is like hovering in a balloon high above an unknown land which is hidden by clouds, for it is a peculiarity of oceanic research that direct observations of the abyss are impracticable. Instead of the complete picture which vision gives, we have to rely upon a patiently put together mosaic representation of the discoveries made from time to time by sinking instruments and appliances into the deep, and bringing to the surface material for examination and study. Our difficulties are greatly increased by the fact that it is impossible to watch our apparatus at work. A trawl, for instance, is lowered to a great depth, and a few fathoms below the surface it disappears from view; later on it is brought on board and found to be empty. Is this because there was nothing to catch where it was operating, or has it somehow or other got out of order, or failed to reach the bottom, or met with some similar mishap, and so been prevented from catching anything? These questions can only be answered by examining the trawl when once more on deck, and drawing one's conclusions accordingly.

Importance of development of mechanical aids in deep-sea work.

Obviously, therefore, the progress of oceanography depends to a great extent upon the development of mechanical aids, by which we mean not only the scientific instruments employed, but also the whole arrangements of the ship itself. To be able

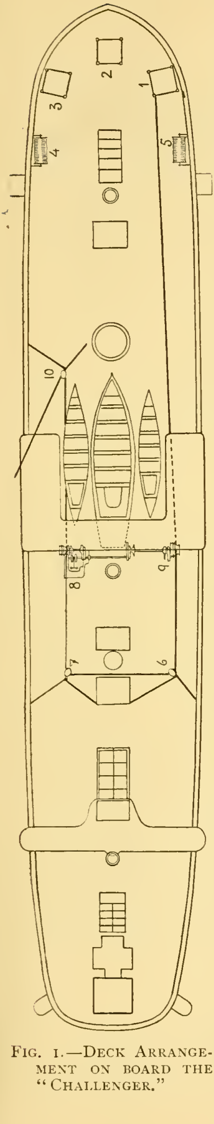


FIG. 1.—DECK ARRANGEMENT ON BOARD THE "CHALLENGER."

to haul in some thousands of fathoms of line within reasonable time would be quite out of the question without a steam-winch, and it is precisely because the use of steam first made it possible to examine properly the vast marine areas of the world that oceanic research is such a comparatively new science. The cruise of the "Challenger," the first great expedition specially fitted out to investigate the ocean, took place during the years 1872–76. Since then oceanography has made giant strides, and we have now many appliances at our disposal that were unknown to the pioneers of those days.

It is interesting to compare our modern methods with those of the "Challenger" Expedition, for we can then see what great advances have been made, and realise to what extent we have availed ourselves of the scientific inventions of our times. A critical examination of the mode of working adopted by the "Michael Sars" will be of use in this connection.

The "Challenger" Expedition.

The "Challenger" was a spar-deck corvette of 2306 tons displacement, with an auxiliary engine of 1234 indicated horse-power. The length of her deck was 226 feet, and her greatest breadth was 36 feet.

Almost amidships on her main deck, and just before the main mast, was a big steam-winch of 18 horse-power, with a long axle that extended right across the ship and carried large end-drums (see Fig. 1, 8). Hemp lines were used, which were hauled in by being passed round the end-drums.

Methods employed on board.

The sounding-line was operated by two large reels on the forecastle, 5 feet long and $2\frac{1}{2}$ feet in diameter (4 and 5), 3000 fathoms of line, one inch in circumference, to each reel. The breaking strain was about 700 kilos (14 cwt.), and the weight of 3000 fathoms of line in water was roughly 108 kilos. When heaving the lead the weight used was sometimes 150 and sometimes 200 kilos. During the whole of the voyage of the "Challenger" only two temperature lines with eight thermometers, and nine sounding-lines with thirteen thermometers, were lost; eleven thermometers collapsed under high pressure at great depths.

For dredging and trawling they employed hemp lines 2, $2\frac{1}{2}$, and 3 inches in circumference, with a breaking strain from 1600 to 2550 kilos, spliced together to form a length of 4000 fathoms, which was coiled on the forecastle (1, 2, and 3). An attempt was made to use swivels to keep the line from twisting, but this had to be abandoned owing to their being damaged in the blocks.

It is evident that in the arrangement and working of all the apparatus account had to be taken of these immense lengths of line. In the first place, they were extremely bulky, and required a large amount of deck space for coiling and handling, as the line had first to be led from the forecastle to the winch, and frequently from the end-drum on one side of the axle to its fellow on the other side, when the strain on the dredging rope was so great that the friction of the revolving drum was not sufficient to make it bite. This happened sometimes even when ten or twelve men were holding on abaft the winch. A second important consideration was the severe strain on the line every time the big heavy ship lurched, or when the lead or the dredge stuck fast on the bottom.

The weight of 3000 fathoms of sounding-line in water was, as already stated, over 100 kilos, and the weights amounted to 200 kilos, so that there was not much margin left for friction in the water and accidental jerks, when we remember that the breaking strain was only 700 kilos. Accordingly, when sounding or trawling great care had to be taken to provide against such contingencies, and large accumulators were used, consisting of rubber bands 3 feet long and $\frac{3}{4}$-inch thick, which could be extended to 17 feet, and thus counteracted sudden jerks on the line. For sounding, forty of these were employed, while for trawling there were as many as eighty, which together could support $2\frac{1}{2}$ tons, or the breaking strain of the line.

Fig. 2 shows the two accumulators, one for sounding and the other for trawling, attached to blocks high up on a yard, thus enabling them to expand and contract freely.

Before sounding all sail was taken in, and the ship was brought head to wind by means of her engine to keep her from drifting off too much. With three or four heavy weights of

Method of sounding.

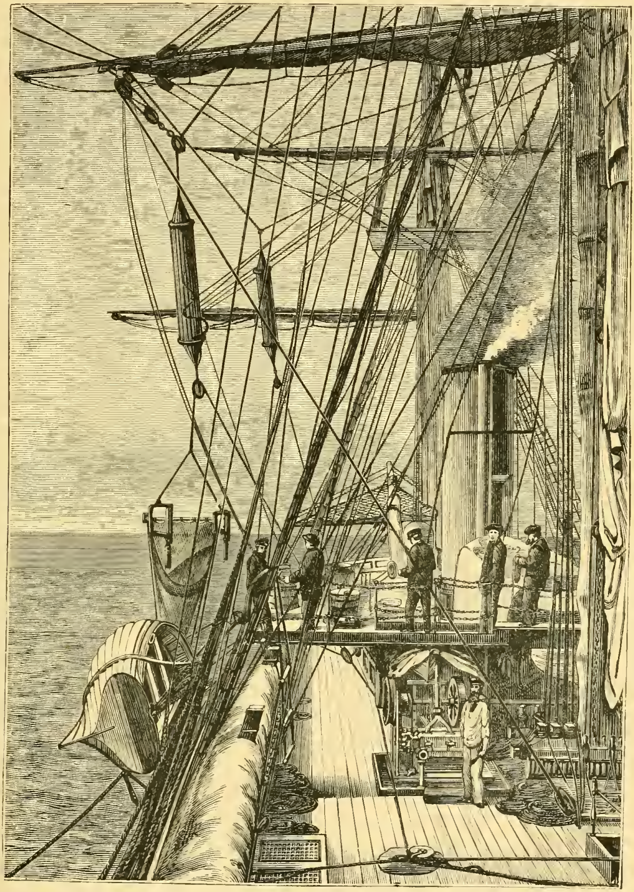


Fig. 2.—Sounding and Trawling on board the "Challenger."

50 kilos each attached, the sounding-lead was heaved, and the apparatus was so constructed that the weights slipped off upon reaching the bottom, thus doing away with the necessity of hauling the entire mass up again. The Baillie sounding

machine (Fig. 3) was the one in general use on board the "Challenger."

Time required for sounding in deep water.

From the Narrative of the Cruise we get the following particulars regarding the time required for sounding in deep water:—

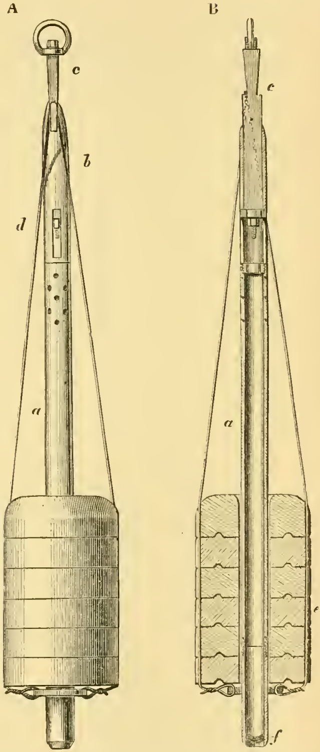


FIG. 3.—BAILLIE SOUNDING MACHINE. The tube (f) was generally made to project 18 inches below the weights (e).

Station 81. Began sounding 5 P.M.; found bottom at 2675 fathoms; finished hauling in at 6.20 P.M.

Station 225. Began sounding 12.30 P.M.; found bottom at 4475 fathoms; finished sounding at 3 P.M.

We see, therefore, that sounding in about 3000 fathoms took nearly an hour and a half, whereas for about 4500 fathoms two and a half hours were required, which must be considered very quick work. On the same line and with the same arrangement as for sounding, series of temperatures were taken and deep-water samples obtained.

Method of dredging and trawling.

Heavy lines and strong accumulators were, however, necessary for the dredge and trawl, which were each fastened to a stout 2-inch line, paid out through a block attached to the big accumulator (see Fig. 2). From 300 to 500 fathoms first ran out, then a weight of about 80 kilos was allowed to slide down the line till it was stopped just a little in front of the appliance. The weight consequently reached the bottom before the appliance, with the result that this latter merely skimmed the ocean floor.

All this time the ship lay with her head to the wind to enable the appliance to reach the bottom, for which operation about three hours were required. When all was in readiness the ship was allowed to drift with the wind abeam, and thus towed the dredge or trawl along.

Hauling in was done rapidly, as will be seen from the following extracts :—

Station 79, depth 2025 fathoms. The dredge was lowered at 11 A.M., and 2800 fathoms of line paid out; at 4 P.M. commenced hauling in, and the dredge came up at 5.45 P.M. Time required for dredging and trawling.

Station 244, depth 2900 fathoms. The trawl was lowered at 4 A.M., and 3500 fathoms of line paid out; commenced hauling in at noon, and the trawl came up at 3.50 P.M.

Thus in the course of twelve hours it was possible to carry out a successful trawling at a depth of about 3000 fathoms.

With such means as they had then at their disposal—a sailing ship with auxiliary engine and hemp lines—it was scarcely possible to devise a more thorough system of working. During the whole three and a half years, when trawlings and dredgings were made at 354 stations, there were only eleven cases of the parting of the dredge or trawl line. But gear of this kind necessitated lavish space and a large number of hands, both of which were generally to be had on the old sailing ships. It entailed ample space on deck for the coils of line and high masts for the accumulators, while numbers of men were needed to coil the lines and to hold on abaft the end-drums of the winch. A sailing ship, however, required much less coal than a steamer, which is a great advantage on a voyage round the world.

In the Narrative of the "Challenger" Expedition it is mentioned that at the time the vessel was being got ready for her cruise, Sir William Thomson (Lord Kelvin) was engaged in trying once more to solve the problem of taking soundings with wire instead of with a hemp line, and that a sounding apparatus constructed by him was placed on board just before the ship sailed; the drum, however, collapsed when first used. Notwithstanding this Sir William Thomson continued with the utmost energy, and eventually with complete success, to develop his method, and it was employed by the American sounding vessels "Tuscarora" (Captain Belknap) and "Blake" (Captain Sigsbee). Wire has great advantages over a hemp line, firstly, because it enables soundings to be taken more quickly, since the steel wire meets with far less friction in the water; and secondly, because it requires much less space. Recent methods. Lord Kelvin's experiments on sounding with wire.

Fig. 4, which is taken from Sigsbee's excellent book,[1] represents sections of the hemp lines used by the "Challenger," Advantages of wire over hemp line.

[1] Sigsbee, *Deep-Sea Sounding and Dredging*, Washington, 1880.

and of the steel line (piano wire) afterwards adopted for sounding. It will be obvious at once what a saving of space is obtained by the use of a steel line. This will be clear, too, if we look at Sir William Thomson's sounding machine, the principle of which is clearly illustrated by the following instructive figure from Sigsbee's book (Fig. 5).

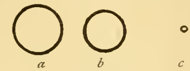


FIG. 4.—SOUNDING-LINE AND WIRE.

a and *b*, Circumference of the hemp sounding-line of the "Challenger"; *c*, piano wire. (From Sigsbee.)

Thomson's sounding machine.

The wire is wound in by a large wheel consisting of a drum 2 feet 6 inches in circumference between two thin galvanised iron plates 6 feet in circumference, the object of making this wheel of such a size being to enable the line to be paid out and hauled in quickly.

Precautions necessary in making soundings.

In taking soundings the art consists in getting the wheel and line to stop the moment the plummet touches the bottom.

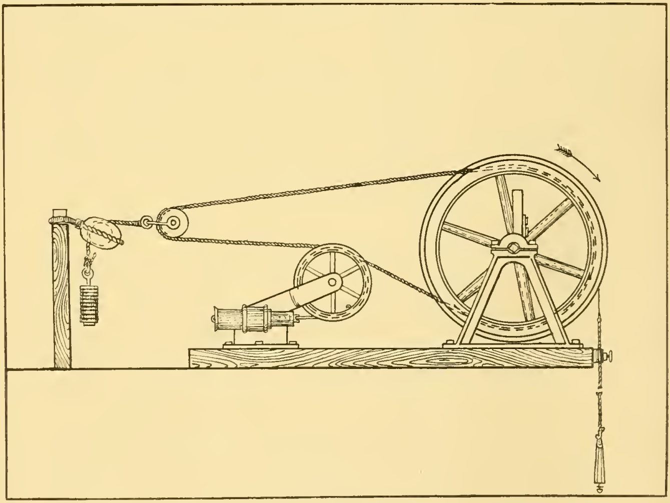


FIG. 5.—THOMSON'S SOUNDING MACHINE. (From Sigsbee.)

The line drifts when free of the lead, as it is, of course, relieved of the weight as soon as the bottom is reached, but there still remains the weight of the line itself, while the momentum of the wheel will cause it to continue revolving for a little while. The wheel must consequently be made as light as possible, and a resistance of some sort must be provided, rather stronger at any moment than what is necessary to counteract the weight of the length of line paid out. Thomson obtained this by means of a brake, a hemp line running in a separate groove at the side of the big wheel, and passing from there to a block, through which the brake could be tightened by means of weights.

Fig. 6.—Sigsbee's Sounding-Tube. (From Brennecke.)

Sir William Thomson used a plummet weighing 34 lbs., and commenced his sounding with a counter-weight of 10 lbs. on it. This was sufficient to run out the line at the rapid rate of 2000–3000 fathoms in thirty to fifty minutes. Gradually, as more line was paid out, the counter-weight was increased proportionately to the length of wire in the water (12 lbs. for each 1000 fathoms of wire), and this caused the wheel to stop almost instantaneously when the bottom was reached. The depth could be ascertained from the number of revolutions on the register. If the wheel did not stop instantaneously, an error would result in the determination of the depth, and if the steel line came into contact with the bottom, it easily kinked, and the plummet was likely to be lost. To obviate this a few fathoms of hemp rope were inserted between the plummet and the steel line.

Recent sounding machines.

Obviously this sounding machine is a great advance on the old hemp lines.[1] Economy of space, smaller weights, greater speed, less friction in the water (and consequently a more perpendicular line, resulting in greater accuracy), are some of the advantages. For this reason attempts have continually been made to improve Thomson's machine, and in the course of time a number of very good sounding machines have been constructed, amongst others those of Le Blanc, Sigsbee, and Lucas. Sigsbee's sounding-tube is shown in Fig. 6. All of them are based on Thomson's model; thus Sigsbee says of his own admirable machine: "The modification or improvement made by me on the original Thomson sounding-machine lies chiefly in the employment of a peculiar kind of accumulator, and its adap-

[1] It is interesting here to observe that the "Challenger" hemp line could be used for sounding in depths down to 26,000 fathoms before reaching its breaking strain, whereas the wire could only be used down to a depth of 16,700 fathoms. Depths beyond 26,000 fathoms, should such depths exist, could not be explored by either method.

tation to the various uses of accumulators, dynamometer, brake, correct register, and governor."

Lucas sounding machine.

On board the "Michael Sars" we employed the sounding machine constructed by Lucas. It was selected originally because it had been extensively used by the telegraph cable ships, and because it was the smallest and the cheapest. Weights used as brakes in Thomson's machine are replaced by spiral springs, which can be tightened or slackened with a screw, and can at the same time be relied upon in a high sea as accumulators (see Fig. 7, which explains the construction).

During the winter of 1877–78 the United States Coast Survey steamer "Blake" undertook a cruise in the Gulf of

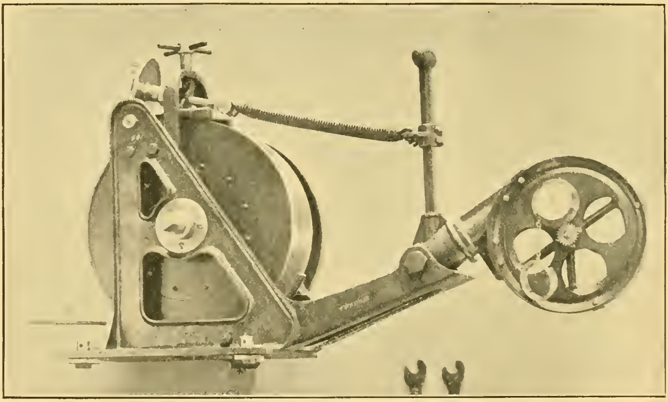


FIG. 7.—LUCAS SOUNDING MACHINE.

Wire rope for dredging.

Mexico, under the command of Captain Sigsbee and under the personal supervision of the late Alexander Agassiz. As it was proposed to carry out investigations with the dredge and trawl along the bottom, Agassiz suggested the use of a wire rope instead of hemp ropes. Thanks to Sigsbee's inventive genius and practical methods, this plan was successfully adopted, and has since been adhered to by every expedition of any importance.

Fig. 8 shows sections of the "Challenger" hemp lines, 3 inches, $2\frac{1}{2}$ inches, and 2 inches in circumference (*a*, *b*, *c*), and of the wire rope, $1\frac{1}{8}$ inch in circumference, used by the "Blake" (*d*).

The wire rope consisted of six strands, each made up of seven wires (like piano wires about 1 mm. in diameter), or altogether forty-two wires, with a tarred hemp line in the middle. The breaking strain of the whole was about 4 tons. Its weight per fathom was 1.12 lbs.

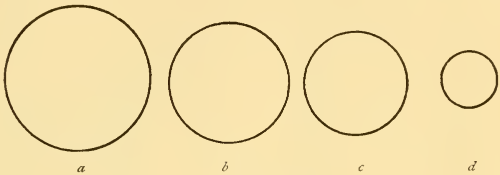


Fig. 8.

a, *b*, *c*, Circumference of hemp lines used for trawling on board the "Challenger," and *d*, of wire rope used for trawling on board the "Blake." (From Sigsbee.)

in the air, and 1 lb. in the water. We thus get a breaking strain of about 4000 kilos; weight in water of 5000 fathoms 2300 kilos; so that with 5000 fathoms out, there were about 1700 kilos over for resistance (friction) in the water, and for strains due to heavy seas or sticking fast on the bottom. The great strength of this line made it less necessary to use accumulators, and they were only employed occasionally during the "Blake" expedition.

Method of using wire rope.

Fig. 9 shows how Sigsbee worked the wire rope on board the "Blake." It was wound round a big drum (1), driven by a small steam-winch, and led from the drum over blocks of considerable diameter (2) to the large steam-winch (3), which had a large end-drum 55 centimetres (22.6 inches) in smallest diameter. From here the line went to a big boom (4) on the foremast (5).

When dredging or trawling the appliance was first lowered to near the bottom, while the ship was stationary, and afterwards the vessel went astern during the process of paying out and dredging. This manner of working was so successful, and conduced to

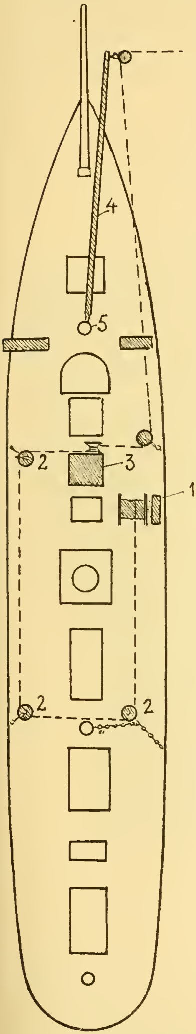
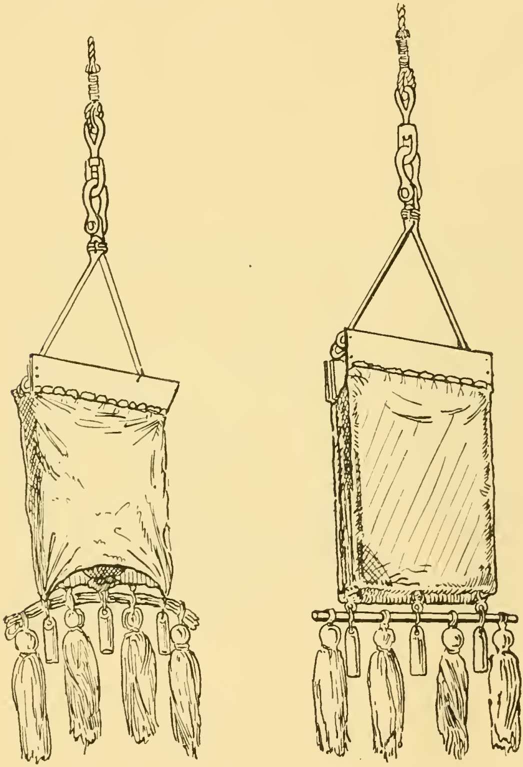


Fig. 9.—Deck Arrangement of the "Blake." (From Sigsbee.)

such precision, that it may be considered quite the equal of any system adopted by subsequent expeditions. Sigsbee relates that he made one day, off Havana, between 7 A.M. and 5 P.M., as many as ten hauls with the dredge at depths varying from



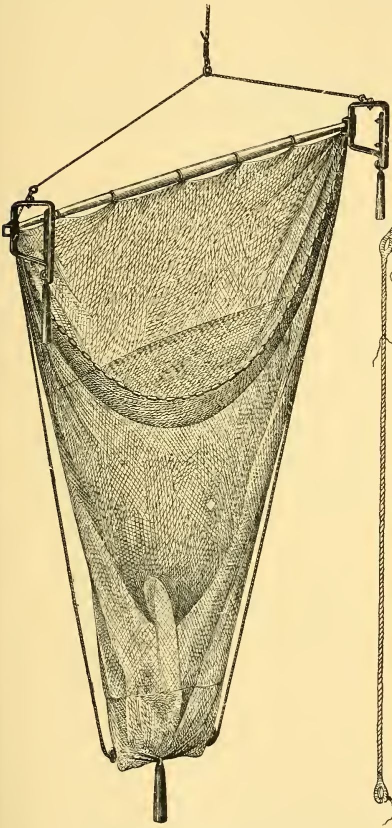
a *b*

FIG. 10.—DREDGES.
a, Previous model; *b*, Sigsbee's dredge. (From Sigsbee.)

50 to 400 fathoms. Although the bottom was unsatisfactory and the dredge stuck fast every time, he managed to avoid an accident and made very successful catches. He allowed from three to five minutes for lowering or for hauling in a line of a hundred fathoms, and from ten to thirty minutes for the actual

dredging, the time required for dredging depending, of course, upon the nature of the bottom.

The joint labours of Agassiz and Sigsbee led to a great



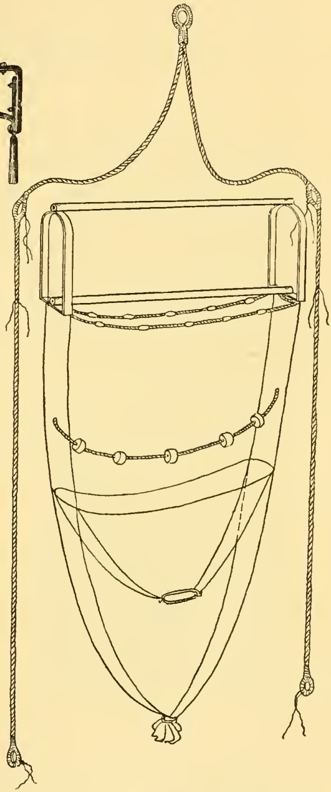


FIG. 11.—THE "CHALLENGER" TRAWL. FIG. 12.—SIGSBEE'S TRAWL. (From Sigsbee.)

improvement in the appliances. Previously the dredges had ploughed into the ocean floor (Fig. 10, *a*), but the one employed by Sigsbee (Fig. 10, *b*) was believed to have skimmed over it, and so collected the animals which lived upon the surface, sweeping them up from a wide extent of ground. Both kinds of dredge have, however, their advantages, according to the animals it is desired to procure.

"Challenger" trawl.

The "Challenger" used a trawl (Fig. 11) constructed like the ordinary beam-trawl, which was employed particularly by

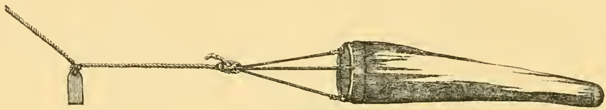


Fig. 13.—Tow-Net fixed at End of Line ("Challenger").

the fishermen in the shallow waters off the flat English coasts. The beams were of different lengths, 17, 13, and 10 feet, but the 10-feet length was found to be the best for deep water. It was, however, difficult to tell, when the depth was at all great, whether the trawl had reached the bottom right side up, and whether it was open while being towed. Sigsbee solved this difficulty by having tripping lines on both sides (Fig. 12); otherwise the size of his trawl was identical with that of the "Challenger," viz. 10 feet between the runners.

Sigsbee's appliances and methods of working were adopted by the "Valdivia" and other recent expeditions.

Fig. 14.—Tow-Net fixed on the Line ("Challenger").

Pelagic appliances of the "Challenger."

During the cruise of the "Challenger" the appliances used for making pelagic captures consisted of small nets resembling long night-caps, of fine muslin or calico, and 10 to 16 inches in diameter at the mouth. They were towed at various depths, even as far down as 800 fathoms, with a weight attached a little in front of the opening (Fig. 13), or they were sometimes made fast to the line (Fig. 14) and lowered to a depth of about 2 miles (over 3600 metres), the object being to ascertain whether or not organisms lived in the deeper layers of water different from those captured in the surface layers.

Since the time when the "Challenger" conclusively proved that life was present everywhere in the ocean, not only over the bottom at the profoundest depths, but also in the intermediate layers of water, much labour has been expended upon the investigation of the animal life of the sea. The appliances for capturing animals at the bottom have undergone only slight alterations, whereas many different kinds of contrivances for capturing the pelagic animals have been tried from time to time, some of them being of real practical value. Closing nets for intermediate waters.

Chun has done more perhaps than any other naturalist in the way of studying the vertical distribution of organisms. Together with Petersen he constructed a vertical net that could Chun and Petersen closing net.

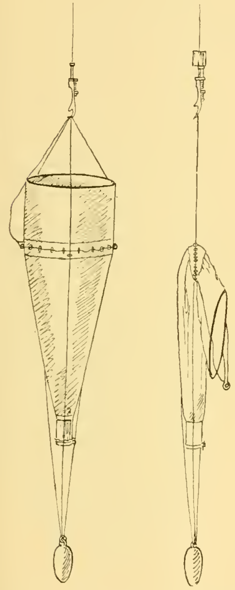


FIG. 15.—NANSEN'S CLOSING NET.


FIG. 16.—CHUN'S NET. (From Chun.)

be let down closed, then opened, and finally closed again, so as to catch the smaller organisms existing in a specified layer of water, say between 400 and 200 metres beneath the surface. Subsequently other closing nets were constructed on the principle of this invention. Fig. 15 shows Nansen's closing net open (*a*), and shut (*b*), the construction of the net itself and the closing mechanism being easily understood from the illustrations. It is extremely simple and reliable, and we have tested it in various ways during the cruises of the "Michael Nansen closing net.

Sars." We have found that if the appliance is sent down open to a considerable depth, immediately closed and hauled in again, it fails to capture anything, thus proving that vertical appliances need not be closed while being lowered.

Chun large net.

For studying the vertical distribution of larger organisms Chun used during the "Valdivia" Expedition a large silk net, 4 metres in length (Fig. 16). By lowering it to different depths

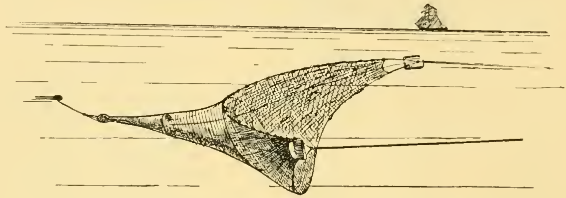


FIG. 17.—MONACO'S PELAGIC TRAWL. (From Steuer.)

and comparing the catches so obtained, he could determine at what particular depths the animals lived, and he succeeded in collecting by this means valuable data as to pelagic deep-water forms.

Prince of Monaco's pelagic trawl.

The Prince of Monaco has also added largely to our knowledge of the habitats of the larger pelagic organisms by means of his pelagic trawl (Fig. 17), which is designed for

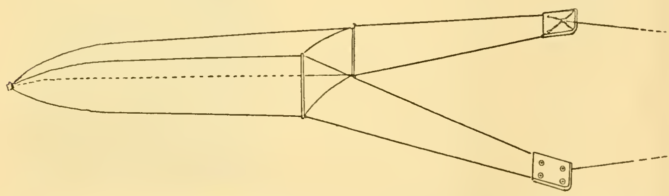


FIG. 18.—C. G. JOH. PETERSEN'S PELAGIC YOUNG-FISH TRAWL. (From Schmidt.)

being towed horizontally through the water. In addition he made some remarkable captures of large pelagic animals, chiefly cuttle-fish, by shooting whales and examining their stomach contents, for the whale is still far more capable of catching living marine creatures than any scientific appliance hitherto invented.

Petersen young-fish trawl.

The young-fish trawl designed by C. G. Joh. Petersen (Fig. 18) is a considerable improvement on the Prince of Monaco's pelagic trawl. It is very easy to construct, and may be of any size or mesh. For catching young fish, etc., he generally uses sackcloth, but a better fine-meshed material would undoubtedly be more desirable.

Hensen evolved various forms of apparatus for a quantitative study of the pelagic organisms, that is to say, for estimating the relative amounts of plankton organisms present in a given volume of water. He recommends vertical nets of the finest silk cloth, such as is used in the milling industry (see Chapter VI.).

FIG. 19.—HENSEN'S LARGE PLANKTON NET. (From Chun.)

In actual practice, however, it has been found impossible to capture pelagic organisms of every sort with the same net; for the larger forms may escape the net altogether, while the smallest forms may pass through the meshes of even the finest silk. There are other objections to the method, for it is an almost impossible task to ascertain the total quantity of floating organisms in deep and shallow water where there are strong currents; and it is hardly likely that the larger organisms at any rate, even though the nets succeed in capturing them, are uniformly distributed throughout the water-masses over large areas, so that an estimation of their total number could not be arrived at with our present appliances. Still, Hensen's theoretical analysis of plankton problems has been of great service to oceanic research, and so, too, has his plankton net (Fig. 19), whose coefficient of capture naturalists have attempted to calculate. It has been of the utmost value, for instance, in investigating certain uniformly distributed minute species in less extensive areas. The apparatus consists of a filtration net of miller-silk, with a brass cylinder at the lower end of the net, and a large conical part made of canvas, the object of which is to control the amount of water entering and so enable the silk net to filter it.

Hensen plankton net.

The "Michael Sars."

The steamer "Michael Sars" was built in 1900 by the Norwegian Government to undertake researches in connection with the Norwegian fisheries, and to study the natural conditions on which they depend. It was therefore necessary to have a vessel capable of making investigations similar to those carried on by oceanic expeditions, and at the same time suitable for practical fishery experiments, which are every year becoming of more and more importance in the work of scientific research. A ship of this kind, however, had to be small, otherwise it was impossible to reckon on sufficient means for its upkeep. Accordingly the size we selected was that of a first-class fishing trawler. Her length is 125 feet between perpendiculars, and she is of 226 tons burden; her engines indicate 300 horse-power, and can give her a uniform speed of 10 knots; her coal consumption is small, being about 5 tons per twenty-four hours when going at the rate of 9 knots, and she can carry in her bunkers about 80 tons. As will be seen from Fig. 20 there is plenty of space on deck forward of the engines. The big winch is placed here just abaft the hatch of the storeroom, in which there is cold storage for 10 tons of fish, and stowage for appliances, instruments, cases of glass bottles, etc. Forward of this storeroom are the cabins of the engineers and mates and the quarters of the crew. Abaft the engines there is a laboratory on deck, and below there are cabins and a messroom for the scientists. The deck is perfectly clear on either side of the deck-house, so that there is ample room for working with appliances and instruments.

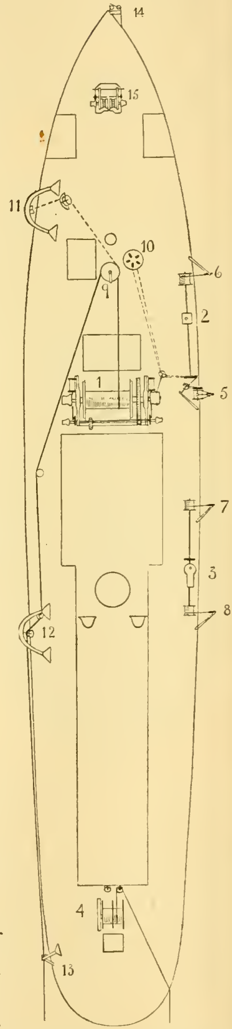


Fig. 20.—Deck Arrangement on board the "Michael Sars."

Methods employed on board.

If we compare Figs. 20 and 21 we shall get a good idea of the appearance of the deck of the "Michael Sars." On the starboard side there are two small winches, the forward one of 3 horse-power and the aft one of 1 horse-power. The forward winch (2), by means of a long axle (see also Fig. 22), drives a big reel with 6000 metres of wire, 3.5 mm. in diameter, for the hydrographical instruments and the Lucas sounding machine (6 and 5), and it can also be used to drive the big centrifuge (10) by means of a hemp line. By a similar arrangement the aft winch drives two drums with 2000 metres of wire, 3 and 4 mm. in diameter, for the vertical nets and hydrographical work in moderate depths.

In calm weather and when the currents are slight all the appliances may be operated simultaneously, provided care be

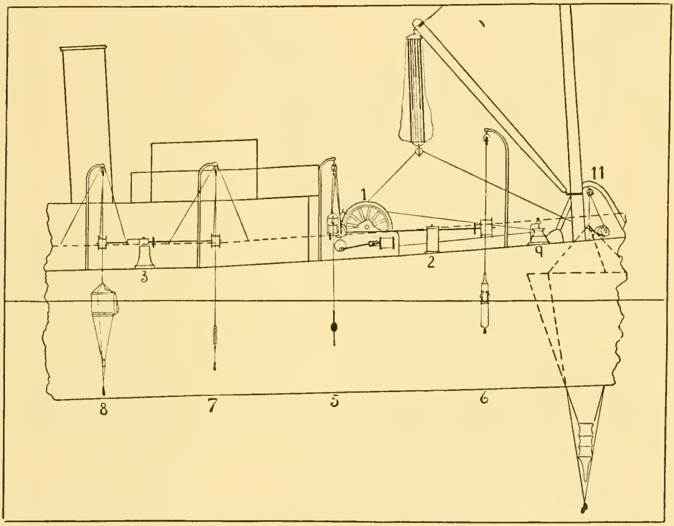


FIG. 21.—SIDE VIEW OF ARRANGEMENT OF GEAR ON BOARD THE "MICHAEL SARS."

taken that one appliance, let us say, is lowered while others are being hauled in. But when there are strong currents there is always a danger of the appliances colliding, and it is best in that case to work one at a time from each winch.

For the larger nets and the trawl we use the big winch (1), which takes the long steel line, 9000 metres in length, increasing from 34 mm. to 44 mm. in diameter. When trawling the line passes round the big reel (9), on which there is a register, and from there it is led to the gallows (12 and 13) and paid out astern. When operating the big vertical nets, the line is passed round a block in the accumulator, which hangs from the boom on the foremast, and is then led to the forward gallows (11).

Pelagic appliances, to be towed horizontally, are either fastened to the trawl wire like the trawl itself, or else the wire is led round a smaller winch (4), situated abaft the deck-house, and then paid out over the stern.

The vessel may thus tow both steel lines at the same time,

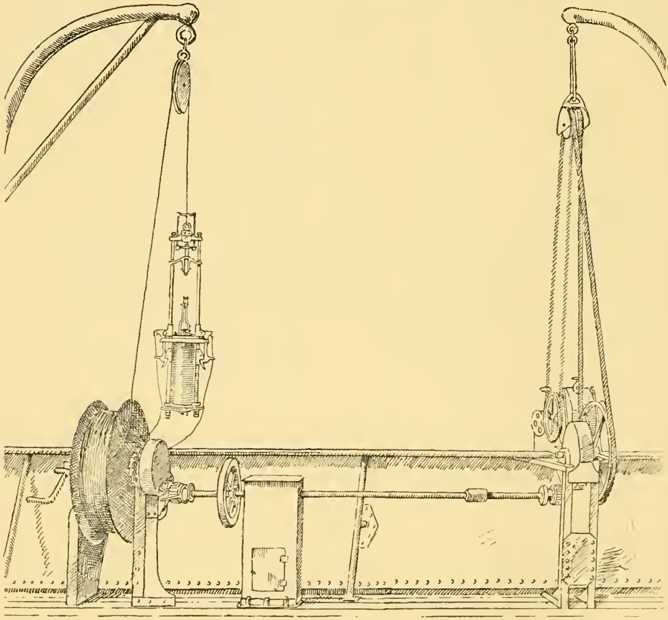


FIG. 22.—THE FORWARD STARBOARD WINCH.

and a number of appliances may be operated simultaneously. This mode of working differs in many ways from the system adopted in former expeditions.

Fig. 22 shows the forward starboard winch. The little Lucas sounding machine may also be seen, fastened quite simply to the rail of the ship, taking up very little space and requiring the attention of only one man. The large Pettersson-Nansen water-bottle, used for hydrographical observations at great depths, is also in a handy position. What simplifies matters very much, and enables us to dispense with the big projecting structures, or sounding platforms, that were formerly necessary, is the fact that in our little ship we are so near the surface of the sea that the person taking observations stands only a few feet above the water, and it is consequently much easier to get the appliances on board as soon as they come up. It is much easier also to manœuvre with a little steamer, so as to humour the appliances and keep the lines perpendicular whilst being lowered or hauled in. Obviously these are great advantages, not merely at the moment of taking observations, but also in our whole system of working; being able to operate a number of appliances simultaneously, for instance, means a great saving of men and time.

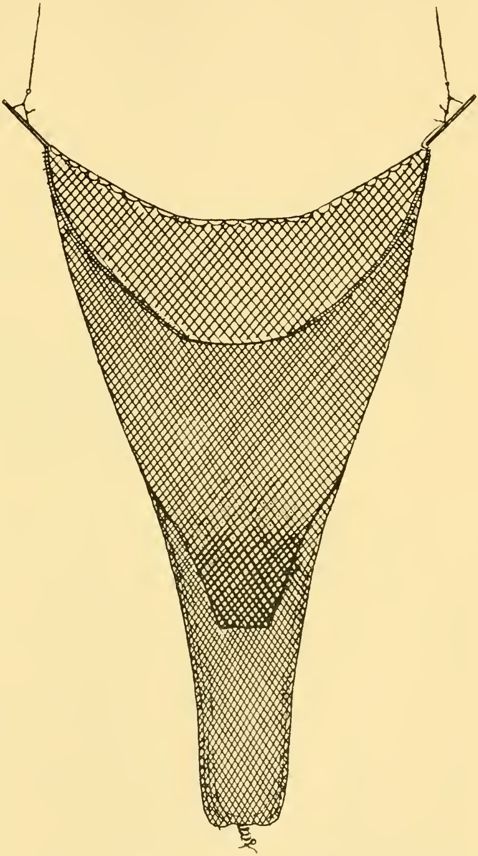


FIG. 23.—THE OTTER TRAWL.

In the case of both sounding machine and hydrographical apparatus we are able to haul in the line at the rate of 120 metres per minute, or 6000 metres in fifty minutes. But the forward starboard winch was unfortunately too weak to keep up this speed when there was much line out and the weight was considerable.

Trawling. For trawling, former expeditions employed the model designed by Sigsbee, 10 feet in breadth. This appliance, notwithstanding all its good points, is too small for catching large animals. Modern fishing steamers, which are quite small compared with the expedition ships of former days, mostly operate trawls 120 feet in length, having a span of about 60 to 80 feet, with a height at the entrance many times greater than that of the trawls employed for scientific purposes. Seeing then that a great many trials have been made in all oceans with the dredge and with Sigsbee's trawl, it was advisable to try whether a larger appliance would not yield different species and bigger catches, and it was natural to select as a model the appliance supposed to be best adapted for catching fish, namely, the otter trawl in use among fishermen.

Otter trawl.

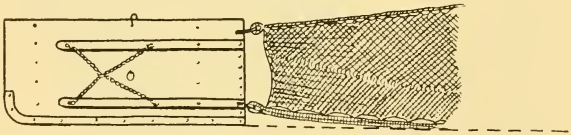


Fig. 24.—The Otter Board.

The difference between the otter trawl (Fig. 23) and the beam trawl (see the "Challenger" trawl, Fig. 11) is that in the case of the former the appliance is kept distended by means of otter boards, working on the principle of an otter for trout fishing or a kite in the air. The otter boards (Fig. 24) are attached to the line by bridles, and thus have a tendency to spread when towed along through the water. The regular trawlers use two steel lines of colossal dimensions, up to 3 inches in circumference and with a breaking strain of 20 tons; these are wound round two large drums that are keyed on to the slow axle of the trawl-winch (see Fig. 25), from which each line passes to its gallows and then astern, being carefully fastened with chains during the time that the vessel goes ahead towing the trawl after it. Sigsbee, it will be remembered, went astern when trawling, and he had one winch for winding the wire round the drum and another for the actual hauling in.

It is quite evident that the system adopted by the regular trawlers economises labour, for it is simple, and space is saved by using only one winch. The otter trawl, again, has to be towed at a good speed to keep the boards in position, and the vessel skilfully steered, so that the lines must necessarily be towed from the stern. It was found very difficult, however, to adopt this plan to our requirements, the chief drawback being that everything must be of the very strongest materials. Sir William Thomson long ago, when working at his sounding machine, discovered that the drums were easily burst, and the trawlers too have had similar experiences, in spite of their using drums of cast metal several inches thick.

The "Michael Sars" could not, of course, use such large appliances, for if in addition to overcoming the resistance of two ponderous otter boards, 6 feet by 10 feet, she had to tow a pair of wires each many thousands of metres long, she could obviously not have got over much ground; and besides, it would have been next to impossible to prevent such long lines from fouling one another. We were compelled therefore to trust to a smaller size of trawl, and to substitute a single warp, from the end of which we led a connecting line, 50 fathoms in length, to either otter board (see Fig. 26, line and bridle). A similar arrangement for small otter trawls had been already successfully tried by C. G. Joh. Petersen. During previous cruises of the "Michael Sars" we had operated a trawl with 50 feet of headrope at a depth of 1830 metres, and during our Atlantic expedition we succeeded in working the same appliance at a depth of 5160 metres. Our success must be ascribed to the solid construction of our gear. The drum of the winch which took the 9000 metres of wire was of the best cast steel, and the blocks were made as substantial as possible, though even then they had to be changed during the cruise, because the

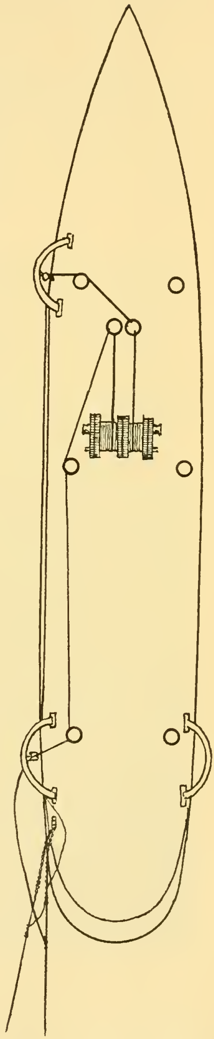


Fig. 25.—Deck Arrangements of a Trawler.

steel wire soon wore deep grooves in them. Our trawlings, too, took a long time, for the 20 horse-power winch that wound in

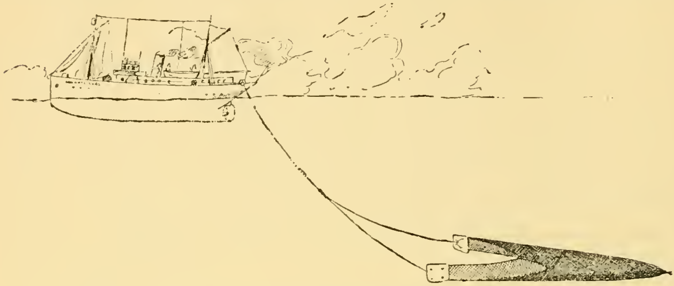


Fig. 26.—The "Michael Sars" trawling with one Wire Rope and Otter Trawl.

the wire directly on to the drum was unable to maintain its full speed when the load was unduly heavy.

Time for trawling in deep water.

On 31st May, at Station 48, the trawl was shot at a depth of

Fig. 27.—Hauling in Long Lines by means of Line Winch.

5160 metres with 8750 metres of wire; we commenced lowering at 5.45 A.M. and started trawling at 11.20 A.M.; hauling in began at 2.50 P.M., and the trawl was once more on board at

9 P.M. Hauling in took, therefore, six hours ten minutes, and the average rate was 24 metres per minute, or about a third of the speed at which Sigsbee hauled in his little trawl.

Lines and drift nets.

In addition to the trawl the "Michael Sars" can use lines and drift nets, in which respect she is equipped like an ordinary fishing steamer. The lines are passed out over the stern and hauled in amidships by means of the little after starboard winch, which is really the same as the little winch used for the hydrographical instruments. This is moved forward on the deck, and the lines are hauled in as in Fig. 27. Herring drift nets are

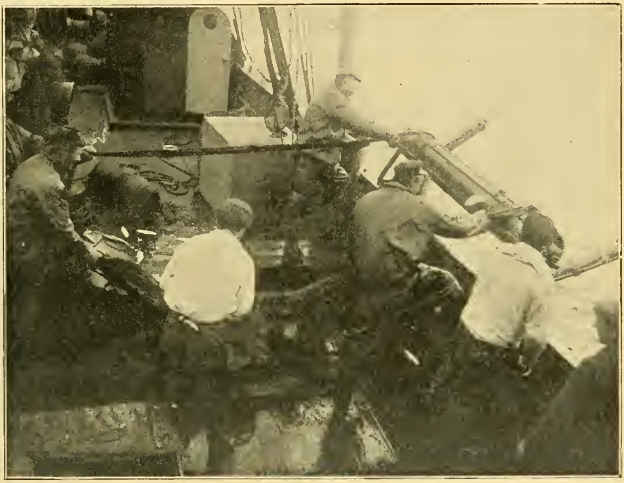


FIG. 28.—HAULING IN DRIFT NETS.

set from the stern; when all the nets are out the vessel swings round on the warp. This warp is hauled in by means of the large end-drum on the big winch and over the reel in the bows, and the nets are hauled over the side on to the fore part of the deck (Fig. 28).

Pelagic appliances.

As regards the net constructed by Victor Hensen (Fig. 19), a great deal of work has been devoted to studying its "coefficient of capture"; it is suitable for making quantitative studies of the occurrence of such plankton organisms as copepods, peridinii, etc., but for other purposes it has little practical value. Its upper part is furnished with a canvas cone, which allows no water to filter through, and therefore offers an effectual resistance to the water, both while being lowered and while being hauled in. It is, besides, quite useless for towing, for which purpose it was never intended.

"Michael Sars" tow-nets for horizontal and vertical hauls.

In the construction of our nets on the "Michael Sars" our idea was to make the fore part in such a way that as much water as possible might percolate through. As a rule they are 1 metre in diameter at the entrance and 4.5 metres long (see Fig. 29). The fore part is cylindrical for a length of $1\frac{1}{2}$ metres and of the same size as the entrance. There is first half a metre of shrimp net, then 1 metre of coarse silk with a mesh of 12.5 mm., and the after part, consisting of a cone, 3 metres long, of finer silk with a mesh of 0.8 mm. These filter the water admirably. We can tow them at a great speed and haul them on board rapidly, even with the little after starboard winch; and they capture young

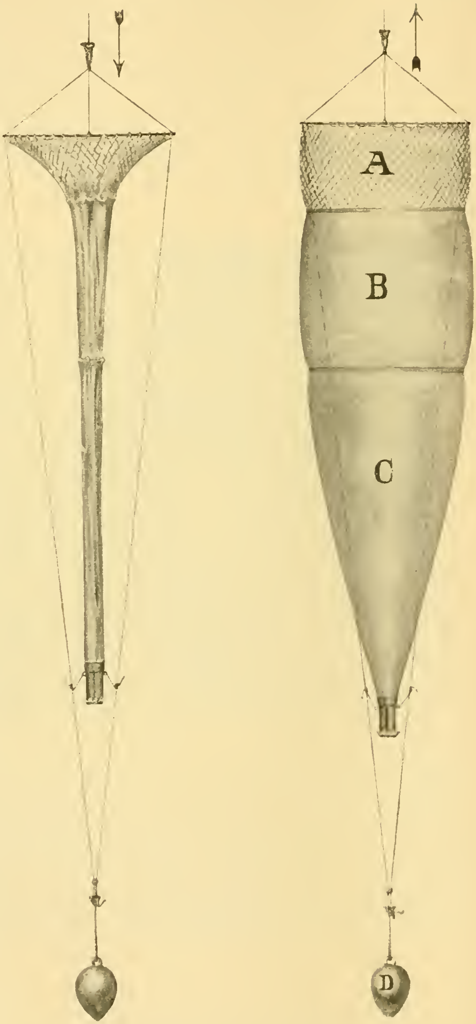


FIG 29. THE "MICHAEL SARS" TOW-NET.
A, net; B, coarse silk; C, finer silk; D, lead.

fish almost as well as the trawl itself. The cylindrical fore part is largely responsible for this, as it retains within its walls the animals that do not pass immediately into the after part, which, owing to its great length, lets the water filter easily through. One great advantage of these tow-nets is that they can be lowered very rapidly when used as vertical nets. They then

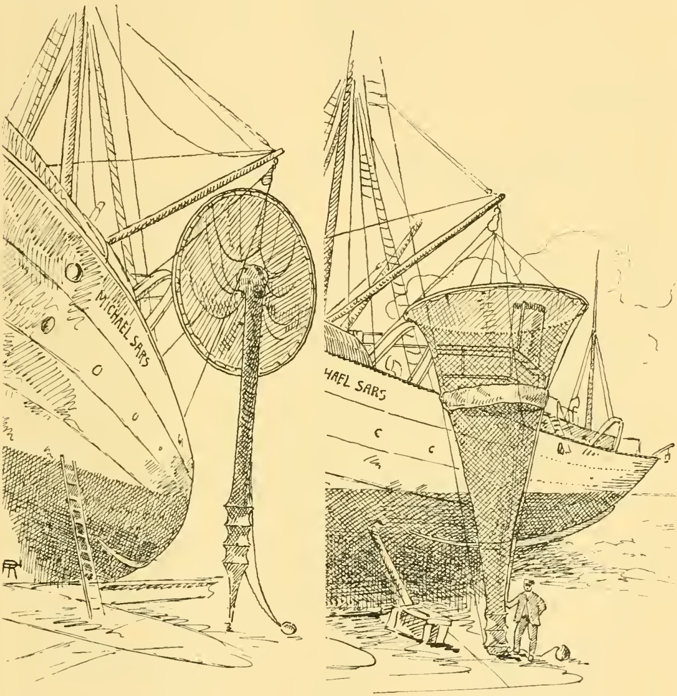


FIG. 30.—LARGE VERTICAL CLOSING NET.

assume the shape depicted on the left in Fig. 29. The net in the foremost portion of the cylinder is the only part that offers any resistance, and it too is wide meshed, so that the water easily passes through it; the rest descends like a thick rope. They can also be used as closing nets, and we have actually employed in that capacity nets $\frac{1}{2}$, $\frac{3}{4}$, and 1 metre in diameter at the entrance.

We further constructed two large closing nets, 3 metres in

Large closing nets.

diameter at the mouth and 9 metres long, one of silk and the other of net; one of these is depicted open on the right and shut on the left in Fig. 30. They proved to be our most successful pelagic appliances. We used them sometimes as vertical nets and sometimes for towing. The closing mechanism (Fig. 31) was constructed on Nansen's principle. A slip-weight sets free the cords that support the ring, which falls down and leaves the whole hanging by a noose. This noose draws the net together so that nothing more can enter it. Two sizes of mesh are used in the construction of these nets; in the fore part a mesh of about 1 centimetre and in the after part one of almost $\frac{1}{2}$ centimetre from knot to knot.

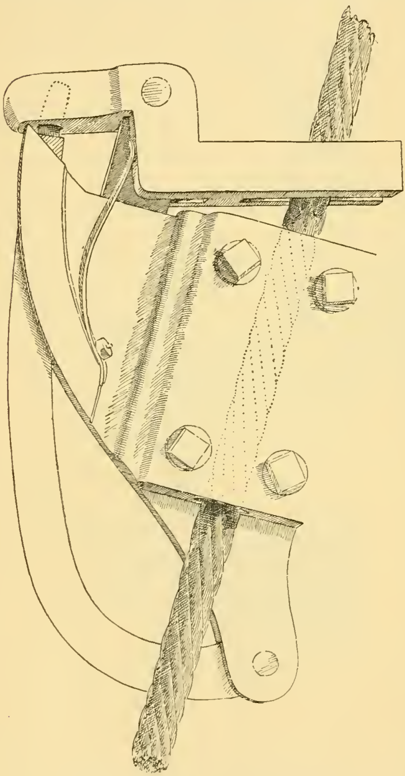


FIG. 31.—CLOSING MECHANISM.

In deep waters, however, and especially out in the open ocean, even these large appliances, if merely used as vertical closing nets, fail to furnish a representative picture of the animal life. The animals can only be captured by long horizontal hauls, and therefore to ascertain what exists at the different depths we must tow a large number of appliances simultaneously.

Method of using tow-nets.

Fig. 32 shows the plan we generally adopted during the Atlantic cruise of the "Michael Sars." Two lines were used: a long line from the big winch for the deep-water appliances, and a shorter one from the after winch for lesser depths. Silk tow-nets either 1 metre or $\frac{3}{4}$ metre in diameter, and Petersen's young-fish trawls were alternately attached, and to the end of the longest line we fastened the large tow-net just described.

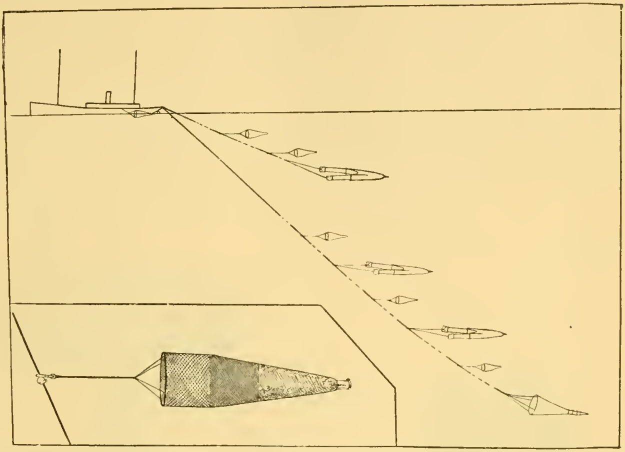


FIG. 32.—THE "MICHAEL SARS" TOWING TEN NETS AND PELAGIC TRAWLS. (Surface net not shown.)

A difficulty which arose when organising this system was that the cord by which a tow-net or trawl is attached to the wire becomes easily entangled, in which case the appliance is rolled round the wire or else torn off. To avoid this we screwed a brass knob (Fig. 33) on the wire and

FIG. 33.—BRASS KNOB FOR TOW-NETS.

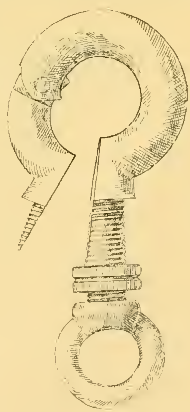


FIG. 34.—BRASS RING FOR TOW-NETS.

fastened the tow-net to a brass ring, which could be threaded on above the knob (Fig. 34). The appliance is thus kept from sliding down the wire, and is free to move in any direction (see also Fig. 32). This method of working enables one to operate as many appliances as the vessel is able to tow through the water, and by comparing the catches in the manner described in Chapter IX. one can ascertain the depths at which the animals lived. It is really a development of the plan adopted by the "Challenger," which towed its small nets along at different depths, or else attached them to the sounding-line (see above, p. 34).

Centrifuge. The pelagic investigations of recent years have shown that a great many marine organisms are so small that they pass through the meshes of all nets—even the finest silk nets (see

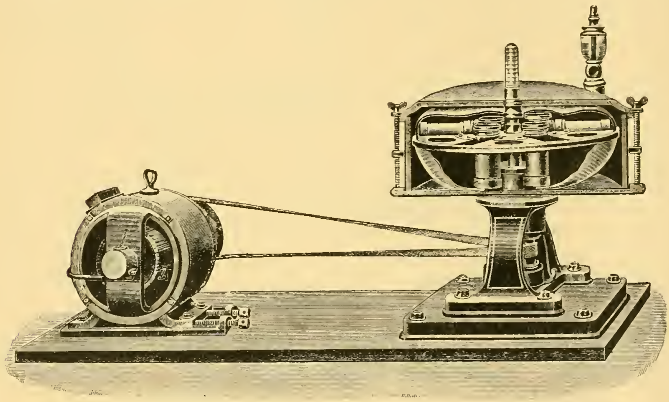


FIG. 35.—CENTRIFUGE DRIVEN BY ELECTRIC MOTOR. (From a catalogue.)

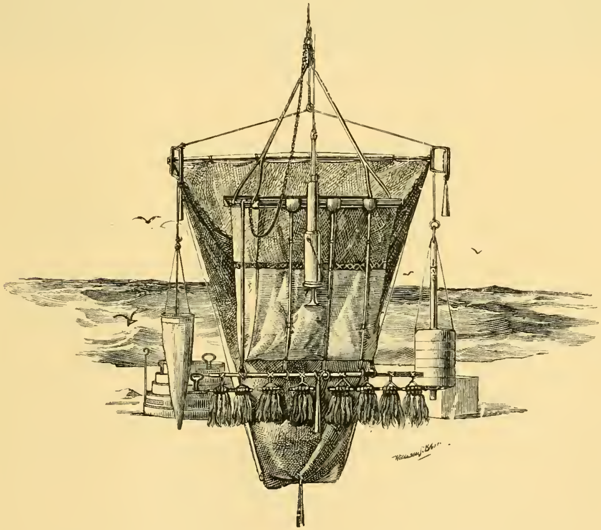
Chapter VI., where these organisms and their occurrence are described). To catch them in greater quantities we employed a large centrifuge (Fig. 35) as used by physiologists, which could centrifuge 1200 cubic centimetres at a time. The centrifuge was driven by one of the small steam-winches usually for a period of seven minutes and at a speed of 500 to 700 revolutions per minute.

This short description of the outfit of the "Michael Sars" does not claim to be exhaustive. During past years probably most kinds of fishing gear and scientific instruments available for the investigation of the sea have been made use of by us. When undertaking a definite limited cruise, however, a programme of the researches contemplated must necessarily be drawn up in advance and the gear selected accordingly.

Our Atlantic cruise proved that a greater number of appliances could hardly have been employed during a cruise of a few months' duration. But on the other hand a number of problems arose during the cruise, which we would fain have had the opportunity of investigating further.

It is especially our knowledge regarding the physical and biological conditions in the waters of the abyssal regions, and regarding the large pelagic organisms, that may still be considered as very imperfect. In order to study these problems more effectively, still more powerful winches, longer lengths of wire, and larger and better pelagic fishing gear are the principal things wanted. Future expeditions will thus have to face a serious task, not free from technical difficulties.

J. H.



Group of Appliances used on board the "Challenger."

S.S. "Michael Sars" in Plymouth Harbour.

CHAPTER III

THE WORK AND CRUISES OF THE "MICHAEL SARS"

In this chapter it is proposed to point out briefly the nature and extent of the oceanographical work and fishery problems in which the S.S. "Michael Sars" has been engaged in the Norwegian Sea during the past ten years. Thereafter we will turn to the special cruise in the North Atlantic from April to August 1910, and will recount the operations of the ship and the proceedings on board at the observing stations along the coasts of Europe, Africa, and Newfoundland, and during the voyages across the whole extent of the Atlantic.

Cruises of the "Michael Sars" since 1900.

Since the summer of 1900 the "Michael Sars" has made a great number of cruises in the Norwegian Sea. Fig. 36 shows the location of the stations occupied during the years 1900–1904, and a good deal more work has been done there subsequently. In the winter our task has been a particularly arduous one. We have found that stormy weather nearly always prevails at that season, and it is light for only a few hours each day. The temperature of the air is so low that all the water that falls on the deck and rigging freezes, and the quantity of ice thus formed is sometimes sufficient to weigh down the ship.

Iversen's account of a winter cruise.

Captain Iversen has given an account of one of the cruises,

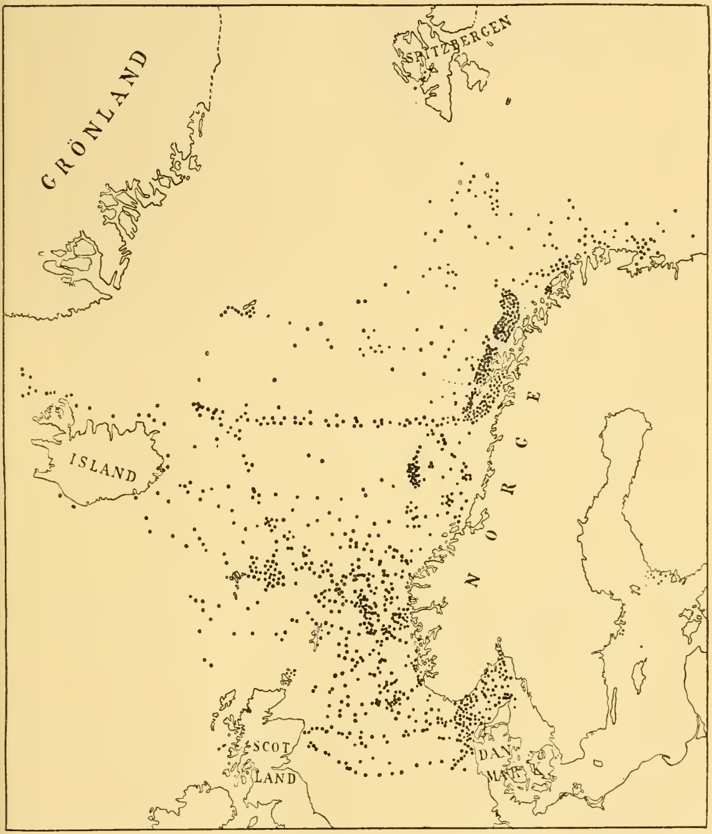


FIG. 36.—THE "MICHAEL SARS" OBSERVING STATIONS DURING THE YEARS 1900–1904.

that to Jan Mayen in February 1903, and his description presents such a vivid picture of the difficulties to be encountered when studying the Norwegian Sea and its fisheries, that it may well be printed here :—

We came in here (*i.e.* Lofoten) yesterday with all well on board.

We could not quite keep the course proposed, as the weather took charge of us a bit sometimes and no mistake. I will endeavour to give a few particulars of the trip.

We were pretty deep in the water when we left Bergen on the afternoon of the 9th February, every available hole and corner being crammed full of coal; consequently we got a bit of a washing that night. We had a hard gale dead ahead, but managed all the same to take up three stations before she refused to look at it about midnight of the 10th. All the 11th we lay hove-to, though we were able to take up one station; and on the 12th we stopped the engines to save coal, and got sail on her. Not till the afternoon of the 13th did the sea and wind go down enough for us to continue our course. During this storm we had frequent spits of snow and shipped a lot of water. To enable us to take up our stations we stretched a rope from davit to davit along the whole of the starboard side where we had to work. We did this to have something to hold on to, and so save us from being washed overboard. Koefoed was given a rope to tie round him, which fastened him like a dog to the davit where he worked. Otherwise everything was all right, except that the sheet of the mainsail parted so that the sail was damaged and a couple of thermometers were smashed. An interesting sight was a school of bottle-nose whales which we observed in lat. 63° 3′ N., long. 2° 44′ E. They were seven in number, most of them being males, "barrel hoops."

On the 14th and 15th we had good weather with little snow, so we made excellent progress northwards and took up a few stations. On the morning of the 16th we had clear weather and could see the ice-blink, the water at the same time becoming cold. After taking up a station during the night just clear of the ice we steamed through ice-floes all the next morning. We saw Jan Mayen in the distance, but the ice lay thick all round it. About midday we had to look sharp and get out again, as the wind increased to a gale, accompanied by severe frost and remarkable shrouds of mist, which assumed the most fantastic shapes and were constantly in motion. I have never seen anything like them before. We shaped our course for Vesteraalen, and got sail on her to steady her a bit. The whole of the afternoon we were pretty well cased with ice—hull, spars, and standing rigging—and on running suddenly into the middle of an ice-floe about nine o'clock that evening we had a hard job to get the ship round against the wind, her sails being so stiff with ice that it was impossible to take them in. However, we managed gradually to get her bows up against a large cake of ice and brought her round with the help of the engines. There was just room to turn her and that was all. We then set our course back the way we had come, and so got clear.

The stations we took up during the severe frost were the reverse of easy, as the metre-wheels froze up, and we had to keep them warm with thick, red-hot iron bars that were brought from the engine-room and held close to the wheel-axles.

On the night of the 17th we ran into another storm, which lasted till we arrived in port.

On the 19th, at midday, we saw land, but were unable to make it out, as the fog hid everything except a strip along the shore. All that day we tried to establish our whereabouts, but were compelled to lie to for the night in a hard south-westerly gale. Next day we found that we were off Gaukvaer Island and stood in for the land. After burning a little coal our vessel behaved splendidly, and after we had used up most of our coal and water, and so were very light, we could run before the sea in any direction without even having to keep the laboratory door closed. We wanted all our electricity this journey, for it was practically night the whole time.

Investigations by the "Michael Sars."

The "Michael Sars" has carried out a great many different kinds of investigations in the Norwegian Sea, viz.: observations on the salinities, temperatures, and movements of the water-layers; observations on the floating organisms of various sizes and kinds; observations on the bottom fauna, especially bottom fishes. We have also made practical fishing experiments to discover what kinds of fish may be caught in the different areas of the sea.

To describe all the cruises that have been made would take too long and lead to much repetition. In the subsequent chapters of this book the most important results are summarised.

In order to study the movements of the water-layers and the distribution of floating organisms, cruises were undertaken at different seasons, as opportunity offered, from the coasts of Norway to Iceland, Jan Mayen, and Spitsbergen. To ascertain the fluctuations in the water-layers we have run a line of observations, nearly every year since 1900, and always in the month of May, from the Sognefjord to the north of Iceland. This route lies exactly across the axis of the Atlantic water that streams through the Faroe-Shetland Channel into the Norwegian Sea, and we have consequently been able to obtain a section of this layer every year, and to compare its volume in different years. Besides a great many special studies, measurements of the velocity of the currents have been made out in the open sea and in the fjords.

Investigations to develop the fishing industry.

At the time the "Michael Sars" commenced working there were hundreds of square miles of coast banks where no fishing had ever taken place, and there was therefore a real fascination in experimenting in these virgin areas with the appliances in common use along the coast, more particularly with long lines. Expeditions were made for several years along the whole coast for capturing spawning cod on all the banks where the depth was 30–100 fathoms, and for halibut, tusk, and ling on the continental slope; drift-net fishing was also undertaken for herring.

In these investigations we have chiefly aimed at ascertaining the geographical distribution, horizontal as well as vertical, of the most important species of fish, especially during the spawning period, when many of them are most sought after, and when each species may be supposed to congregate at localities where the natural conditions, such as depth, salinity, and temperature, are especially favourable and characteristic. These breeding places have been discovered partly by searching for the spawning fish, and partly by charting the distribution of the newly-spawned eggs, which float immediately above the shoals of spawning fish.

The development and growth of the fish, and the geographical distribution of the different stages, formed another important subject for our scientific studies. By various means it is now possible to ascertain the age of the different individuals in a shoal of fish, and we are in consequence able to study the growth of fishes in different areas.

Some of our fishing experiments have had an immediate influence on the development of the fishing industry, and have led to fish being found on hitherto unutilised banks, which have since turned out to be profitable fishing grounds. The study of the natural history of fishes may be said to have as its main object the widening of our knowledge regarding all the physical and biological phenomena on which depend the life of the fishes and the fishing industry.

The Atlantic cruise of 1910.

During the winter of 1909–10 a great deal of time was spent in preparing the "Michael Sars" for an extended cruise in the North Atlantic, in selecting the route to be followed, and in preparing instruments and apparatus of the latest and most approved patterns.

Depth of the North Atlantic.

A glance at the depth map is sufficient to make it clear that the greater part of the North Atlantic is deeper than 2000 fathoms. The coast plateaus off Africa, Spain, and the United States are very limited, and the continental slope is, as in the Norwegian Sea, very steep. The bathymetrical curves for 500 and 1000 fathoms lie in close proximity to one another. Only off Newfoundland and from the Bay of Biscay northwards along the western shores of Ireland and Great Britain do we find the continental shelf or coast banks widening out into tolerably broad plateaus. From the coast banks round Iceland a low ridge extends in a south-westerly direction, known as the Reykjanes Ridge. This is continued southwards as the Dolphin Rise, with deeper water on either side. From this low ridge rise the Azores and St. Paul's Rocks, and other volcanic cones and islands of small extent rise from the deeper water, like the Bermuda, Madeira, and Canary Islands, and the Dacia, Josephine, and other banks.

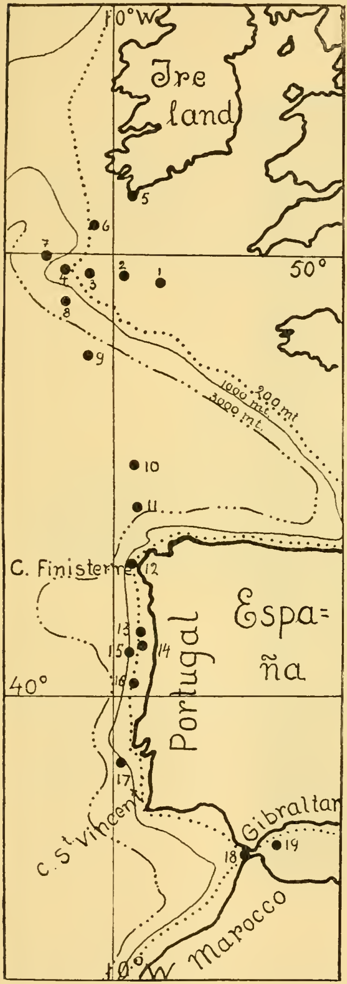


FIG. 37.—THE "MICHAEL SARS" OBSERVING STATIONS FROM PLYMOUTH TO GIBRALTAR.

Route of the "Michael Sars."

The route of the "Michael Sars" from Plymouth to Gibraltar (Fig. 37) was selected in order to find the most favourable localities for using the fishing gear, that is to say, where the continental slope is less steep than usual, and where accordingly the gear would be working on comparatively level ground. We expected to find the best ground where the coast banks are broadest; for instance, off Ireland, in the Spanish Bay (Gulf of Cadiz), south of the Canaries, and off the Newfoundland Banks. In our crossings of the ocean we had particularly to take into consideration the distance between the coaling harbours.

From Plymouth to Gibraltar.

All preparations being complete, the "Michael Sars" sailed from Bergen on the 1st April, the first port made being Plymouth, where Sir John Murray joined the expedition. While at anchor at Plymouth the captains of trawlers informed us that the bottom on the coast banks and on the continental slope was very rough in some places, but that if we took a westerly direction we should have a good opportunity of using the trawl down to great depths. Our previous cruises had taught us what damage a rough bottom, especially coral, may do to the fishing tackle. Fig. 38 shows a piece of such coral brought up by the "Michael Sars" when fishing on the slope between the North Sea and the deep water of the Norwegian Sea. To avoid the corals we followed the advice given us and took a westerly course when we left Plymouth on the 9th of April, and from the outermost westerly skerry, Bishop's Rock, we steered out over the coast banks to the continental slope. Everything was meanwhile got ready for trawling and for the hydrographical and plankton observations.

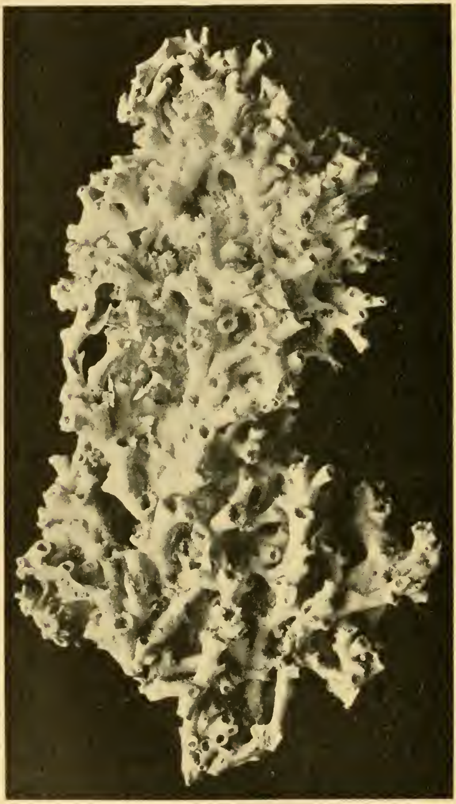


Fig. 38.—Piece of Coral (*Lophohelia*). About ½ nat. size.

Before leaving the coast bank we made observations at our first three stations in depths of 146, 149, and 184 metres, partly to test the winches and instruments and partly to get a section of the waters on the bank. All our arrangements for hydrographical and pelagic work were found satisfactory. We secured a number of samples, and thoroughly tested the appliances. It was particularly important to see if the closing nets were to be relied on, so we lowered them to a depth of 50 metres, and closed them immediately. They came up empty, showing that they do not catch anything when sent down open. Successful trawlings at Stations 1 and 3 resulted in both cases in catches of over 300 fishes belonging to the ordinary coast-

a

b

c

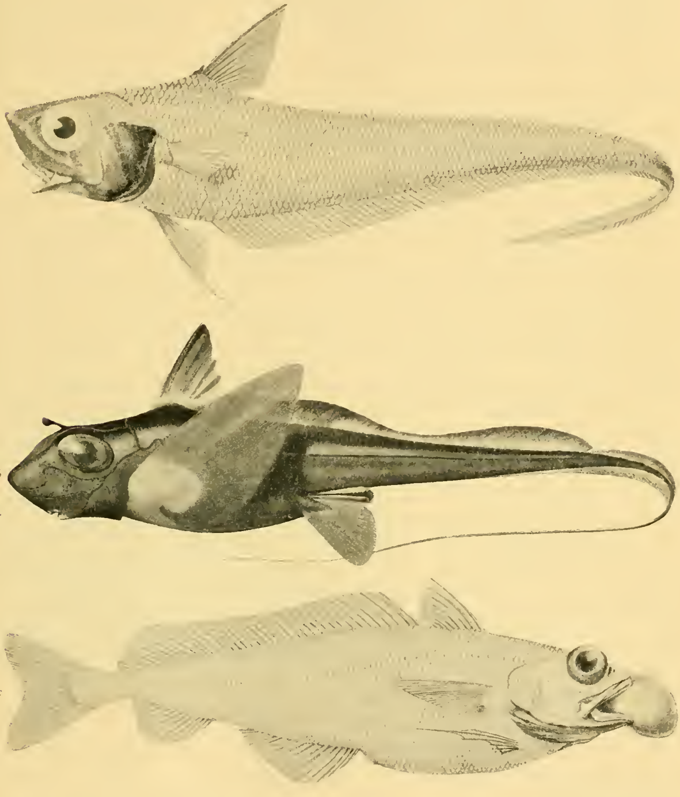


FIG. 39.—THREE DEEP-SEA FISHES FROM STATION 4, 923 metres (about 500 fathoms).
a, *Macrurus æqualis*, Gthr. Nat. size, 23 cm.
b, *Chimæra mirabilis*, Collett. Nat. size, 71 cm.
c, *Mora mora*, Risso. Nat. size, 45 cm.

bank species. Even these first hauls, however, made it evident that the big winch did not run smoothly when paying out line.

On the morning of Monday, 11th April, a sounding at Station 4 gave us 923 metres. The big trawl was shot with 2360 metres of wire. At 3 P.M. we assumed that it was on the bottom, and towed it for three hours till 6 P.M., when hauling in began. It came up at 7 P.M. with a catch of 330 large fishes (*Macrurus*, *Mora*, *Lepidion*, *Chimæra*, etc.; see Fig. 39). This haul was a thorough success. Perhaps never before had so large a draught of fish been made at such a depth. The trawl itself worked most satisfactorily, and considering its size hauling in was done rapidly (about 40 metres per minute). During the process of lowering, however, the big drum got jammed on the axle, and in spite of all our efforts we could not move it. There was nothing to be done, therefore, but to make for the nearest port to repair it, so we steamed into Cork and had it put right at the workshop on Wednesday morning (the 13th). We found after finally getting the drum off the axle that a lot of sand from the foundry had been left in by mistake, which accounted for its not working properly. By Friday (15th) the sand had all been scraped off, and the drum was once more in its place. But in the meantime a strong north-easterly gale had set in, and it was not till Saturday (16th) that we were able to steam westwards under the lee of the Irish coast. The wind continued strong and northerly, but for all that we steamed back to Station 4, occupying a couple of small stations (5 and 6) on our way, and recommencing our interrupted section, proceeded out to still greater depths.

Successful haul with the trawl.

On Sunday, 17th April, a sounding at Station 7 gave us 1813 metres. The trawl was shot with 4000 metres of wire and towed for two hours. It came up all twisted and tangled, due to the fact that the swivels for keeping the wire and bridle from twisting had failed to act. The small steel balls in the bearings of the swivels had been crushed by the severe strain or the bend in the blocks. The trawl was got ready for a fresh attempt, but in the meantime the wind and sea rose to such an extent that we decided to give up further work in the deep water. To wait for good weather would have delayed us too long, so we set our course for the north-west point of Spain.

The pelagic life of the upper 150 metres was extremely uniform. Several series of hauls with fine-meshed closing nets revealed the fact that quantities of the same diatoms extended down to a depth of over 150 metres. This was particularly interesting evidence as to the depth at which plant life can exist, even as far north as about lat. 49° 30′ N., under special conditions. From this and other experiments made later Gran is of opinion that the same vertical circulation which produces

Depth to which plant life extends.

a uniform temperature throughout the deep layer also introduces materials, particularly nitrogenous matter from the surface—that is to say, indirectly from the coasts—which are favourable to the development of plant life. The plants were in consequence extraordinarily abundant. At Station 3 we found great quantities of diatoms, even in a haul with the closing net from 160 metres up to 100 metres.

On our way southwards from Station 7 we were prevented by the high sea from attempting any fishery experiments, so we had to content ourselves with making hydrographical observations (at Stations 8 and 9), and it was not till we were well down in the Bay of Biscay at Station 10 that the sea became calmer and the weather moderated. We sounded here and got 4700 metres, so that we now had an opportunity of trying our appliances in really deep water (see Fig. 40).

Fig. 40.—The Captain sounding in 4700 Metres.

Vertical hauls.

We commenced at this station, while the ship was still hove to, by taking a series of twelve water-samples as far down as 4500 metres, and made a number of vertical hauls with the closing nets down to 1000 metres. Everything was found to work splendidly, and all these operations took only about three hours.

Temperatures in deep water.

Temperatures were recorded by means of the best kinds of reversible thermometers, which give readings exact to within a few hundredths of a degree even at the greatest depths. At this station we found the temperature at 3000 metres to be 2.40° C. and at 4500 metres 2.56° C. It was thus apparently warmer near the bottom than 1700 metres (or nearly 1000 fathoms) above the bottom. It has often been thought that the water might derive a certain amount of heat from the sea-bottom, and this may have been the case here, but there is also another possibility, namely, that the water at 4500 metres had sunk from the upper layers and had been slightly warmed while sinking, just as happens with air that suddenly sinks from a great height towards the earth. This rise of temperature has also been attributed to decomposing organic matter and to radio-active matter in the deposits at the bottom. Whatever may have been the cause, we certainly found a similar slight rise in the temperature of the deepest layer on several subsequent occasions during our cruise.

Trawling in deep water.

We next resolved to try the big trawl, and to reach the bottom at 4700 metres we estimated that it would be necessary to allow 8000 metres of wire, that is to say, 8 kilometres (Fig.

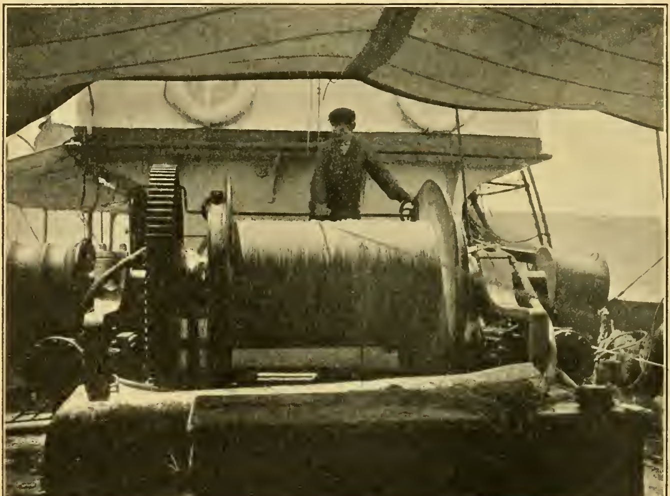


FIG. 41.—THE LARGE WINCH.

41). We were engaged in paying out line from 5.30 P.M. to 7.15 P.M., and at midnight we commenced hauling in, which lasted for about six hours. The trawl contained only two fishes (*Macrurus*) and a number of lower forms of animals: holothurians, a few worms, a gasteropod, a chalk-coloured crab, some ascidians, and one or two other things (see Chapter VII.).

This seemed to us such a poor catch that we came to the conclusion that something had gone wrong. The trawl was therefore dropped again, and could be seen sinking down in perfect order. After being towed for three and a half hours, it suddenly stuck fast and stopped the ship. Hauling in took eight hours, and the trawl came up (Fig. 42) in perfect order, containing an enormous mass of perhaps a ton of clay-like Globigerina ooze, that was as stiff as dough, and looked as if it might have been dug out of a chalk pit. We carefully sifted and washed it all with the hose, and found only the following animals: four actinians, of which two were growing on hermit crabs, two cirripeds, a holothurian, some gasteropods, and a few worms. The question now presented itself—was animal life really so sparse down at those depths, or did our catch fail to represent it properly? Had the trawl perhaps, when dragged through the ooze, been rendered incapable of doing its work of capture? If so, how had we been able to go on towing for such a length of time? This was a problem that could only be solved by further experiment. A number of glass floats, about 3 inches in diameter, were sent down with the trawl, and were found to have been reduced to the finest powder by implosion through the immense pressure at this great depth.

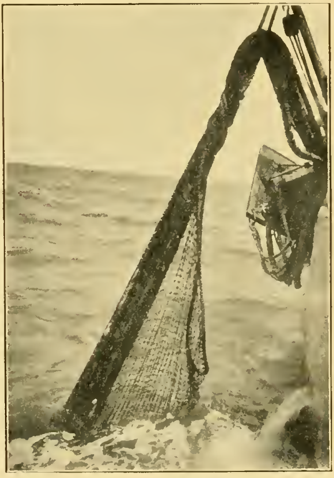


Fig. 42.—Otter Trawl coming up.

One thing at any rate we had learned. The enormous weight of 8000 metres of wire, with a huge trawl at the end, had worn deep grooves in our blocks and rollers in a very short space of time. It was necessary, therefore, to have rollers in reserve if much of this work was to be attempted.

After a few successful pelagic hauls we resumed our course on the morning of the 21st April in the direction of Spain, our intention being to do some trawling at different depths on the continental slope, where the trawlers had told us the bottom was good. But when we made the coast of Spain at Cape Sisargas, an easterly gale sprang up and put a stop to all work, so after a few hydrographical observations (Stations 11 and 12) we steered southwards along the coast of Portugal. On the 22nd the weather cleared up, and off the town of Vianna we saw the first line-buoys, and shortly afterwards the picturesque fishing-boats with their red lateen-sails came into view on the horizon.

Portuguese fishing industry.

One of these came close to us, and we had an opportunity of learning something of their industry. Their boats were flat-bottomed, with a deep rudder that acted as a sort of keel. They were working with nets on a hard bottom, and, as a rule, in 30–40 fathoms of water. Their catches consisted of the lobster-like "languste" (*Palinurus vulgaris*), large crabs (*Cancer*, *Lithodes*), skates (*Raia clavata*, *R. circularis*), sharks (*Centrina* and *Mustelus*), and breams (*Pagellus centrodontus*). They also earned some money by going on board the trawlers and getting the small fish (small whitings, hake, etc.), which are generally thrown away. We came across the trawlers themselves not long afterwards, and boarded a boat belonging to Boston, England. They were trawling for soles (*Solea vulgaris*) and large hake; otherwise they got, as a rule, only skates and whitings. We shot our own trawl to see what there was on the bank, and captured the same fishes that the trawlers had spoken about (Station 14).

Fig. 43.—Portuguese Fishing-Boat.

The fine weather tempted us to try to make a series of hauls at different depths along the edge of the coast banks. We accordingly lowered the following appliances in the evening: a tow-net at the surface and two more at 50 metres and 100 metres respectively, a young-fish trawl at 150 metres, tow-nets at 300 metres and 500 metres, and another young-fish trawl at 750 metres.

We had, however, scarcely begun towing our nets before a northerly gale sprang up. Hauling in had therefore to be done in the dark, and the sea became high and broke over the stern, where the gear was being got in. The result was that the violent pitching of the ship tore the silk cloth of the nets and did considerable damage. We lost the tow-nets sent to 100 metres and 500 metres, as well as the young-fish trawl at 750 metres, and a good deal of harm was also done to the others. All the same we managed to get some samples of interesting deep-sea forms, though such catches were of a more or less fortuitous nature.

Off Lisbon the sea became calm, and we took hydrographical observations at Station 17, obtaining water-samples from many depths. Here, out on the edge of the continental slope, and in the Spanish Bay, the weather was beautifully warm, and the sun shone brightly. We now met with some extremely interesting forms of animal life. Numerous dolphins swam round our bows, and when standing in the fore part of the ship we saw thousands of small pelagic crabs (*Polybius*; see Fig. 46), sometimes as many as fifty of them in three minutes. We also sighted a turtle.

FIG. 44.—BARGAINING.

While steaming along Gran studied the plankton filtered from water obtained by a pump, and found in every sample more than forty species of diatoms and peridinii, whereas to the west of Ireland we had come across a diatom-plankton, rich in individuals but very poor in species, consisting of the ordinary North European coast diatoms. This showed that we had now reached a southern and warmer marine region, with a totally

Gran's investigations on the plankton.

distinct assemblage of animal and plant life in the upper water-layers.

On the morning of Monday 25th April we anchored off Gibraltar, where we had our boilers overhauled, and procured reserve rollers and blocks, as well as new swivels for the trawl line.

FIG. 45.—PORTUGUESE FISHERMAN.

Currents in the Strait of Gibraltar.

During our stay at Gibraltar we made two short trips: one to the Strait to study the currents, and the other to the Mediterranean to test our pelagic appliances. The Strait of Gibraltar has for a long time past attracted the attention of hydrographers. Through this narrow channel the exchange of water between

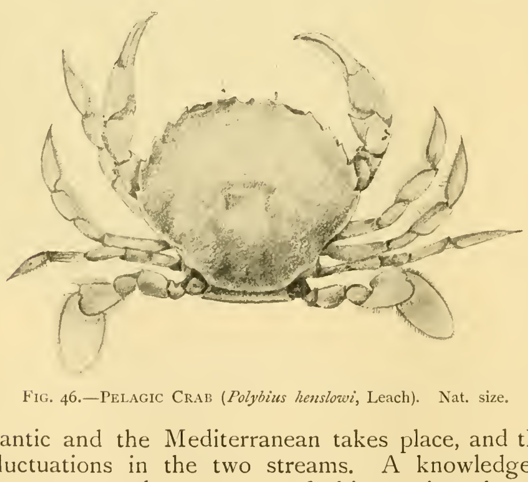


FIG. 46.—PELAGIC CRAB (*Polybius henslowi*, Leach). Nat. size.

the Atlantic and the Mediterranean takes place, and there are great fluctuations in the two streams. A knowledge of the laws that govern the currents of this marine thoroughfare is accordingly of the utmost importance, not merely because of the light it throws on the question of ocean circulation, but also because of its value to navigation. As early as 1871 Nares and Carpenter made a study of these currents, and important investigations have been made in later days by the Danish research vessel "Thor" under the direction of Joh. Schmidt. No direct measurements of the actual velocities of the currents at different depths and their direction had previously been undertaken, but current-meters, especially the excellent one constructed by V. W. Ekman, put it in our power to make the attempt.

The "Michael Sars" had previously measured currents off the coast of Norway by anchoring a life-boat fore and aft with grapnels and a stout hemp line. We endeavoured to work on the same principle in the Strait of Gibraltar (Station 18), but were unsuccessful at first; one line after the other parted, owing to the velocity of the current. Finally we had to anchor the ship itself with $1\frac{1}{2}$-inch steel line and a warp anchor, in 400 metres of water on a hard bottom. This held, and she lay at anchor from 1.30 A.M. till 5 P.M. on the 30th April. During this time Helland-Hansen worked unceasingly. One current-meter was used continuously at a depth of 10 metres, and another was lowered to different depths right down to the bottom. In addition he took a series of water-samples and temperatures at different depths.

He found that there were two strong currents in the Strait, one going east from the Atlantic into the Mediterranean in the upper layers, and one going west at the greater depths. The limit between them was for the most part at a depth of about 150 metres, but it varied so much that in the afternoon between 2 and 2.30 P.M. it was at a depth of 50 metres, while between 4 and 5 A.M. even at the very surface the current went westwards. These variations practically coincided with the tidal movements.

There were high velocities in the upper east-going current; at 10 metres the velocity varied between 1 and $2\frac{1}{2}$ knots, and at 25–30 metres between 1.7 and 3 knots. At a depth of 100–120 metres the current was always westerly, but the velocity was only between half a knot and a knot, whereas at 150–200 metres, where the current was also westerly, the velocity varied from 0.3 knot to as much as 5 knots; close to the bottom a velocity of $\frac{1}{4}$ knot was measured. Helland-Hansen's interesting observations are the first reliable figures regarding the movements at the different depths, and they are of great assistance towards a proper understanding of the water circulation in the Strait of Gibraltar.

Pelagic investigations in the Mediterranean.

At Station 19, a few hours' steaming from the entrance to the Mediterranean, we experimented with different appliances, to ascertain the best way of arranging our subsequent pelagic investigations. The big silk tow-net, 3 metres in diameter, was lowered to a depth of 900 metres and immediately hauled up again. It was found to work well, and captured a number of pelagic fish (eight specimens of *Argyropelecus*, a few scopelids, and some young fish), but our catch seemed to indicate that vertical hauls were not nearly so productive as horizontal hauls, and we therefore decided to make long horizontal hauls our principal mode of catching pelagic fish during the remainder of the cruise.

Water strata in the Mediterranean.

At this part of the Mediterranean there was a sharply defined limit between an upper water-layer, where the temperature was fairly high and the salinity almost identical with that of the upper layer in the Spanish Bay in the Atlantic, and a lower water-layer with "bottom-water" of uniform temperature (a little below 13° C.) and salinity (over 38 per thousand). Several series of temperatures and water-samples were taken, and the limit between the two layers was found at a depth of 150–200 metres, though subject to considerable variation, as in the Strait of Gibraltar but not to such an extent.

Noctiluca.

The surface water here was so full of phosphorescent *Noctiluca* as to be almost as thick as broth, and when the contents of the tow-net were emptied into a glass they formed a sediment a centimetre in thickness at the bottom of the glass. In the evening the sea resembled a star-spangled sky, and the wires following the vessel looked like gleaming stripes. During the day we now saw for the first time the beautiful surface organisms of the south, such as *Velella* and the Portuguese man-of-war (*Physalia*), with which zoologists and sailors in Mediterranean waters are so well acquainted.

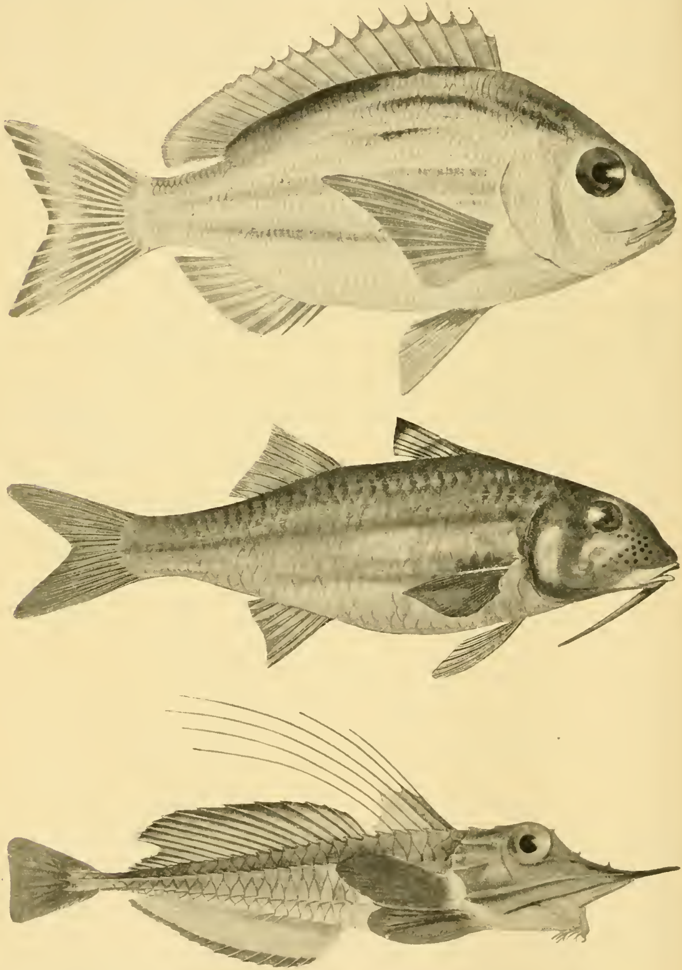
From the Spanish Bay southwards along the north-west coast of Africa.

The region from Spain along the coast of North Africa is well known to zoologists from the successful labours of the French "Travailleur" and "Talisman" Expeditions. Series of trawlings at various depths were undertaken by these two ships with only small beam trawls, so that we had every hope of accomplishing something with our large trawl. We were able besides to turn to good account the information acquired from the fishermen, large numbers of whom have shot their trawls along these shores in recent years. They had given us to understand that we could reckon on finding good trawling grounds as far down as 250 fathoms on many of the coast banks off Morocco, such as the stretch from Cape Spartel to Casa Blanca, from Mogador to the bay at Agadir, and south of Cape

FIG. 47.—DEPTHS AND STATIONS IN THE SPANISH BAY.

Juby on the inner side of the Canary Islands. We also learned that their catches chiefly consisted of hake (*Merluccius vulgaris*), which, as a rule, made up two-thirds of the whole; soles (*Solea vulgaris*), and different kinds of silvery or brilliantly-coloured spiny-finned fish (mostly Sparidæ), which they call "salmon."

Our plan was to carry out two series of trawlings from the coast banks outwards to great depths, one in the Spanish Bay and one south of the Canary Islands, so as to have a general idea of the fauna at different depths in different latitudes. We wished also to take a thoroughly good hydrographic section right across the Spanish Bay, with water-samples and tempera-



a

b

c

Fig. 48.—Three Shore Fishes from Station 20, 141 metres (about 75 fathoms).
a. Dentex maroccanus, Cuv. et Val. Nat. size, 25 cm.
b. Mullus surmuletus, L. Nat. size, 29 cm.
c. Peristedion cataphractum, Cuv. et Val. Nat. size, 30 cm.

tures from all depths, and we hoped to trace the course of the salt-water layer that flows out from the Mediterranean to the Atlantic, which we felt would be interesting to all hydrographers.

Trawlings in Spanish Bay.

We left Gibraltar on 4th May and steamed through the Strait and past Cape Spartel in perfect weather till we came to the coast bank, where at Station 20 (see Chart, Fig. 47) we saw seven trawlers at work. Our trawl was dropped in 141 metres, and towed for two and a half hours. The resulting catch of 163 fishes was a good sample of the ordinary species to be found there, namely hake, different kinds of gurnard (*Trigla* sp.),

FIG. 49.—TWO DEEP-SEA FISHES OF THE FAMILY ALEPOCEPHALIDÆ.
a. Alepocephalus from Station 23 (1215 metres). Nat. size, 60 cm.
b. Conocara from Station 25 (2055 metres). Nat. size, 20 cm.

mullet (*Mullus surmuletus*), and silvery or brilliantly-coloured spiny-finned fishes (*Capros*, *Pagellus*, *Dentex*; see Fig. 48).

The next station (Station 21), in 535 metres, yielded 117 fish, including hake, but all the beautifully-hued fish had disappeared. Instead we found the deep-sea fauna coming into evidence (*Macrurus*, *Chimæra*), and at the three following trawling stations our catches were made up entirely of true deep-sea fish (Fig. 49), namely :—

Station 23 at 1215 metres, 77 fishes.
Station 24 at 1615 metres, 32 fishes.
Station 25 at 2055 metres, 29 fishes.

From a technical point of view these hauls were in every way satisfactory, as our winch, trawl, and all connected with them worked perfectly smoothly. The new swivels (Fig. 50) procured at Gibraltar were a thorough success, and stopped the twisting in the trawl-warp and bridle. The bottom was everywhere well adapted for trawling.

At Station 23 we towed a small young-fish trawl at 1215 metres. It touched the bottom and brought up a quantity of empty pteropod shells which had been sifted out from the bottom deposit. It is extraordinary to find these deposits of shells belonging to plankton organisms only at certain relatively shallow and intermediate depths, for, when alive, the pteropods float over all depths.

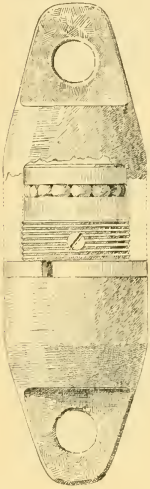


Fig. 50.—The New Swivel.

Our trawlings further resulted in a fine collection of invertebrate animals; at Station 24, for instance, we found the trawl full of siliceous sponges.

These waters offer a good field for a thorough study of the distribution of animal life, for the nature of the bottom and the gentle slope permit of trawling at all depths. Our time unfortunately was too short to permit us to do more than obtain a general impression.

We next turned our attention to the hydrographical investigations, and steamed to the north side of the bay near Cadiz (Station 26), whence we ran a series of stations, at all of which careful hydrographical observations were made (Stations 26–30).

At the conclusion of the "Challenger" Expedition Buchan showed that it was possible to trace the course of the comparatively warm Mediterranean water out into the North Atlantic Ocean. In 1909 the Danish expedition in the "Thor" under Schmidt made some observations from the Strait of Gibraltar westwards, and secured extremely accurate determinations of temperature and salinity, showing that the Mediterranean water (in a very diluted state) makes its way out through the Spanish Bay, sinking down to a depth of 1000–1200 metres.

Relation between Mediterranean and Atlantic waters.

In our investigations we aimed at studying more closely the relation between Atlantic water and Mediterranean water, and we also endeavoured to become familiar with the currents on both the Spanish and Moroccan sides of the bay. Unfortunately we had to abandon our current measurements, but the variations of salinity and temperature from our many adjoining stations give a fairly good idea of the conditions. It is enough to mention here that in the neighbourhood of Spain the diluted Mediterranean water was found at far less depths (as near the surface, in fact, as 400 metres) than farther south in the bay. The surface current runs along the Spanish coast in an easterly or south-easterly direction, and off the Moroccan coast in a southerly or south-westerly direction (see Chapter V.).

Hydrographical investigations were continued all the way southwards along the continental edge to the Canary Islands. We were prevented from attempting any other kind of work, as near Mogador we encountered a stiff north-east trade-wind, before which we had to run. Every now and then a heavy sea broke over our quarter, sweeping the deck clean. Not till we reached the Canaries did the wind and sea go down. At Lanzarote we met with calm weather, so we did some pelagic work, taking vertical and horizontal hauls. The latter resulted in the capture of several interesting deep-sea fish, a number of leptocephali, and the beautiful transparent *Plagusia*.

FIG. 51.—A FISHING SCHOONER SAILING INTO PORTA DE LA LUZ.

On Saturday, 14th May, we anchored at Porta de la Luz, the harbour of Grand Canary.

In Porta de la Luz we obtained a good deal of information regarding the fishing industry from a number of fishing schooners which work along the African coast, several being in port at the time of our visit.

Most of them are well-boats, which carry live fish in addition to the ones they salt. They employ partly hand lines and partly curious large basket-traps, baited with fish and placed on the bottom in the position shown in Fig. 52.

African coast fisheries.

When the boats arrive in port they transfer the live fish into big floating tanks, of which we saw many. We were able to examine the kinds they caught, and learned from the people the names in current use. This was a piece of good fortune for us, because the local guide-books give misleading information. The fish caught are spiny-finned and silvery, or of brilliant colours. The following are the commonest species :—

Chiacarone	= *Dentex vulgaris.*
Besugo	= *Pagrus vulgaris.*
Burr oor Chierne	= *Diagramma mediterraneum.*
Chopa	= *Cantharus lineatus.*
Saifia	= *Sargus rondelettii.*
Dorado	= *Chrysophrys aurata.*

Most of them are at present sold alive and eaten fresh, but some are salted, being first split down the back and sliced. They are also occasionally dried, though this kind of stock-fish does not keep long.

Fig. 52.—A Basket-Trap on board a Fishing Schooner.

The harbour pilot was thoroughly acquainted with the industry. He himself owned one or two schooners, and had taken part in the fishing round the islands and off the African coast. According to him the best places were on the stretch from Cape Juby and beyond Cape Bojador to the River Ouro, and down near Cape Blanco. The trawlers found it too expensive to go so far. Only hand lines and traps are used at present, and most of the fishing is done on a hard bottom in about 16–30 fathoms of water. He advised us to go as far as Cape Bojador, where there was a little bay sheltered from the trade-winds. We decided to follow his advice, partly because we hoped to see a little of the mode of fishing practised in the Canary Islands, and thus learn more about the animal life than we ourselves could expect to learn in the short time at our disposal, and partly with the idea of making a series of trawlings like those we had made in the Spanish Bay.

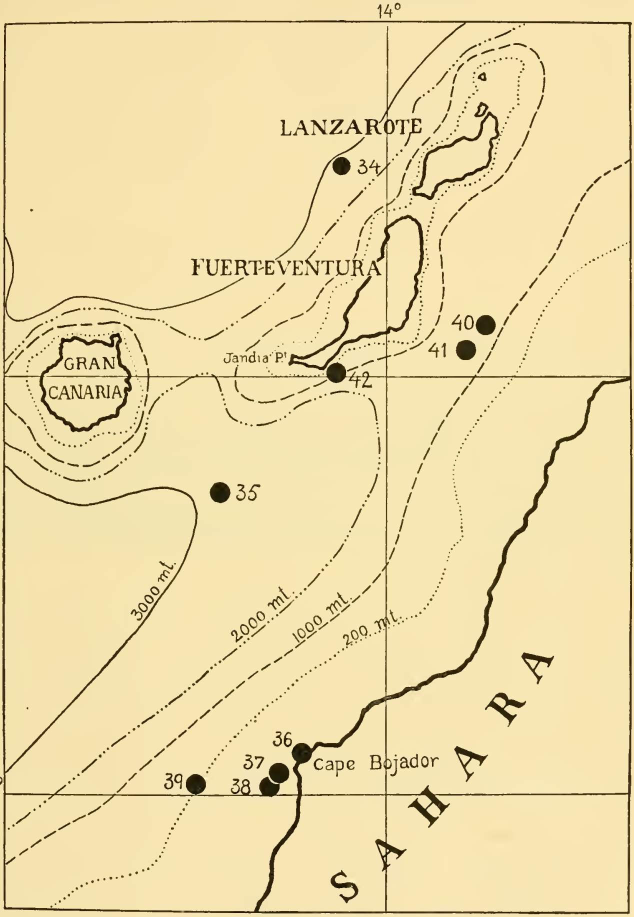


FIG. 53.—"MICHAEL SARS" OBSERVING STATIONS OFF THE CANARY ISLANDS AND COAST OF AFRICA.

Accordingly we left Gran Canaria on 18th May, and steamed for Cape Bojador (see Chart, Fig. 53). On the way we resolved to try our trawl in deep water, as the weather was fine.

We sounded, therefore, at Station 35 and got 2603 metres. The trawl was dropped with 5200 metres of wire and towed for about two hours till 6 P.M. At 9 P.M. it was on board again with an extremely interesting catch, including two baskets of holothurians and twenty fishes, several of which were remarkable bottom forms (*Harriotta*, *Bathysaurus*, *Halosaurus*, *Alepocephalus*, and different species of *Macrurus*). There were also several pelagic fish, including the interesting *Gastrostomus bairdii*, with its huge gullet, which had previously only been found on the American side of the Atlantic.

At Bojador there were seven fishing schooners and two smacks at anchor. Some of the people were rowing about in boats setting traps, while others were jigging from the vessels themselves. We went on board the "Isabelita." Along the port-rail stood ten men with hand lines, each furnished with three hooks, by means of which they hauled up the big grey "burro" as fast as they could pull. Every now and then they captured "chiacarone" and smaller silvery fish with red fins and strong teeth. Their bait consisted of anchovies and sardines, which they secured near the shore by means of a seine net. We were told that at daybreak next morning they were going close inshore to use their seine, and we obtained a promise to be allowed to accompany them. To our surprise we were asked to bring carbines and revolvers, as the fishermen were very much afraid of the Arabs.

Seine-net fishing.

Before daybreak we rowed towards the shore along with the fishermen to work the seine. The view was magnificent. For miles we could see the coast stretching away in a straight, clear-cut line like a mole, a hundred feet or so above the sea; up beyond the cliffs the land apparently was quite flat, and the sun rose over this line as it does from the horizon at sea. Unfortunately the breakers prevented us from landing, and we had to lie a short distance out from the shore. On the heights above we could see the dreaded Arabs, with their long, thin firearms ready for use; but they sat as motionless as statues, and were probably only thinking of defending themselves.

The Spanish fishermen now made several casts with their seine (see Fig. 54), but were unsuccessful. They had expected to catch large quantities of sardines for bait. We got from them, however, some interesting samples of the small fish that live in quite shallow water, which it would otherwise have been difficult for us to obtain. Among them were young fish (sardines and anchovies), and a number of small spiny-finned fish (*Sargus, Box, Pristipoma*), besides fry of the horse-mackerel (*Caranx trachurus*), and hake. The fishermen gave us the whole of the catch and would take nothing for it. On parting from them we felt that we had made the acquaintance of capable energetic men, engaged in an interesting industry.

The guide-books sold on the islands state that the fishing industry is undeveloped, because the island population is apathetic, and the Spanish Government little interested in it. This is hardly correct; their African fishing seems to evince both enterprise and a power of adaptation to circumstances. It is no small matter to have to sail in the trade-winds, which are sometimes very violent off the coast of Africa, and there is besides an absence of harbours. The fish caught are best suited for selling alive in the local markets, and it is

FIG. 54.—HAULING IN THE SEINE.

extremely doubtful whether it would pay to start a fishery on a large scale, as has often been proposed, and commence salting and drying. The kinds of fish may possibly be unsuitable for curing, and the warm climate is very likely less favourable than that of northern lands. As long ago as the middle of the eighteenth century an enterprising man named George Glas made great efforts to establish a fishery, and maintained that the Spanish did not need to depend on Newfoundland for their fish, as they could make their African coast fishery the richest in the world. He did his utmost to prove the truth of his assertion, but failed, partly because of the natural difficulties, and partly owing to various tragic occurrences. Taking everything into account, the conditions under which it is carried on and the present state of the markets, the fishing industry of the Canary Islands is quite creditable, and the friendliness of the fishermen towards our expedition was much appreciated by all on board.

Our plan after leaving Bojador was to undertake a series of trawlings over the coast banks and continental edge. This

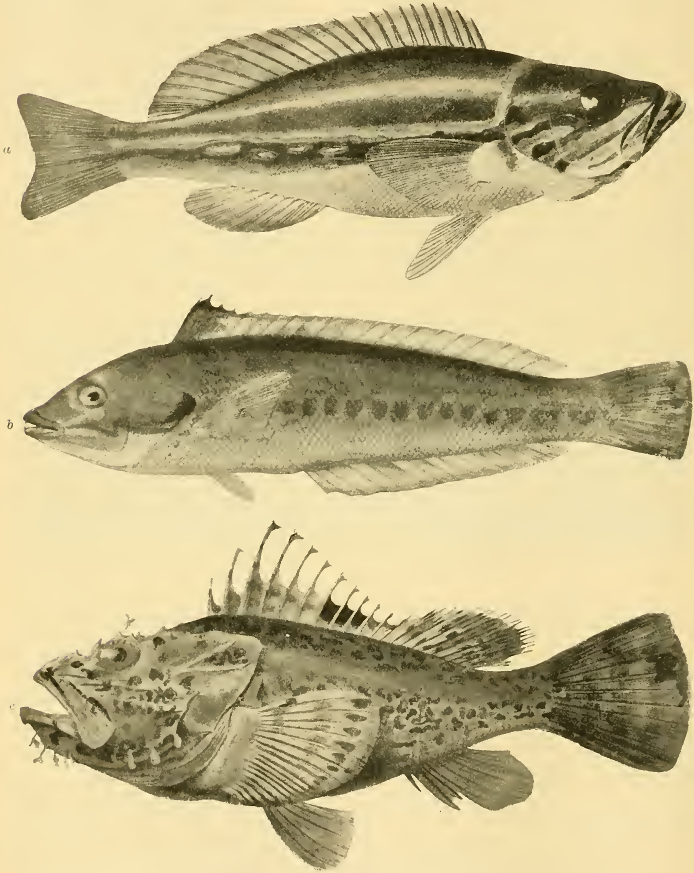


FIG. 55.—THREE COAST FISHES FROM STATION 37, 39 metres (about 20 fathoms).
a. Serranus cabrilla, L. Nat. size, 21 cm.
b. Coris julis, L. Nat. size, 18 cm.
c. Scorpæna scrofa, L. Nat. size, 48 cm.

proved, however, a matter of great difficulty. Both at Station 37 (see Fig. 55) in 39 metres of water, and at Station 38 (see Fig. 56) in 77 metres, the trawl stuck fast on the hard bottom.

Still, we succeeded in making some small catches of the animals that live on the bank, including soles and megrims (*Solea* and *Arnoglossus lophotes*), gurnard, weevers, monkfish, a large

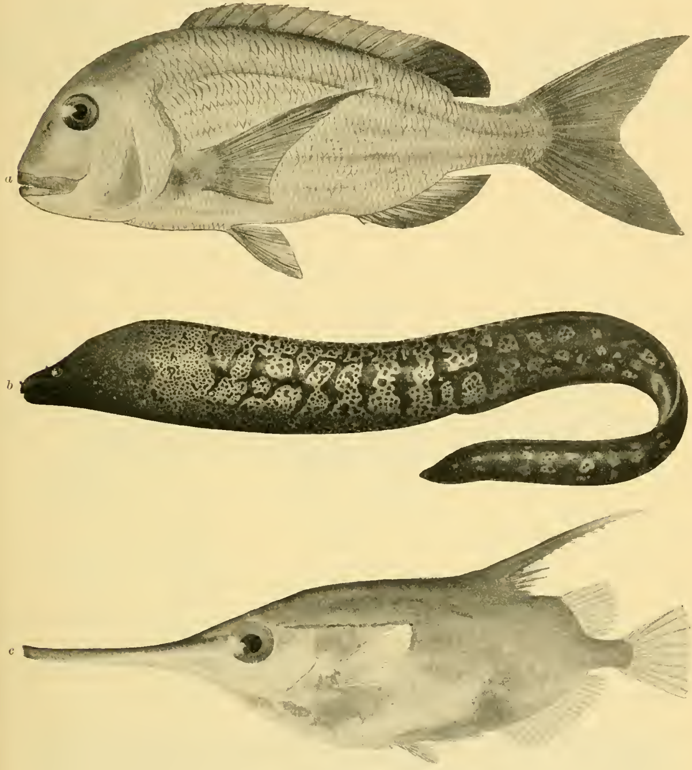


FIG. 56.
a. Pagrus vulgaris, Cuv. et Val. Nat. size, 50 cm.
b. Muræna helena, L. Nat. size, 102 cm.
(*a* and *b* from Station 38, 77 metres—about 40 fathoms.)
c. Centriscus scolopax, L. Station 39, 267-280 metres.

beautifully-coloured muræna (*Muræna helena*), and a number of skates. At Station 39 (see Fig. 56, *c*) in 267–280 metres of water, we were more successful, catching a quantity of spiny-finned fish (*Dentex*, *Pagrus*, *Scorpæna*, *Trigla*), hake and skates, and quite a number of deep-water fish. A pelagic haul on the edge of the continental slope yielded some interesting captures, especially several spotted eel larvæ (leptocephali).

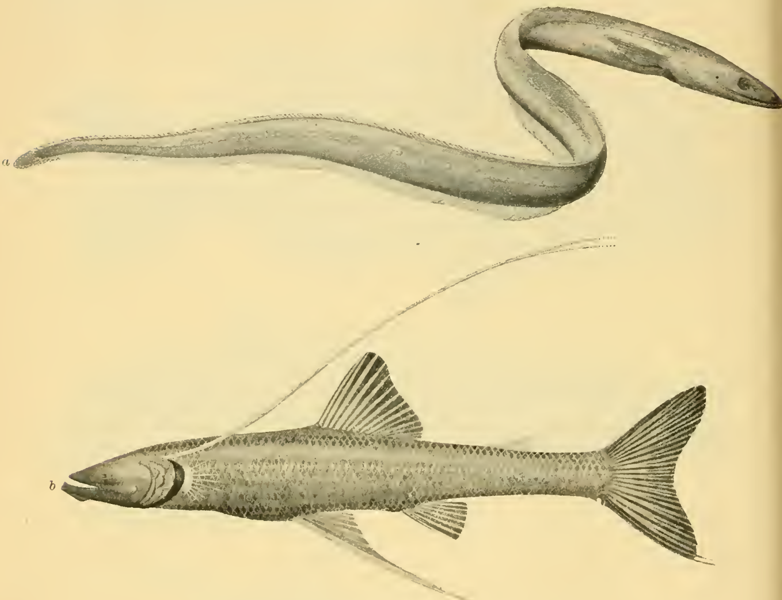


FIG. 57.—TWO DEEP-SEA FISHES FROM STATION 41.
a. Synaphobranchus pinnatus, Gron. Nat. size, 31 cm.
b. Bathypterois dubius, Vaill. Nat. size, 17 cm.

Deeper trawlings were impracticable. The captain sounded in several places to try and find a spot where there was a chance of trawling along the slope at a fairly uniform depth, but the

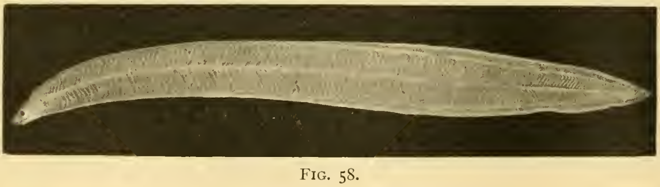


FIG. 58.
Leptocephalus Congri vulgaris.

slope was too steep, and we had to abandon the idea. The only place where, according to the chart, there was any prospect of trawling at so great a depth as 1000 metres was between the coast of Africa and the island of Fuerte Ventura. Here we

Fig. 59.
Ceratias, n.sp. Nat. size, 13 cm. Station 42.

sounded at Station 41 and got 1365 metres. We shot our trawl with 3400 metres of wire, and towed it for three and a half hours. Hauling in took an hour and fifty minutes. Our catch consisted of about fifty deep-sea fishes (see Fig. 57), several baskets of holothurians, and a number of interesting invertebrates, including some beautiful, large, red-coloured prawns, no less than 30 centimetres long. This catch was extremely interesting, as it yielded the same species of fish that we got in our hauls to the west of Ireland (*Mora*, *Trachyrhyncus*, *Alepocephalus*, *Synaphobranchus*).

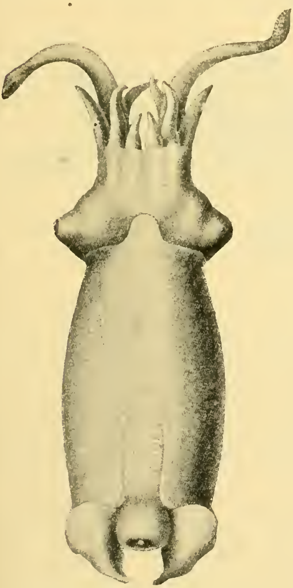


Fig. 60.—*Spirula*. (From Chun.)

The trade-winds had meanwhile freshened considerably, so we steamed under the lee of Fuerte Ventura, and at Station 42 used our pelagic appliances at various depths. The captures were particularly interesting, including as they did nineteen larvæ of eels (leptocephali). One individual among these (Fig. 58) belonged to the ordinary conger-eel (*Leptocephalus Congri vulgaris*), but the other eighteen were all of another species closely resembling the conger larva, but

Eel larvæ.

differing from it in the number of muscle segments; some of them were only 4.2 cm. long. There were further some remarkable deep-sea fish, including a curious *Ceratias* (Fig. 59), and the little rare cuttle-fish, *Spirula* (Fig. 60), which is of such interest to zoologists.

During the night some flying-fish (Fig. 61) with mature eggs came on board, and on our way back to Gran Canaria we saw a quantity of flying-fish near the island. We anchored once more at Porta de la Luz on Tuesday, 24th May.

From the Canaries to the Azores.

From Plymouth to the west coast of Africa we had been chiefly cruising over the coast banks and continental slopes.

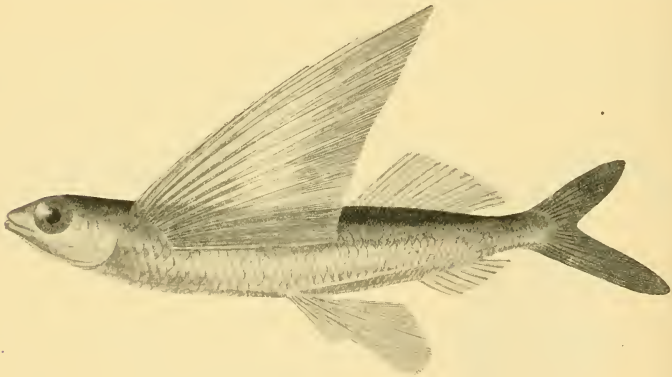


FIG. 61.—FLYING-FISH (*Exocœtus spilopus*, Val.). Nat. size, 32 cm.

Now we were to begin a voyage across the Atlantic from the Canary Islands to the Azores and thence to Newfoundland. Our task henceforth was therefore to investigate a deep ocean, the average depth of which may roughly be put at 5000 metres. Everything accordingly had to be so arranged that we could lower our instruments and appliances to profound depths.

The experiences of previous expeditions had made it clear that the larger organisms, at any rate, are sparsely scattered over the vast ocean depths. We therefore prepared ourselves for long pelagic hauls of a day's or a night's duration, during the course of which it would be necessary to employ simultaneously as many appliances as we could at different depths, partly to accomplish as much as possible in a limited space of time, and partly to discover what creatures inhabit the various water-strata.

While on our way to the Azores we hoped to be able to reach the Sargasso Sea and study its peculiar animal life. Accordingly before leaving Gran Canaria we interviewed some Norwegian skippers, who had spent many years in the waters lying between the Canary Islands and the West Indies, and were advised by them not to steer direct for the Azores, but to follow a westerly course as far as the longitude of those islands and then turn northwards. We followed their sugges-

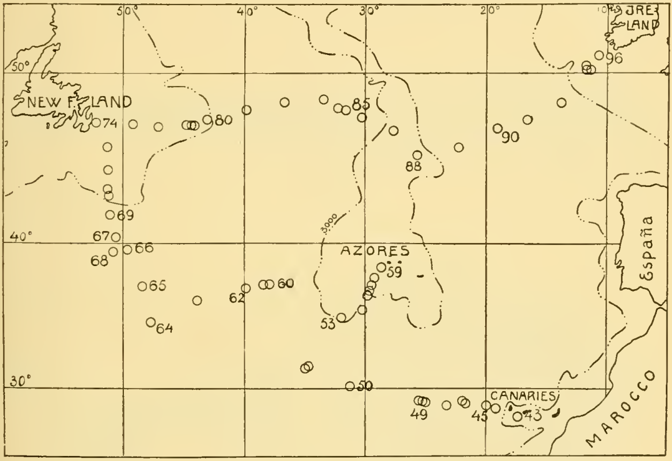


FIG. 62.—"MICHAEL SARS" STATIONS FROM CANARY ISLANDS TO THE AZORES AND NEWFOUNDLAND AND THENCE TO BRITAIN.

tion, leaving Gran Canaria on 27th May, and, as will be seen from the chart (Fig. 62), first steered westwards, making some investigations at Stations 43–52, and then northwards to Fayal, one of the Azores, occupying Stations 53–58, and arrived at Fayal on 13th June.

Hydrographical investigations were made all this time, and we took as many as fourteen water-samples at different depths at each station, from the surface down to 2000 metres, thus securing some excellent material from this area. Fig. 63 shows a section of the ocean on our westerly route. It is remarkable how uniform the hydrographical conditions proved to be. The

Uniformity of hydrographical conditions and of animal life.

curves of salinity and temperature lie exactly parallel, both decreasing regularly as we descend in depth.

The animal life, too, showed everywhere great uniformity. While on this route we made seven long pelagic hauls, some at night, with a number of appliances working at different depths simultaneously. The weather was all that could be desired, and we had therefore a splendid opportunity of testing even the very finest of our appliances. As a result we succeeded in collecting a great variety of forms, a full description of which can only be given after thorough systematic examination. It

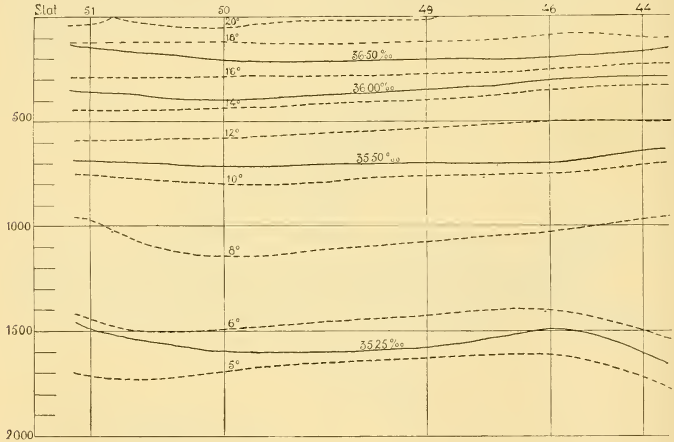


FIG. 63.—HYDROGRAPHICAL SECTION SHOWING THE TEMPERATURE AND SALINITY AT STATIONS 44 TO 51.

will suffice here to mention the main features of the catches, and to describe one or two particularly remarkable forms (especially fishes) that attracted our attention at the time, or during our first cursory inspection in the laboratory. In the following chapters the material collected will be treated in a more systematic manner.

It was interesting to find that from the corresponding depths we always obtained catches practically identical in character. In the appliances towed at the surface and down to 150 metres there were small colourless young fish of many species, and fish-eggs of very different sizes, some even as small as 0.5 mm. in diameter, and leptocephali occurred in considerable quantities. A profusion of crystal-clear pelagic forms, such as the large transparent amphipod (*Cystosoma*), *Velella*, *Cestum veneris*, *Ianthina*, *Pterotrachea*, *Physalia*, and *Glaucus atlanticus*, were also characteristic.

Animal life at different depths.

At depths of 300 metres down to 500 metres silvery fishes were much in evidence. The commonest of them were the flat-

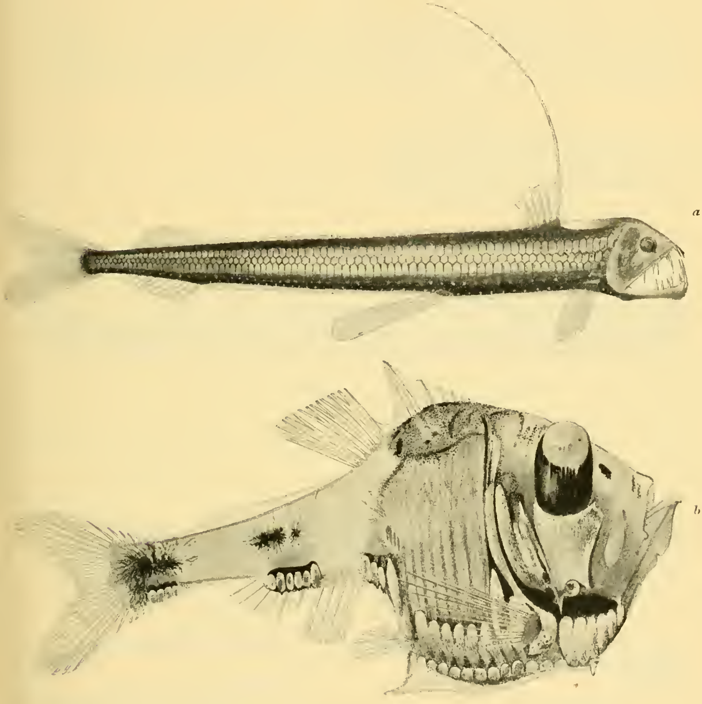


FIG. 64.—TWO SILVERY FISHES FROM A DEPTH OF ABOUT 300 METRES.
a. Chauliodus sloanei, Bl. and Schn. Nat. size, 6 cm.
b. Argyropelecus hemigymnus, Cocco. Nat. size, 3.5 cm.

shaped *Argyropelecus* (see Fig. 64, *b*) *Stomias*, *Chauliodus* (Fig. 64, *a*), and *Serrivomer*. The fish which we met with most frequently, however, was the grey-coloured *Cyclothone signata*, hundreds of which were sometimes taken in a single haul (see Plate I., Chapter X.). Several species of red prawns were also found here.

Our hauls from 1000 metres down to 2000 metres were equally interesting. They invariably contained black *Cyclothone microdon* (see Plate I., Chapter X.), and different species of red prawns in abundance. In addition there were many of the rarer sorts of black-coloured fish, *Photostomias*, etc., mentioned in the following pages, and dark brown medusæ. *Atolla*,

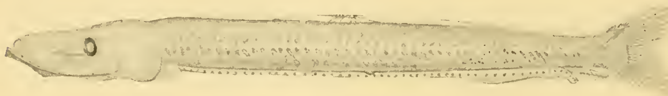


Fig. 65.—Stalk-eyed Fish-larva.

for instance, was especially characteristic, and so were red chætognaths, and at some stations red nemertines.

Besides the commonest forms which are almost always found

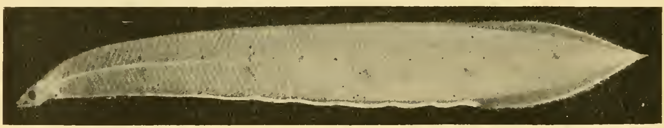


Fig. 66.—New Species of Leptocephalus.

occurring at the same depths, we obtained something of special interest at nearly every station. We can best illustrate this perhaps by a brief description of our most noticeable finds at

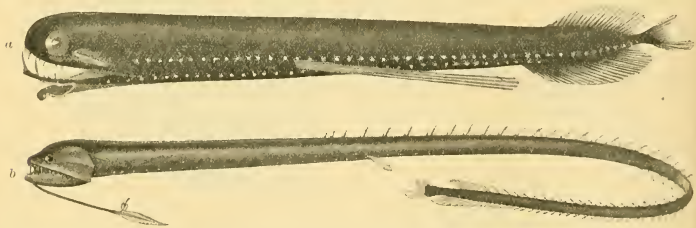


Fig. 67.—Two Black Fishes with many Phosphorescent Organs, sometimes found in the Upper Layers at Night.
a. Photostomias guernei, Coll. Nat. size, 17 cm.
b. Idiacanthus ferox, Gthr. Nat. size, 22 cm.

the stations marked on the chart (Fig. 62), remarking only that in their selection we have been guided by what we consider the most interesting.

At Station 45 we made a haul with seven appliances during the night. In the upper 150 metres there was a quantity of young fish (some of which were stalk-eyed; see Fig. 65), pteropods, leptocephali (one of which displayed remarkable pigment; see Fig. 66), and cuttle-fish. There were besides a few black fish (*Idiacanthus ferox*, *Photostomias guernei*; see Fig. 67).

In the deep hauls at 1000 metres and 1500 metres there were numerous very rare animals. For instance, we secured specimens of the cuttle-fish *Spirula*, and of the fish *Melanocetus krechi*, the type of which had been discovered by the "Valdivia" Expedition in the Indian Ocean, so far removed from the scene of its recapture. Again, *Aceratias macrorhinus indicus*, a small brown fish (28 mm. long; see Fig. 68), and *Cyema atrum* (Fig. 69), had hitherto only been met with in the Pacific and Indian Oceans, and off the coast of Morocco.

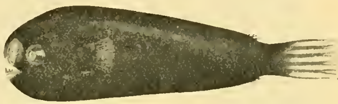


Fig. 68.
Aceratias macrorhinus indicus, A. Br.
Nat. size, 2.8 cm.

It was extremely interesting to find at one spot all these proofs of the wide distribution of such "rare" pelagic fishes.

At Station 47 we sounded in 5160 metres. Trawling was tried, but was a failure, as the trawl got out of order and merely captured a sea-pen (*Umbellula güntheri*). During the night we sighted a turtle, which was thus about 250 nautical miles from the nearest land, the island of Palma.

At Station 48 we made another attempt at trawling. The big trawl was dropped with 8750 metres of wire at 11.20 A.M.

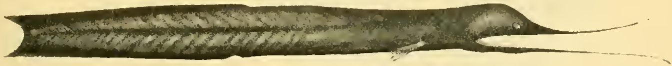


Fig. 69.
Cyema atrum, Gthr. Nat. size.

At 2.50 P.M. we commenced hauling in, and the trawl came up at 9 P.M. This time everything seemed to have gone right, for the trawl apparently went down and came up again in full working order. Strangely enough, the catch was meagre in the extreme, consisting of half a barrel of ooze, a number of pumice fragments, the earbone (bulla tympanica) of a whale, two sharks' teeth (*Carcharodon* and *Oxyrhina*), a fragment of a nautilus shell, two holothurians, about ten pteropod shells, an antipatharian, a sertularian, *Umbellula*, six fishes (*Alepocephalus*, *Malacosteus indicus*, *Argyropelecus*, leptocephalus in its transition stage from the larval form, a new form resembling *Ipnops*

Trawling in deep water.

murrayi, for which Koefoed and I propose the name *Bathymicrops regis*, and an ophidiid not yet determined). All these fishes, if we except, perhaps, *Bathymicrops regis*, were probably captured while the trawl was being hauled in. There were thus no undoubted bottom-fish in this long haul with our large appliance, and taking everything into consideration, we had caught extremely little. Chapter VII. deals more fully with the significance of this result. We were interested to find a fragment of a sea-pen (*Umbellula güntheri*, Fig. 70) which continued shining brightly on the deck, thus furnishing fresh proof of the well-known fact that some of the lower animals from the profoundest depths emit light.

Fig. 70.
Umbellula güntheri (phosphorescent).

While towing the trawl we made some interesting observations on the pelagic animal life, as we put two tow-nets on the trawl wire, the one being towed at about 40 metres, and the other at about 2000 metres, and during the whole of the day we took samples from the surface.

The tow-net at 40 metres contained a mass of red copepods, which were not observed at the surface during the daytime, but suddenly appeared as soon as it grew dark, soon after 6 P.M. The surface plankton comprised *Physalia*, a great many molluscs, such as *Ianthina* and *Pterotrachea*, one of the remarkable little fishes called sea-horses (*Hippocampus*, Fig, 71), and the beautiful belt of Venus (*Cestum veneris*); very many pelagic foraminifera were present in the fine nets.

Our deep tow-net caught a large *Alepocephalus*, showing that this fish may be pelagic. So far as we know it had hitherto been taken only in the trawl, and this catch was all the more interesting, because our trawl at the end of the same wire also captured a specimen; previously one would have taken it for granted that this specimen must have been caught at the bottom.

Fig. 71.—*Hippocampus.*

At Station 49 B we towed seven appliances *in daylight*, and *no black fish* were captured in the upper layers. We observed a number of Portuguese men-of-war (*Physalia*), around which were a great many small fishes — probably horse-mackerel (*Caranx*), which we caught in one of the young-fish trawls—and fry of *Scombresox*. A beautiful large transparent amphipod (*Cystosoma*)

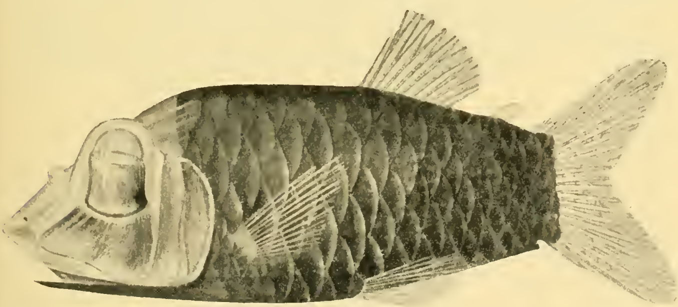


Fig. 72.
Opisthoproctus soleatus, Vaillant. Nat. size, 6.5 cm.

was secured at 200 metres, and young *Argyropelecus* at 500 metres. In the deeper appliances we found large ostracods

(*Gigantocypris*) with eggs, *Opisthoproctus soleatus* (a remarkable little fish, with large telescopic eyes, caught once or twice

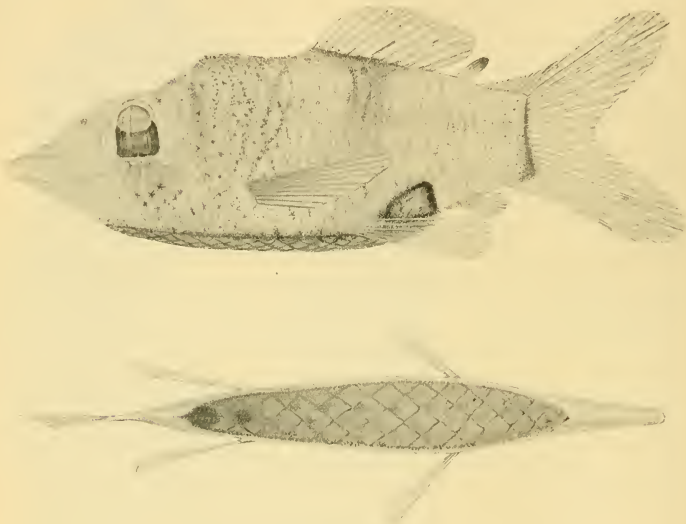


FIG. 73.
Opisthoproctus grimaldii, Zugmayer. Nat. size, 2.6 cm.

previously; see Fig. 72), and another species of the same genus, *Opisthoproctus grimaldii* (see Fig. 73), two specimens of which were taken by the Prince of Monaco off the coast of Portugal.

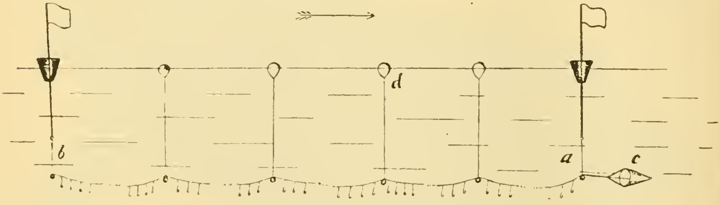


FIG. 74.—FLOATING LONG LINES.
a, *b*, Big buoys; *c*, drift anchor; *d*, leather buoy.

There were also some specimens of the little *Aceratias macrorhinus indicus*.

Drift nets and lines. We had all along intended to try drift nets and floating lines out in the ocean to see whether big fish were to be caught there, so we now made the experiment. A line was set perpendicularly with 1300 cod hooks, a fathom and a half apart (see Fig. 74), and we also put out six cod nets. Only one fish was caught on the line, at a depth of 550 metres, namely, *Omosudis lowei* (Fig. 75), which Lowe captured at Madeira, and is recorded by Günther as having been found near the Philippines by the

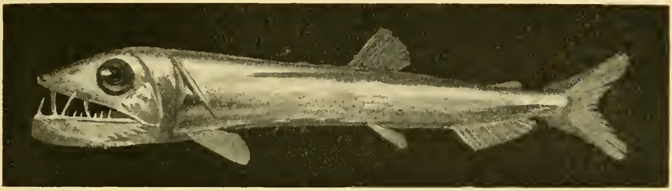


FIG. 75.
Omosudis lowei, Gthr. Nat. size, 14.5 cm.

"Challenger." A large ossified spine springs from its gill-cover and extends right along the side of its body, and it has very large teeth; it has a beautiful silvery appearance. Our bait (sprats) was unfortunately several months old, so that this experiment cannot be regarded as in any way conclusive.

In the nets there were three pilot-fish (*Naucrates ductor*,

FIG. 76.
Naucrates ductor, L. Nat. size, 23 cm.

Fig. 76), and under the boat when hauling in the nets a number of fish were noticed, of which we saw a good many subsequently; they seemed to be plentiful near the surface of the sea, and two species, *Lirus maculatus* (Fig. 77) and *Lirus ovalis*, were eventually secured.

At Station 51 we fell in with larger and smaller patches of drifting Sargasso weed with the ordinary gulf-weed animals clinging to it, such as small crabs, naked molluscs, and fishes

(*Syngnathus*; see Plates V. and VI., Chapter X.), and in the open water between the patches were Portuguese men-of-war, invariably attended by small fishes. This seems to be a phenomenon corresponding to the association of the cod-fry with jelly-fishes in the Norwegian Sea.

At this station we made a very successful haul during the

FIG. 77.
Lirus maculatus, Gthr. Nat. size, 9.5 cm.

night of 5th–6th June with nine appliances. In addition to the ordinary surface animals previously referred to, the tow-net at the surface secured as many as sixty-one leptocephali belonging

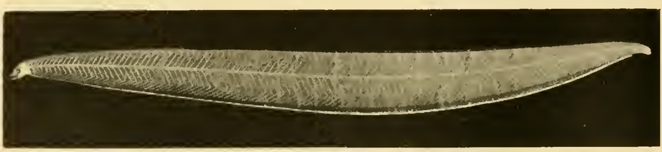


FIG. 78.—NEW SPECIES OF LEPTOCEPHALUS.

to what we have since found to be a new species (Fig. 78), of which twenty-three specimens were captured at Station 52. There was also an interesting high leaf-shaped leptocephalus (Fig. 79), another specimen of which was taken at Station 56.

In the upper appliances there were quantities of fish-eggs and young fish, another *Cystosoma*, and *Ceratias couesii*, which had previously been taken by the "Albatross" off the east coast of North America, by the "Challenger" near Japan, and by the "Valdivia" in the Indian Ocean at the bay of Aden. At this night-station, too, there were black fish in the upper layers, such as *Astronesthes niger* (Fig. 80), a dark *Dactylostomias*, and some black *Cyclothone* at 300 metres. An

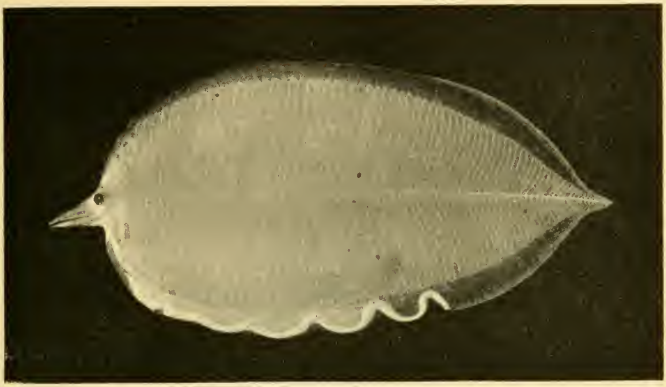


FIG. 79.—NEW SPECIES OF LEPTOCEPHALUS.

interesting cuttle-fish with stalk-eyes was taken at 350 metres, and deeper down we got *Serrivomer*, *Nemichthys scolopaceus*, *Malacosteus niger*, *M. choristodactylus*.

At this station we were able to try an apparatus for

FIG. 80.
Astronesthes niger, Rich. Nat. size, 3.5 cm.

ascertaining the depth to which the rays of light penetrate. It was constructed by Helland-Hansen, and is likely to prove useful in the study of the forms of life in deep water. The apparatus shows the intensity of the light both from above and from the sides. By means of panchromatic plates and colour filters it is possible to tell, not merely whether there is

Helland Hansen's photometer and photometric experiments.

light, but also the proportion of the different prismatic colours at different depths. At the very first attempts the apparatus acted perfectly, and as far down as 1000 metres at any rate showed light in considerable quantities, whereas at a depth of 1700 metres the plates were unaffected even after an exposure of two hours. We may assume accordingly that the amount of light at the latter depth is infinitesimal. The ultra-violet and blue rays are the ones that penetrate deepest. There were plenty of these rays at 500 metres, whereas the effect of the red and green rays there was imperceptible even after an exposure of forty minutes. At 100 metres the rays were of every colour, though red rays were least numerous, while there were rather more green rays, but even at this depth blue and ultra-violet rays predominated. These experiments are of great assistance in dealing with such problems as the growth of plants, for which light is essential, the colours of animals at different depths, and the remarkable modifications in the organs of sight and phosphorescent light-organs that are so characteristic of the higher animal groups in the ocean depths.

Another haul by night was made at Station 52, though only with four appliances, the deepest of which was at about 600 metres. The catches in the tow-nets at the surface and at 30 metres were particularly interesting, including a quantity of young fish, amongst which were young flying-fish and a number of young *Scombresox*, many leptocephali, one of which was afterwards found to be a small undeveloped larva of the common eel; that is to say, a transition stage from the egg to the fully developed leptocephalic larva. It was extremely interesting, too, to find eggs of the deep-sea fish *Trachypterus* at the surface of this deep basin.

Eel larvæ.

In our deepest appliance we found the beautiful *Macrostomias longibarbatus*, captured by us at Station 28 in the Spanish Bay, and previously recorded by the "Valdivia" Expedition from the Gulf of Guinea and the Indian Ocean. We also captured a specimen of *Opisthoproctus soleatus*, as well as a species of *Oneirodes* resembling *megaceros* (Fig. 81). The haul with the trawl resulted in a take of at least two litres of large red prawns.

As we had now reached the Sargasso Sea, at Stations 51 and 52, we set our course northwards towards the island of Fayal, where we intended to coal before crossing over to Newfoundland. While steaming towards the bank which surrounds the Azores, we frequently saw sperm whales, sometimes swimming on the surface and easily recognisable by

Sperm and other whales.

their abrupt heads, and sometimes with their flukes in the air. A school of other whales, probably the "caaing-whale," was also seen.

At Station 53 we reached a lesser depth of water, namely 2615 to 2865 metres, and had, accordingly, arrived at the slope rising from the deep basin of the Atlantic to the plateau of the Azores. A sample from the bottom showed much pumice, pteropod shells, and a large percentage of carbonate of lime, with siliceous spicules of sponges and radiolaria.

We shot the big trawl with 6400 metres of wire, and towed it from ten in the morning till two o'clock in the afternoon. At 5.15 P.M. it came up with a most successful catch. The greater abundance of organisms here as compared with profound depths was surprising. There were at least 500 holothurians belonging

FIG. 81.
Oneirodes sp. Nat. size, 2.5 cm.

to several species, large red crustaceans, fifteen *Pagurus*, a number of actiniæ, lamellibranchiates, and sponges, as well as thirty-nine fishes (different species of *Macrurus*, *Alepocephalus*, *Halosauropsis*, *Bathysaurus*, *Benthosaurus*, and *Synaphobranchus*). This haul proved again that animal life was abundant at about 3000 metres (1500 fathoms).

Our pelagic hauls were equally interesting. They were carried out during the night of 8th June, and nine appliances were towed simultaneously. The surface tow-net contained a quantity of the large medusa (*Pelagia atlantica*), a number of what are sometimes called salmon-herrings (scopelids, most of them *Myctophum coccoi* or *M. punctatum*), and as many as thirteen black *Astronesthes niger*. This was the more remarkable because we had towed appliances on the trawl-wire at a depth of 30 metres the previous day, for at least four or five hours, and had not captured a single scopelid or *Astronesthes*. A better proof of the vertical wanderings of these animals seems hard to find. Young fish, too, were nearly absent during the day, if we except a few specimens taken in a tow-net at 60 metres, but at night we got masses of them at 50 metres. Among these young fish in the upper layers we found again five little eel larvæ of a size smaller than the grown larvæ, and there were besides a number of interesting young fish with telescopic eyes, young flying-fish, and different species of leptocephali. At 150 metres we secured two remarkable leptocephali with long rostrums (see Fig. 82).

In the intermediate layers, that is to say, from 300 to 500

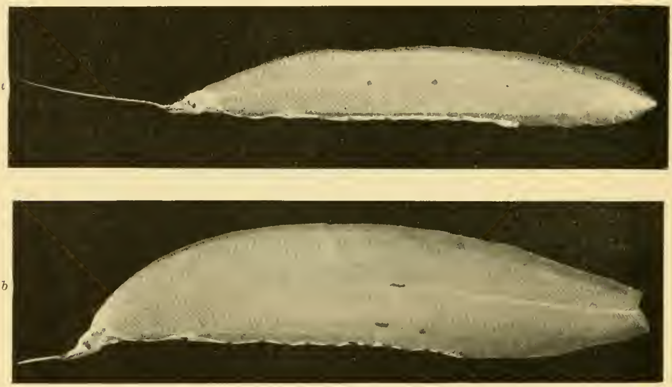


FIG. 82.—TWO NEW LEPTOCEPHALI WITH ROSTRUMS.

metres, we found stomiatids, there being no fewer than fourteen specimens of *Chauliodus sloanei* in a little tow-net half a metre in diameter. At 800 to 1300 metres there were plenty of "rare" fishes; for instance, seven specimens of the large-mouthed *Gastrostomus bairdii*, a specimen belonging to a new genus of the Gastrostomidæ (Fig. 83), a small fish which has not yet been described (Fig. 84), one *Cyema atrum*, three *Aceratias macrorhinus indicus*, masses of black cyclothones, and several others of the more common forms. This station may well be called an El Dorado for collecting zoologists, and instead of a few days, months might profitably be spent to the south of the Azores, where we found so many new and interesting forms.

At Station 56, situated about 100 nautical miles from Fayal, the depth was 3239 metres. Here we lowered nine pelagic appliances on the evening of 10th June, and hauled them in next morning between 2 A.M. and 4.30 A.M. Our catches resembled those at the preceding stations. At 50 to 150 metres there were quantities of fish larvæ and young fish, including two small eel larvæ and also the young of *Macrurus*, a deep-sea fish, the young stages of which thus occur in the upper water-layers. Many of the young fish had telescopic

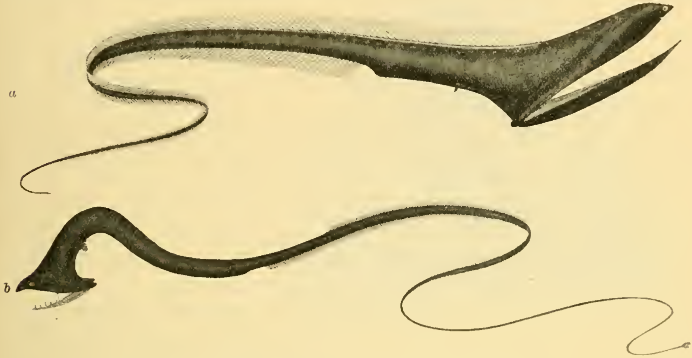


FIG. 83.—TWO GASTROSTOMIDÆ.
a. Gastrostomus bairdii, Gill and Ryder. Nat. size, 47 cm.
b. New genus. Nat. size, 20 cm.

eyes. The fact that we obtained young flounders showed that we were nearing land. At greater depths we secured nothing of any particular note, merely the usual deep-sea forms.

While examining the material from our tow-nets in the morning, we noticed numbers of small silvery fishes near the

FIG. 84.
A new species, not classified yet.

surface; and later on, when we commenced steaming towards Fayal, we came across one turtle after another. The boat was therefore lowered, and a regular turtle-hunt began. Our plan was to row carefully up to the animals, which lay quite still on the glassy surface, seize them by the hind leg with our hands, and heave them into the boat; in this way we captured as many as fifteen turtles belonging to the species *Thalassochelys*

Great capture of turtles.

corticata. Under the turtles there were often quite a number of the little silvery fish alluded to above, and we caught some of them in a net and found that they were horse mackerel (*Caranx trachurus*, see Fig. 86). Some larger fish too were occasionally seen below the turtle near the mouth, just where the neck leaves the carapace. These swam under the boat as soon as the turtle was caught, but we captured three, and found them to be wreck-fish (*Polyprion americanus*). Quantities of blue isopods were seen beneath one or two of the animals. Our meeting with turtles was extremely interesting, as we found that their stomach contents consisted entirely of medusæ and salpæ, immense quantities of which floated near the surface of the sea. In the transparent blue waters we could perceive thousands and thousands of beautifully-coloured and iridescent chains of salpæ, sometimes as much as 6 to 7

Fig. 85.—T. H. Murray on board the "Michael Sars," 11th June 1910.

Fig. 86.
Caranx trachurus, L. Nat. size, 10.5 cm.

metres in length, besides siphonophores and floating aurelias, with little fish in attendance,—a fascinating pelagic animal life.

Nemichthys. We made yet one more pelagic haul at Station 58, and caught a splendid specimen of one of the most remarkable deep-sea forms (*Nemichthys scolopaceus*). This is a long fish, with a long beak like that of a bird, large eyes, quite short body, and an immense tail. Our specimen was about 125 centimetres long, of which the beak accounted for 8 centimetres, while the distance from the corner of the mouth to the anus was 4 centimetres, the remainder being thus over a metre long. This creature has been caught previously in both the Atlantic and Pacific.

After sounding at Station 58 in 1235 metres, we decided to shoot our trawl. Hardly was it well out, however, before it stuck fast, and brought the ship completely to anchor. We availed ourselves of this circumstance to obtain some current measurements, hauled in on the trawl-wire, and passed it forward to the bow, being thus as it were riding on a warp.

Tidal currents in the open ocean.

We commenced measuring the currents at midnight, and went on till 3 P.M. next day, when we attempted to haul in the trawl. Unfortunately, however, the wire parted, so that we lost the trawl and 1500 metres of line as well. Still we had at any rate succeeded in taking some measurements, our mode of working being to have one current-meter constantly recording velocities at 10 metres, while another current-meter was lowered to different depths. The movement of the water-masses at 10 metres *was a typically tidal one*. In deep water, too, there were relatively strong currents as far down as 800 metres, and distinct indications of tidal movements. Generally speaking, the currents in deep water had an opposite motion to those of the surface layers, but a fuller account will be found in Chapter V. It is sufficient to state here that our expedition succeeded in measuring currents out in the ocean at considerable depths, and that we found tidal movements even at profound depths. We anchored at Fayal on 13th June.

From the Azores to Newfoundland.

One of the most interesting tasks of our expedition was to take a section across the western basin of the North Atlantic from the Azores to North America. A section of the Gulf Stream as far south as we could manage would, we felt sure, be of value, and it would also be interesting to compare the animal life which we had found in the eastern basin between the Canaries and the Azores with that of the waters farther west. Unfortunately the accident by which we lost our trawl and 1500 metres of wire on the Azores plateau prevented us from sweeping the greatest depths, but we were still in a position to carry out pelagic experiments.

It would have been desirable to set our course from the Azores to the Bermudas, and then on to Boston, finishing with a series of short zig-zag sections between the land and the edge of the coast-banks, till we reached Newfoundland. We should in that case have been able to study the remarkable transition that occurs on passing from the almost tropical conditions of the Sargasso Sea to those of the icy Labrador Stream, which creeps southwards along the Labrador coast from Baffin's Bay to Newfoundland, and even farther south. The short time at our disposal made this impossible, and we were compelled to cross from the Azores to the nearest coaling station, namely Newfoundland, and then make for home.

Fig. 87.
Lepas anatifera. Nat. size.

The mere distance between the Azores and Newfoundland, between 1200 and 1300 nautical miles, was a serious consideration for our little vessel, for we had to count upon meeting head-winds and currents, especially when we reached the Gulf Stream off the Newfoundland Bank; and there was always the possibility of fog delaying us. We resolved accordingly to go westwards towards the eastern boundary of the Gulf Stream, and then turn northwards, which would increase the distance to 1800 miles, but would offer better conditions of wind and current. We should also be enabled to visit again the Sargasso Sea, the animal life of which we had found so interesting, and we should further be able to take a section right across the axis of the Gulf Stream. To prepare for all emergencies we not only filled our bunkers as full as they could hold with the best Welsh coal, but also piled our decks with as much as we could find room for. This done, we said farewell to Horta's little harbour on the afternoon of 17th June.

During the first two or three days of our journey west we had wind and sea dead against us, so work was limited to hydrographical observations at Stations 59 and 60 (see Chart, Fig. 62). The weather afterwards cleared up, and at Station 61 we met with certain fishes, hitherto regarded as extremely rare, swimming about on the surface of the Atlantic. On lowering a boat to examine a drifting log overgrown with barnacles (Fig. 87), we found it surrounded by fishes like those observed by us in the Sargasso Sea near Station 50, and we succeeded in capturing eleven specimens belonging to the species *Pimelepterus boschii* and *Lirus perciformis.*

At Station 62 we tried nine pelagic appliances at different depths on the night of 20th June. Our catches were very satisfactory at all depths, and much resembled those taken between the Canary Islands and the Azores.

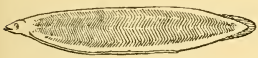


Fig. 88.—The smallest Larva of the Common Eel caught by the "Michael Sars." 4.1 cm. long. Nat. size.

In the upper layers there were some extremely interesting leptocephali, including no fewer than eleven specimens of the common eel larvæ (Fig. 88), 5 to 5.7 centimetres long, showing that the little eel larvæ are to be met with west as well as south of the Azores. We also found two individuals, only 4.7 and 5.1 centimetres long, of leptocephali belonging to the deep-sea fish *Synaphobranchus pinnatus.* This had previously only been met with in sizes approximating to the full-grown larva (10–13 cm.), of which we found several at the different stations; but it was most interesting to come across such small (early) development stages of the species. Eel larvæ.

At depths from 300 metres to 50 metres there were again the same colourless *Cyclothone signata* as well as silvery *Argyropelecus*, *Stomias*, and *Chauliodus*. We got, too, a new species of *Ceratias*. In the deepest hauls, below 500 metres, the forms were the same as in previous hauls. There was the little black fish, *Cyclothone microdon*, once more, red prawns (particularly *Acanthephyra*), red sagittæ, dark-brown medusæ (*Atolla*), large ostracods (*Gigantocypris*), and the same kinds of "rare" fish: *Gastrostomus bairdii*, *Cyema atrum*, *Gonostoma grande*, *Dactylostomias*, and several others.

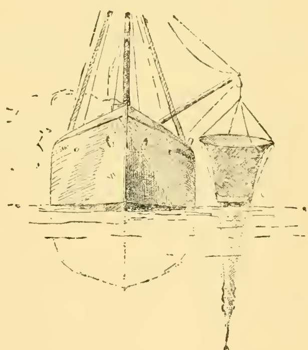


Fig. 89.—Large Closing Net.

These numerous horizontal hauls accorded so closely with each other that we now began to feel that there must be a well-defined conformity in the vertical distribution of the different forms. Still, to avoid any uncertainty, we considered it desirable

Vertical distribution of animals.

to try at the same time some vertical hauls with our *closing nets*. Accordingly, at Station 63 we made two series of hauls, one with a silk net 1 metre in diameter, and the other with the large 3-metre silk net (Fig. 89).

These experiments merely resulted in our capturing the species which occur most commonly,—a fresh proof that it is difficult to become acquainted with the fauna when only vertical hauls are made. A great many of the forms are too scarce to be caught by such means, and can only be taken by long-continued horizontal towing. In the case of the commonest species, however, these vertical hauls do give an indication of the vertical distribution as well as of the quantitative occurrence at different depths. It is advisable, therefore, to supply a few particulars of our experiments with the large net :—

Only 10 fishes were taken in a haul from 4500 metres up to 1500 metres, where we closed the net. All of them belonged to the species *Cyclothone microdon*.

In a haul from 1350 metres up to 450 metres we got 44 fishes; 27 specimens of *Cyclothone microdon*, 3 of *C. signata*, and 14 young fish (stomiatids and others).

In a haul from 500 metres up to 200 metres some small specimens of *Cyclothone signata* and a number of young fish were caught. From 200 metres to the surface there were only young fish.

This agrees with what we found when making horizontal hauls. The black *Cyclothone microdon* is only to be met with in deep water, where the light-coloured *C. signata* is absent, and *C. signata* occurs nearer the surface—from about 500 metres up to 200 metres—but has not been taken in depths less than 200 metres.

It is important to note how much fewer the individuals are in the deepest hauls. Though we drew the net through 3000 metres (from 4500 up to 1500 metres), we only caught 10 fishes, while in the 900 metres of water from 1350 metres up to 450 metres we got 44 individuals, 27 of them belonging to the same species as the 10 fishes from greater depths.

Similar conditions appear to prevail in the case of the red prawns, for in our deepest haul we caught only 11 large red prawns, but in the haul immediately above it there were 35 individuals. This seems to indicate that the deepest water-layers cannot at all compare in abundance of organisms with the intermediate layers.

At this station we also recorded a very large series of hydrographical observations, namely, twenty water-samples and temperature readings down to a depth of 4850 metres. We were interested to discover that the bottom temperature was only slightly under $2\frac{1}{2}^\circ$ C., and thus exactly agreed with what we had previously found in the eastern basin.

During the night several flying-fish came on board, and in the morning we again saw small patches of the Sargasso weed. Sargasso weed. Gran came to the conclusion that these patches must be much younger, or, rather, that they have drifted for a shorter time, than the ones found farther east. They had long vigorous shoots, which reached higher up above the water than the older growths, and it was easy to tell the top in every patch. In the older growths, which had been drifting about for a long time, the shoots in every direction were more stunted, and the patches became mere tangled masses of weed and lay deeper in the water. We found on them the ordinary small crabs (*Planes minutus*), needle-fish (*Syngnathus pelagicus*), frog-fish (*Antennarius*), molluscs, compound ascidians, and hydroids (see Plates V. and VI., Chapter X.).

Station 64 was one of our most successful stations. The pelagic appliances were lowered in the morning between 6.30 A.M. and 9 A.M., and hauled in from 2.30 P.M. to 5 P.M., with excellent results. In the surface layers we secured a quantity of fish-eggs, including various stages of the eggs of scombresocids, tiny young fish with stalk-eyes, two small eel larvæ (4.1 cm. and 4.8 cm. long), a number of remarkable cuttle-fish, and three small leptocephali (1.7 cm., 1.7 cm., and 2.1 cm. in length), all differing in appearance. They cannot belong to the larvæ of the common eel, because they have too many muscle segments (over 130).

In deep water we got the same familiar forms in unusually large quantities. The following table shows the numbers of the species most commonly occurring, belonging to the genus *Cyclothone*:—

	Light-coloured, *Cyclothone signata*.	Dark-coloured, *C. microdon*.
Young-fish trawl at 500 metres .	1240	214 (small individuals)
,, ,, 1000 ,, .	82	448
,, ,, 1500 ,, .	22	322
	1344	984

Thus of the two species we were able to preserve more than 2000 individuals; we endeavoured to keep all that were brought on board, but a good many were damaged by the apparatus, and had to be thrown away.

These results served to confirm the opinion we had formed at the previous station (63) that the light-coloured species lives nearer the surface, while the dark-coloured species inhabits greater depths. Red prawns, sagittæ, and other creatures were found in large numbers in deep water, and we continued to meet with such forms as *Gastrostomus* and *Opisthoproctus*, and a new *Oneirodes* (Fig. 90).

Larval *Gastrostomus*.

We also discovered a curious little young fish, 4 cm. long, which we can only suppose to be a transition stage from a leptocephalus to a *Gastrostomus* (probably *G. bairdii*, which we so often met with). Its head shows clear indications of the

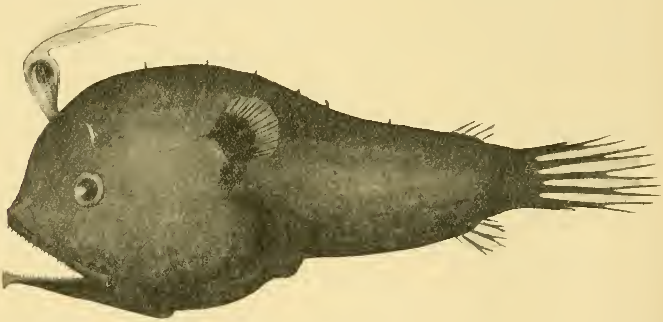


FIG. 90.
Oneirodes, n.sp. Nat. size, 1.4 cm.

remarkable gullet, the tiny eyes far forward near the snout, and the small ventral fin. Posteriorly the body much resembles a leptocephalus, but here, too, there seems to be a commencement of the strange organ which is situated at the end of the long tail of *Gastrostomus*. What is chiefly interesting about this find is that it affords fresh proof of the relationship between the saccopharyngidæ and eels. When search is made, as it probably will be soon, for still younger stages of the common eel larvæ than the ones we found, it will probably be of zoological interest to seek in these teeming waters for transition stages between this strange form and the earlier leptocephalid stages.

Blind fish.

Another deep-sea fish at this station that deserves mention was a form, as yet apparently undescribed, which resembles the undoubtedly blind fish (*Cetomimus*) found at Station 35; the eyes appear very much reduced, just as in the case of its relative. Both of them were taken in deep water, at 1000 metres.

In addition to the silk nets Gran now commenced using his big steam centrifuge (Fig. 91) for centrifuging the water

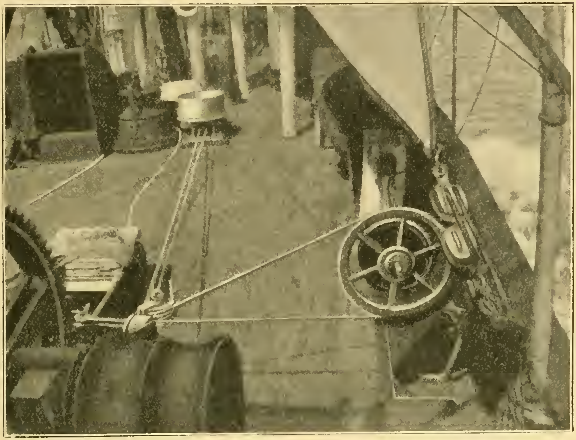


FIG. 91.—THE LARGE CENTRIFUGE.

Use of the centrifuge.

samples from different depths. Several successful experiments had already been made with it, but it was at this station that he started to employ it systematically, and he continued to avail himself of its help until the end of the cruise. By means of it he was able to collect in a little drop below the microscope all the most minute organisms, and in spite of the movements of the little ship and the vibration from the propeller, he was able with his microscope to study the many hitherto unknown forms in their living state, to draw them, and to count the number of the different species (Fig. 92). A full description of these investigations will be

FIG. 92.—GRAN COUNTING THE SMALLEST MICROSCOPIC PLANTS.

found in Chapter VI. A few particulars may, however, be given here.

Among the exceedingly diminutive plants found in the open sea, calcareous flagellates or coccolithophoridæ are the most important, especially in the warmer waters. During the "Challenger" Expedition, Murray discovered that they were distributed everywhere over the surface of all warm seas, and he stated that they were plants. These small organisms occur in far greater abundance, both of species and individuals, than had hitherto been supposed. In reality they, together with diatoms and other algæ, constitute the fundamental source of food for all animals in tropical and sub-tropical waters. In the Sargasso Sea there were in every litre 12 or 15 species and 2000 to 3000 individuals. In colder masses of water they decrease very greatly in quantity, yet even on the edge of the Newfoundland Bank, with a temperature of $2\frac{1}{2}°$ C., we still met with one or two species numbering 50 individuals to the litre. In the Arctic and Antarctic Oceans, on the other hand, they are not found at all.

Great abundance of coccolithophoridæ in the Sargasso Sea.

After occupying Station 64 we were compelled to turn northwards and steer for our next coaling station, St. John's, Newfoundland. We had to abandon any idea of following up in a southerly direction the remarkable finds we had made, and probably thus lost the chance of making the most interesting discovery of all, namely, the earliest stages of eels, *Gastrostomus*, and other forms. Still there was the possibility of learning something about the currents off the coast of North America, as well as the connection between the different water-layers and the plants and animal forms existing in them.

Fig. 93 shows a temperature and salinity section from the Sargasso Sea to Newfoundland. At Stations 64 and 65 we see the vast layer, with a salinity of over 35 per thousand and high temperature down to considerable depths, the same as found by us over the whole distance from away beyond the Canary Islands.

On our way north from Station 64 on 28th June we saw patches of Sargasso weed all the morning, and numbers of flying fish, about 10 centimetres long, started up in front of our bows. This led us to believe that we should capture the same forms as before, when we lowered our pelagic appliances in the evening at Station 66. Great was our astonishment, therefore, to discover next morning on hauling in our appliances that the catches mainly consisted of true "boreal" plankton, that is to say, animal forms which we were accustomed to get in the so-called extension of the Gulf Stream in the Norwegian Sea right up to the very shores of Spitsbergen. There was the amphipod *Euthemisto*, the copepod *Euchæta*, and "whale's food" (the pteropod *Clione limacina*), large quantities of which are met with from time to time in the waters between Spitsbergen and the north of Norway. This last is not an "arctic" form, that is, it is not associated with polar water in the Norwegian Sea, but on the contrary is found in Atlantic water to the south of Iceland,

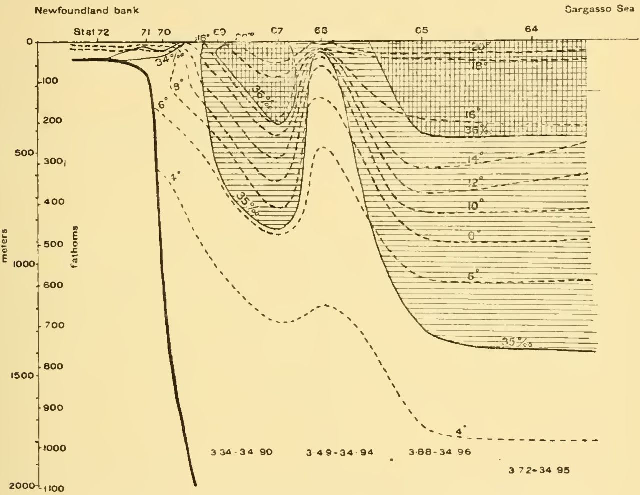


FIG. 93.—HYDROGRAPHICAL SECTION FROM THE SARGASSO SEA TO THE NEWFOUNDLAND BANK.

according to Danish observations. It seems, however, to be associated with the northern portion of the Atlantic and the Atlantic water that enters the Norwegian Sea. These animal forms were entirely absent during the whole of our cruise from the Canary Islands to Station 64, so that their occurrence at Station 66, where lower temperatures were recorded at no great depth beneath the surface, is very significant.

We fancied now that we had said farewell to the Sargasso Sea and its interesting animal life, but at Stations 67 and 69, in close accordance with the hydrographical conditions depicted in Fig. 93, we came once more across more southerly forms.

In the upper layers there were the same young fish, many of them with stalk-eyes, and leptocephali, while flying fish, Sargasso weed, and the familiar Sargasso animals were all once more in evidence.

We found a large cluster of eggs, weighing approximately a kilo, drifting about at Station 69, belonging to the common angler-fish (*Lophius piscatorius*), the development of which was studied by Alexander Agassiz; we hatched out the eggs and obtained the stages depicted by him. Angler-fish only inhabit the coast banks, so that our find of slightly developed eggs, that could not have been drifting many days, indicated that we were now in the neighbourhood of the American coast bank.

In deep water we found once more at Stations 67 and 69 the deep-sea animals of the Sargasso Sea, that is to say, all the black fishes and red crustaceans which we have so often mentioned already. There were not merely the commonest kinds of small fish, but also large ones (such as three examples of *Gastrostomus*), and fishes which are caught in other oceans (*Aceratias*, *Serrivomer*).

While we were hauling in our appliances at Station 67, a storm got up, which gradually increased to a hurricane, worse than anything hitherto encountered by the "Michael Sars." It lasted for twenty-four hours, during which the ship was smothered in spray. Our engines were kept going full steam ahead, yet the vessel was driven a whole degree (60 nautical miles) astern. Still her buoyancy stood her in good stead, and she did not ship a single sea.

At Station 70, on the edge of the coast bank, where the depth was 1100 metres, we discovered that we had for the second time left purely oceanic conditions behind, and once more the true boreal plankton appeared in the surface layers. There was the little copepod *Calanus finmarchicus*, the commonest crustacean in the Norwegian Sea, and we also now met with *Euthemisto*, *Nyctiphanes*, *Krohnia hamata*, *Limacina helicina*,[1] and *Clione limacina*, all species that are regarded as specially characteristic of the Norwegian Sea. Still in the deep water from 350 metres down to 1100 metres we continued to get the familiar pelagic deep-sea fish *Cyclothone signata* and *C. microdon*, as well as the medusa *Atolla* and other forms; so that the area of distribution of these animals extends from Africa to North America, that is to say, in all the water from the one continental slope to the other.

[1] *Limacina* was taken in numbers by Haeckel and Murray off Scourie in Scotland.

Our deepest young-fish trawl was unintentionally towed along the bottom, and came up full of most beautiful bottom-living organisms (*Ophiura*, asterids, *Phormosoma*, pennatulids, crinoids, pycnogonids, lycods, and *Macrurus*, as well as many other forms which need not be detailed here).

We had thus reached the Great Bank of Newfoundland, and had accomplished our task of taking a section right across the Atlantic from the shores of Africa. During the transit we had occupied twenty-nine hydrographical stations, and twenty stations

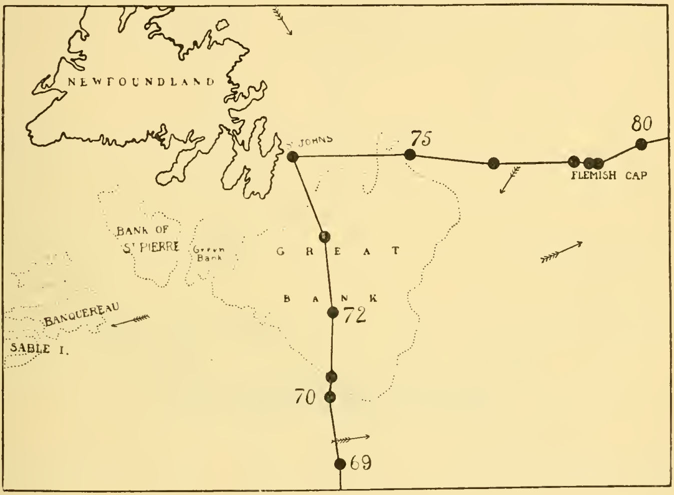


FIG. 94.—"MICHAEL SARS" STATIONS 69 TO 80.

where we towed pelagic appliances, and had besides carried out many other investigations, so that we had every reason to be satisfied with the results of our venture.

The *coast bank* itself (Fig. 94) offered us a totally different field for study, which no doubt would have proved very interesting, but unfortunately our time was too short to attempt systematic researches; we had to steam for our coaling station, contenting ourselves with one or two shallow stations on the way. Newfoundland Bank.

Fig. 95 shows the hydrographical conditions from our last true oceanic station (69) to a station (74) just off St. John's. It is extraordinary what a sudden change there is from the warm salt oceanic water to the cold coast water. The curves of temperature and salinity between Stations 69 and 70 go down straight like a wall—the well-known "cold wall" of oceanographers. Over the bank there is a surface layer, about 40 metres in depth, with a temperature of over 6° C., similar to what we get in the boreal portion of the Norwegian Sea along the coast of Norway. Below that, however, the temperatures are under 2° C., and even as low as − 1.5° C., that is to say, the water may be as cold as what Nansen found near the North Pole. Probably at no other part of the globe are there such peculiar temperature conditions—conditions comparable with those in the Arctic regions, though the latitude is the same as that of Paris. It would have been an agreeable task to trace these conditions by following up the currents and animal life

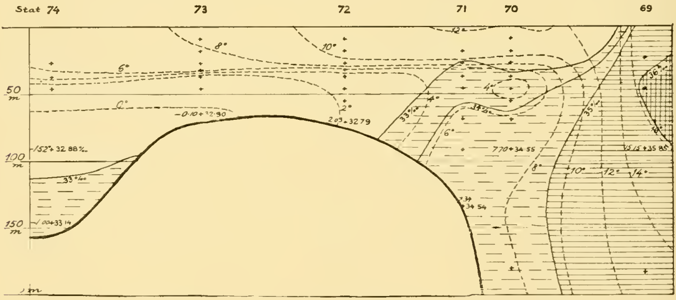


FIG. 95.—HYDROGRAPHICAL SECTION ACROSS THE GREAT NEWFOUNDLAND BANK.

both northwards and southwards. Still even our random investigations furnished interesting results. Thus we discovered that from Station 70 to St. John's there was the same northerly plankton already mentioned, and an examination of the young fish showed that they accorded with what had previously been found by Norwegian naturalists off the coast of Norway, and by the Danes south of Iceland.

On the outer side of the coast bank, at Station 71, we met with larvæ of red-fish (*Sebastes*). At Station 72 there were cod-eggs and numbers of little cod-fry, besides fully developed eggs of haddock (*Gadus æglefinus*) and haddock larvæ, $3\frac{1}{2}$ millimetres in length and upwards, and also young fish of the boreal long rough dab (*Drepanopsetta*). At Station 73 we came across eggs of this dab (besides a number of eggs that we have not yet determined), and the shallow-water form *Ammodytes*. At Station 74 there were neither eggs nor young fish.

Similar catches are taken off the coasts of Norway and Iceland; near and just beyond the continental edge there are larvæ of red-fish, and on the bank in 30 or 40 fathoms of water there are larvæ and eggs of cod and haddock. It was interesting to find the eggs and larvæ of these fish at Station 72, where the bottom-temperature was between 2° C. and 4.6° C., whereas nearer land, where the bottom-temperature was 0° C., or even less, they were absent.

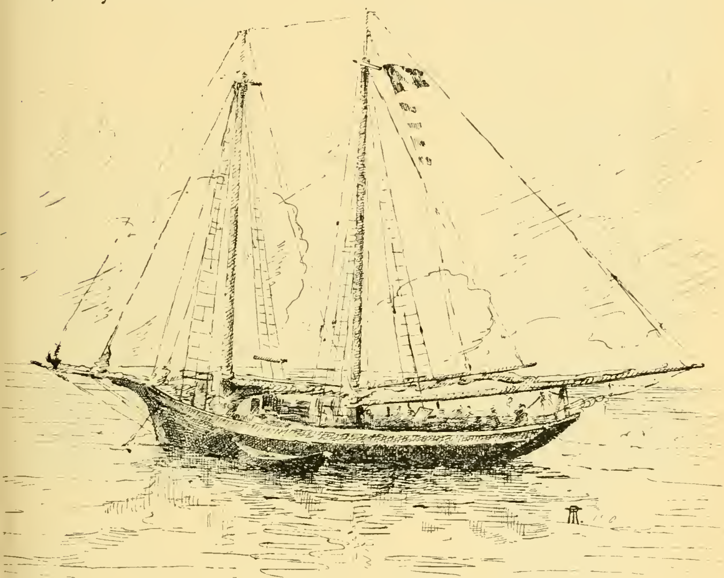


FIG. 96.—FRENCH FISHING SCHOONER.

At Station 72 we sighted the first fishing-boats (Fig. 96). They belonged to Frenchmen from the Island of Miquelon, south of Newfoundland, and as the weather was good, we paid them a visit, spending a very pleasant time with these hospitable fishermen, who willingly gave us information about their industry (Fig. 97). They sail from Brittany and Normandy in April, and reach the Newfoundland Bank in May, at which time of the year there is ice over the whole northerly portion of the bank. They commence fishing in the south-eastern portion, which is probably the only part having warm bottom-water, and collect their bait by lowering nets with cod-heads in them.

Fishing industry on the Newfoundland Bank.

Quantities of gasteropods (most likely a species of *Buccinum*) creep into the nets, and form a very serviceable bait, just as on the eastern side of the Atlantic. Afterwards they remove to the southern portion of the bank, where they were when we met them. This was, according to the captain, lat. 44° 30′ N., and long. 53° 34′ W. The cod spawn here in July, and were just on the point of doing so. They were from 60 centimetres to over a metre long, and upon inspecting the catches of several dories (flat-bottomed boats used for cod-fishing in Norway also) we found the roes to be quite mature. The fishermen also catch squid (*Gonatus fabricii*; see Fig. 98) with a grapnel

FIG. 97.—HAND-LINE FISHING.

—a red piece of metal with hooks all round it—exactly in the same way as they are caught on the north and west coasts of Norway.

After July the fishermen work their way northwards, probably because the cod move northwards along the bank as the cold water recedes during the course of the summer. According to their statements, which would justify a thorough investigation, there are for the most part only small-sized cod farther south and west on the banks off Nova Scotia and Cape Breton Island, or on what they call the "Banquereau." Is it perhaps the case here too, as in Norway and Iceland, that the larvæ and young fish drift with the current and grow into cod far away from the place where they were spawned?

On the Norwegian coast the cod chiefly spawn between

Romsdal and Tromsoe, but the young fish are found in greatest quantity off Finmarken, that is to say, along the northernmost portion of the coast, to which they are carried by the current. Similarly in Iceland they spawn on the south and west coasts, but the young fish are chiefly found on the north and east coasts. The current there goes from the south to the west, and thence round the north and east coasts, making a circuit round the island.

FIG. 98.—BAIT (*Gonatus fabricii*). Nat. size, 27 cm.

The current off Newfoundland runs along the coast in a south-westerly direction, towards Nova Scotia and the United States. It is possible, therefore, that it is mostly young fish that are found down south, derived to some extent at any rate from eggs spawned on the Great Newfoundland Bank.

Cod spawn on the Norwegian coast banks as far north as lat. 70° N., and chiefly during March and April. Here on the Newfoundland Bank, a little north of lat. 50° N., and in the vicinity of the warm oceanic water their spawning season was in July.

The bottom-temperature on the bank was, as we have seen, very low—lower indeed than in the north of Norway during March—and it was interesting, therefore, to note the summer growth periods and winter stagnation periods in the scales of cod which we procured from the French fishermen. Scales (see Chapter X.) illustrate the growth of the cod by means of "summer-belts" and "winter-rings." Those which we examined had extremely distinct winter-rings, and although it was already July, the summer-belt for the year had not yet commenced. It must therefore have been the winter season still down in the deep water where the cod were taken—and this though we were in the latitude of Paris and the month was July.

On 3rd July the "Michael Sars" anchored in the harbour of St. John's.

From Newfoundland to Glasgow.

It was our original intention to go from Newfoundland to Reykjavik in Iceland, as this was the nearest coaling station on our way back to Europe, and we hardly expected when starting on our expedition that the little ship would be able to steam right across the Atlantic without having to put in anywhere for coal. We had now, however, formed such a favourable opinion of her seaworthiness, and her coal-consumption had been so small, especially on the voyage from the Azores to St. John's, that we decided to venture across the ocean without a stop. The distance from Fayal to St. John's by the way we had come was about 1800 nautical miles, and from St. John's to Ireland was roughly 2000 miles, so that the difference was not so very formidable.

As far as our scientific work was concerned, the direct route to Ireland was bound to be the more interesting. It is true that very little is known about the sea leading to Baffin's Bay, but the physical conditions, and therefore also the animal life, are presumably very uniform and not likely to differ much from the conditions prevailing to the eastward of the Newfoundland Bank. The direct route to Ireland, on the other hand, would give us a fresh section across the Atlantic, and enable us to study the varying conditions in the northerly portion of that ocean. Another reason for selecting this route was the possibility of again studying the remarkable conditions in the Gulf Stream observed on our southern section between Stations 64 and 70 (see Fig. 93). We therefore filled up our bunkers once more and piled the deck with the best coal we could procure, prepared ourselves for as long a cruise as the ship was able to accomplish, and left St. John's on the 8th July.

The water-masses of the North Atlantic may be roughly divided into four principal groups: (1) true Atlantic oceanic water, or Gulf Stream water, (2) Mediterranean water, (3) Arctic polar water, and (4) the so-called *bottom-water*, all of which we were able to study on our voyage across to Ireland. Fig. 99 shows the positions of Stations 79–93, and the vertical distribution of the different water-masses in their relation to one another on our route from the Newfoundland Bank to Ireland. Near America, on the actual coast bank and just outside the edge of the bank (Stations 75–79), we found only the cold Labrador Current, which descends from Baffin's Bay, follows the coast of Labrador, and sweeps south-west past Newfoundland. Immediately outside St. John's we met several icebergs of the kind so familiar to all who cross the North

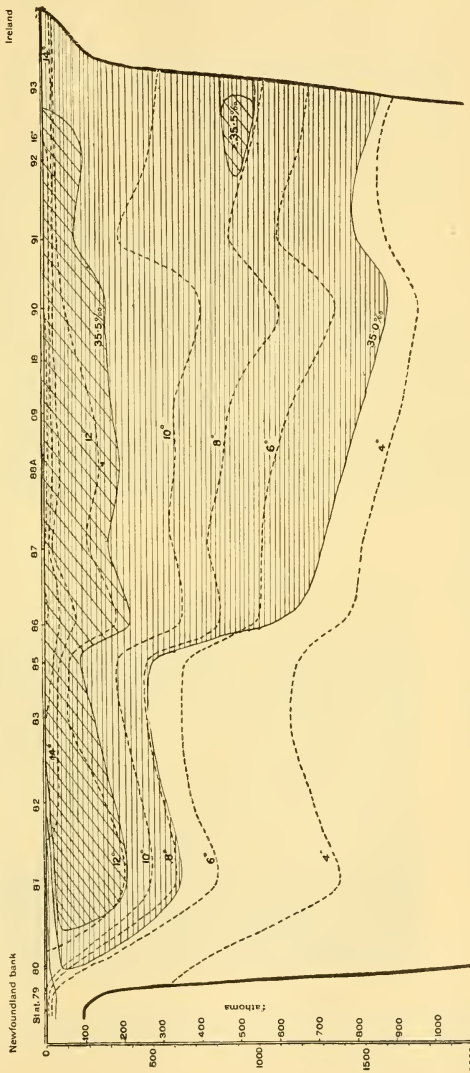


Fig. 99.—Hydrographical Section, Newfoundland to Ireland.

Atlantic (Figs. 100 and 101), and we had thus an ocular demonstration of the origin of the cold water on the Great Bank, as

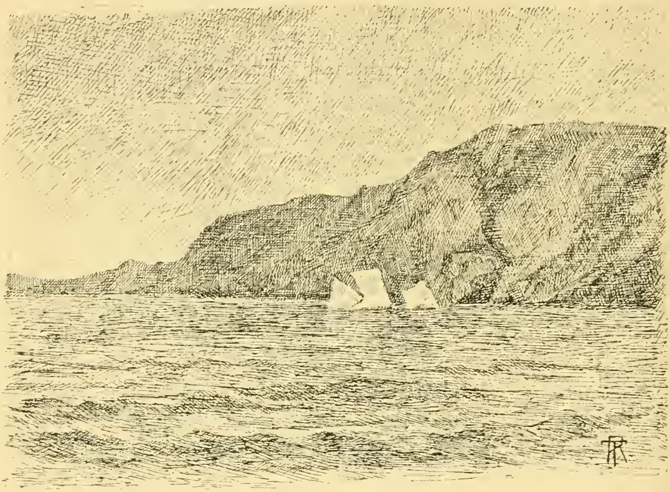


FIG. 100.—ICEBERGS OUTSIDE THE HARBOUR OF ST. JOHN'S.

well as of the dangers which the bank-fishers have to face. Icebergs, fog, and the great ocean-steamers are the chief perils

FIG. 101.—ICEBERG OUTSIDE ST. JOHN'S.

these men have to reckon with, and it was an unpleasant sensation for us also to have to steam for three whole days over the bank in fog.

At Station 80 we became aware of the influence of Atlantic water, and at the same time we got clear weather, but, as the figure will show, it was at Station 81 that we first met with the real Atlantic or Gulf Stream water with a salinity of about 35.5 per thousand, which extended in a layer 100–200 metres deep right across to near the coast bank outside Ireland. Below this layer the salinity and temperature decrease till we come down to bottom-water, with a salinity of less than 35 per thousand; the temperature was the same as what we had found in bottom-water to the south of the Azores, namely, a little under $2\frac{1}{2}°$ C. Our investigations made it apparent that this bottom-water is in continuity with the surface water in the north-west corner of the Atlantic.

Our investigation of the plants of the sea was continued during this cruise; we made collections with silk nets, and centrifuged water-samples with the big steam centrifuge, with the result that, in spite of high seas and heavy rolling of the vessel on the eastern side of the ocean, Gran was able to proceed with his classification and enumeration of the minute living organisms that had hitherto eluded observation. Plants.

At almost every station he determined the number of extremely small organisms, chiefly coccolithophoridæ, per litre of sea-water, and ascertained that here, too, on our northerly route they constituted the greater portion of the plant plankton. An exception must, however, be made in the case of the coast banks of Newfoundland and Ireland, where there was also a very abundant plankton of larger organisms, large enough to be retained by the tow-nets. One single species (a calcareous flagellate) at a station just outside the European coast bank numbered 200,000 per litre, and actually affected the transparency of the sea.

Gran succeeded in collecting abundant material for the study of these little-known forms (many of them new to science), and for a proper understanding of their significance in the total plant life of the sea. In Chapter VI. he has set down the chief results of his observations.

We found again a complete accordance between the distribution of the different water-masses and the occurrence of characteristic "societies" of pelagic animal life. At Stations 75–79 on the Newfoundland Bank (see Fig. 94) the boreal organisms were mixed with arctic forms. Thus there were: Pelagic life of Newfoundland Bank.

Calanus finmarchicus and *C. hyperboreus*, *Euchæta*, *Euthemisto*, *Limacina*, *Aglantha*, *Beroë*, *Pleurobrachia*, *Mertensia*, *Sagitta arctica*, and *Krohnia hamata*—forms that in the Norwegian Sea are met with in "Gulf Stream water" or in "Polar water."

At Station 80—just beyond the continental slope—this animal life was still typically represented at all depths examined, but in deep water we found co-existing with it our black fish and red crustaceans of the southern section. We made a few hauls here with the closing net, and obtained the following:—

In a haul from 525 metres to 235 metres we got calanids co-existing with *Cyclothone signata*.

In a haul from 950 metres to 525 metres we found *Euchæta norvegica*, *Calanus finmarchicus*, *Calanus hyperboreus* and *Clione limacina*, together with *Cyclothone microdon* and the medusa *Atolla*.

Besides this, our horizontal hauls gave us *Gastrostomus bairdii* and large red prawns (*Acanthephyra*).

Boreal pelagic life.

All the *arctic* forms had disappeared, however, at Station 81, and they did not occur again in our hauls during the rest of our section to Ireland. In their place we found the *boreal* animals, such as we are familiar with in the Gulf Stream water of the Norwegian Sea right up to Spitsbergen, strongly represented, everywhere mingled with true oceanic Atlantic forms, like those that predominated in the southern section. At Station 81 we secured at the surface a quantity of eggs and young of scopelids, as well as radiolaria, salpæ, small *Pelagia*, and different kinds of leptocephali; of pteropods we got *Clio pyramidata*. In deep water there was the abundant oceanic fauna observed in the Sargasso Sea previously referred to. If we consider this short account of the animal life, together with the hydrographical section (Fig. 99), the accordance will become apparent. It is at Station 81 that the real oceanic "Atlantic water" or "Gulf Stream water" occurs, whereas at Station 80 the cold Labrador Current is still the controlling influence.

Generally speaking, the same pelagic fauna was noted from here across the Atlantic, though no doubt a closer investigation may reveal various differences in the different areas traversed. There is one feature that deserves particular mention, notwithstanding the incompleteness of our material, namely, the extraordinary abundance of forms met with *from Stations 86 to 88. These stations lie exactly over the longitudinal ridge that stretches northwards from the Azores.* Just as was the case on the plateau south of the Azores, so here too we made exceptionally big catches at all depths, and the surface contained millions of chains of salpæ the one day and of medusæ (*Pelagia*) the next.

We caught a large moonfish (*Mola rotunda*, Fig. 102), which was moving along near the surface with its dorsal fin above water; we harpooned it from a boat, and got it on board with block and tackle and the steam winch. The length was 2.11 metres, and the height of the body 1.2 metres. A huge Moonfish.

FIG. 102.—*Mola rotunda*, Cuv. Nat. size, 211 cm.

cuttle-fish, too, was found drifting about. Do these creatures, like the turtles farther south, feed on the abundant salpæ and medusæ, and was that the reason why we found them here? Is a richer pelagic life generally to be found just over the ridge, in the same way that we always find a richer plankton over the slope of the coast banks? These problems must be left for future solution.

On the eastern side of our section, towards the Irish coast bank, the conditions were again peculiar, especially at the surface. We found here increasing quantities of young of the needle-fish *Nerophis*, *Fierasfer*, *Arachnactis* and *Lepas fascicularis*, as well as young stages of coast-bank forms, stray specimens of which were also met with just off the slope (Stations 92 and 94).

It will be an interesting task to compare the western and eastern portions of this section, as well as the whole of this northerly section, with the section farther south from the Canary Islands past the Azores to the Gulf Stream. One thing which did strike us particularly was that the boreal plankton—the Gulf Stream forms of the Norwegian Sea—were entirely absent from the southern section (Stations 45–64), but were everywhere present in the northern section. It must be remembered, however, that our pelagic hauls did not reach the very deepest water-layers, which may have the same plankton in both sections, including the boreal species known from the Norwegian Sea. We further noticed in the southern section more of the remarkable "rare" deep-sea fish that have been found in other oceans (the Indian Ocean, for instance) than in the northern section.

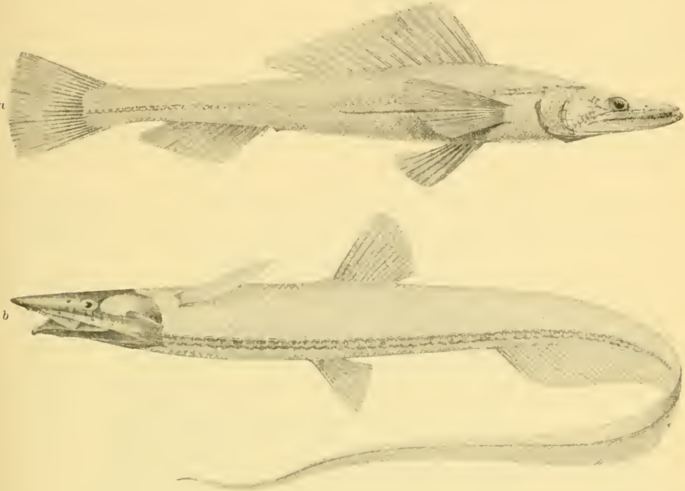
Eel larvæ.

The distribution according to size of individuals belonging to the different larval forms was noteworthy. As previously mentioned, we came across very small larvæ—from 4 cm. to 6 cm. long—of the common eel to the south and west of the Azores; on the northern section also we found larvæ of the eel, but they were all full-grown leptocephali. This distribution does not seem to be specially characteristic of the eel, for on the southern section we came across many small larvæ and eggs belonging to other forms, none of which were met with farther north. Future investigations will doubtless make all this clear, and may lead to valuable discoveries.

Trawling on the Mid-Atlantic ridge.

The accident to our trawl on the Azores bank, already mentioned, prevented us from trawling in very deep water, but for all that we were able to carry out two successful trawlings at considerable depths. The first was at Station 88, on the longitudinal ridge north of the Azores, where we shot our trawl in 3120 metres of water. There were numbers of echinoderms of all kinds (starfish, sand-stars, sea-urchins, and holothurians), as well as a score of bottom-fish (*Macrurus*, *Synaphobranchus*, *Bathysaurus*). The haul was extremely interesting, as it gave a fresh proof of the abundance of animal life as far down as 3000 metres—not in this case on a continental slope, but out on a ridge in the middle of the ocean. Off the coast of Ireland we succeeded in trawling at 1000 fathoms (1797 metres, Station 95), which we had attempted in vain after leaving Plymouth, and we towed the big trawl for two and a half hours with very satisfactory results. There were quantities of echinoderms (300 holothurians, 800 ophiuroidæ), molluscs, corals, crustaceans, and 82 fishes (*Macrurus*, *Antimora viola*, *Alepocephalus*, *Bathysaurus* (Fig. 103 *a*), *Notacanthus*, *Halosauropsis* (Fig. 103 *b*), Trawling off coast of Ireland.

a



b

FIG. 103.—TWO DEEP-SEA FISHES FROM STATION 95, 1797 metres (about 1000 fathoms).
a. Bathysaurus ferox, Gthr. Nat. size, 42 cm.
b. Halosauropsis macrochir, Gthr. Nat. size, 60 cm.

and Synaphobranchi). We also found in the trawl a basketful of stones, coal, and cinders.

The "Michael Sars" anchored at Glasgow on the 29th July after a passage from Newfoundland lasting three weeks. During this time we had worked at twenty-two stations, and had made investigations all the way across the Atlantic. In spite of having steamed about 2000 miles, and having been three weeks at sea, we had still nearly 37 tons of coal left, or enough for another week's work. We had thus proved that a little vessel may carry out investigations formerly attempted only with large ships, and this fact is certain to be taken into account when future expeditions are planned. Taking everything into consideration, we had made very satisfactory hydrographical and biological observations over a large part of the North Atlantic. As previously stated, one of the principal objects of the expedition was to carry out researches in the North Atlantic likely to increase our knowledge of the marine area explored by the "Michael Sars" during the past few years, namely, the Norwegian Sea lying between Norway, Greenland, Iceland, and the North Sea. It was important, therefore, to

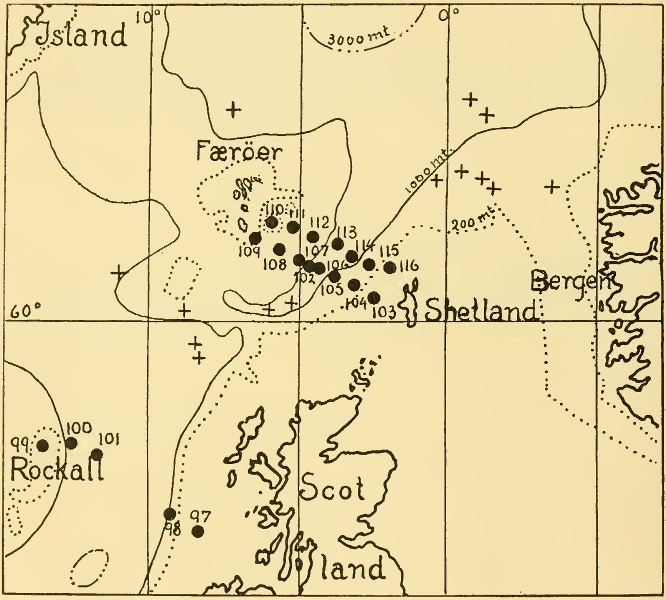


FIG. 104.—"MICHAEL SARS" STATIONS FROM GLASGOW TO BERGEN.

examine the adjoining portion of the Atlantic and to investigate the inflow of the Atlantic water.

After leaving the vicinity of the Newfoundland Bank, the Gulf Stream bends sharply eastwards and forms the surface layer examined by us between Stations 81 and 92 (see Fig. 99). Off the edge of the Irish coast bank a portion turns northwards towards the Norwegian Sea. The sea-bottom is here very complicated, for the deep basins of the Atlantic and Norwegian Sea are separated by a submarine ridge (see Fig. 104). To the north-west of Ireland the wide Atlantic plain narrows to a kind of valley, which is bounded on the west by the Rockall bank, and on the east by the coast bank of Scotland. Farther north this valley shallows towards the extensive ridge that stretches from Iceland past the Faroe Islands to Shetland, and separates the Atlantic Ocean from the Norwegian Sea at all depths beyond 400 to 500 metres. The part of this ridge between the Faroe Islands and Shetland is known as the Wyville Thomson Ridge, which has frequently been examined, first by British, afterwards by Danish, naturalists; in fact, it may be regarded as a classical field for oceanic research (see Chapter I.). The

FIG. 105.—ROCKALL.

"Michael Sars" had made investigations there previously, both on the Atlantic side south of the ridge and in the Norwegian Sea to the north of it. In Fig. 104 our former research-stations are marked with a cross.

It was desirable, however, to re-investigate this area, employing there the same methods of working as we had adopted in the North Atlantic, and we felt it necessary to have a section south of the Wyville Thomson Ridge and another one to the north of it. The valley between Britain on the one side and Rockall and the Faroes on the other is really the only connection between the two deep basins, for it is only through this channel that the water of the Atlantic streams into the Norwegian Sea; to the west of the Faroes, over the long ridge that extends to Iceland, the Atlantic water is checked by the East Iceland Polar current.

Glasgow to Bergen.

Our southern section was from Glasgow to Rockall, with stations on the British coast bank, on its seaward slope, and on the Rockall Bank. We had beautiful weather in which to make

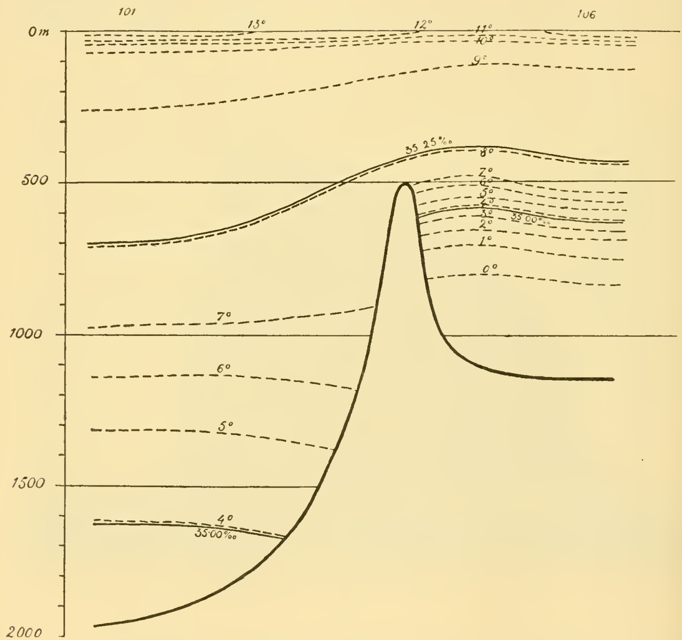


Fig. 106.—Section across the Wyville Thomson Ridge.

investigations, and approached close to the rocky little islet, which we photographed (Fig. 105). This rock is well known,

Rockall.

owing to many a sad disaster (only recently the transatlantic steamer "Norge" was wrecked there), and shows distinct traces of the power of the waves. All its brown granite-like sides are clad with small algæ (green-spored algæ), kept moist by the spray, and the top is covered with a thin layer of guano; the rock and its surroundings swarm with auks and gulls.

After completing this section, we proceeded towards the Wyville Thomson Ridge, and occupied a station (101) at a depth of 1000 fathoms, where we employed the trawl as well as a number of pelagic appliances, and then concluded our work by taking two sections on the northern side of the ridge (see stations in Fig. 104). Wyville Thomson Ridge.

The *hydrographical conditions* here have often been described. Fig. 106 gives a general idea of what we found at Station 101 south of the Wyville Thomson Ridge, and at Station 106 to the north of it. South of the ridge salinities and temperatures are rather lower than what we found in our northern Atlantic section, but the differences are not very considerable either in deep water or in the upper layers. The upper layers extend with little variation down to the level of the ridge in 500 metres, but the difference in the deep water on the two sides of the ridge is unmistakable, as the ice-cold bottom-water of the Norwegian Sea comes close to the northern margin of the ridge.

These conditions, however, are generally known, and our attention was chiefly turned in another direction. During our previous investigations in the Norwegian Sea we discovered that the hydrographical conditions often varied very considerably within a short distance or in the course of a short period of time. The variations were not always of the same character. A number of eddies, both large and small, occurred apparently during the movements of the water-layers, and there were up and down movements in the boundary-layers—possibly big submarine waves or something of that sort—as well as distinct pulsations in certain currents. We resolved, therefore, on our way over to Bergen to make a careful study of these phenomena in the Faroe-Shetland channel. To be able to do so, it was necessary to have our stations very close together and to occupy them in rapid succession, and also to lie stationary for at least twenty-four hours at one of them.

Altogether we had fourteen stations north of the ridge in the Faroe-Shetland channel (Nos. 103–116; see Fig. 104) along two nearly parallel sections, the distance from one station to another being about 20 nautical miles, and the distance between the sections a little over 25 miles. We found that the hydrographical conditions varied greatly in the different localities, and that there was an extraordinary difference between the two sections. At Station 115, on the continental edge to the west of Shetland, we anchored a buoy, and remained stationary there Investigations in the Faroe Channel.

for twenty-four hours, taking continuous observations of temperature and salinity at different depths. It was quite evident that there were considerable vertical fluctuations, the intermediate layers showing up and down movements with an amplitude of as much as 35 metres during a period that corresponded practically with the tidal period.

Pelagic hauls. After leaving Glasgow we made pelagic hauls with our silk nets and young-fish trawls on the coast bank, on the slope, out in the deep channel, near the southern flank of the Wyville Thomson Ridge (Station 101), and to the north of it (Station 102). At every depth our catches to the south of the ridge closely resembled those we made in our northern Atlantic section between Newfoundland and Ireland, and particularly the catches made in the eastern portion of that section.

In the upper layers there were all the boreal animals characteristic of Atlantic water in the Norwegian Sea, as, for instance, *Euthemisto* and *Clione limacina*. But there was also a mass of Atlantic forms that do not occur all the year round in the Norwegian Sea, though they are known to wander in at certain seasons of the year, as at the end of the summer or during autumn. The tow-nets gave a mixture of *Arachnactis*, *Salpa fusiformis*, numbers of scopelids, leptocephali (full-grown larvæ of the common eel), the young of *Macrurus*, and *Nerophis æquoreus*.

At a depth of 300 metres we captured the silvery *Argyropelecus*, and in deep water, from 500 metres downwards, there was the characteristic fauna of black *Cyclothone microdon*, red crustaceans (*Acanthephyra*), and other forms, which thus occur *right up to the southern slope of the Wyville Thomson Ridge.*

On the northern side of the ridge we towed our appliances at 50, 100, 150, 200, 300, 500, 700, and 750 metres (Station 102) *without catching a single specimen of these Atlantic deep-sea forms*; but in the upper layers there were not merely boreal forms, but also salpæ, the area of distribution of which is mainly Atlantic.

These results quite accord with our previous observations during the cruises of the "Michael Sars." Hauls in the deepest waters of the Norwegian Sea have not yielded any pelagic fish other than the black *Paraliparis bathybii* (Fig. 107), which used to be considered a bottom-fish; it is interesting to note that it is black. There was a complete absence of *Cyclothone* and the red Atlantic crustaceans belonging to the genus *Acan-*

thephyra, the only pelagic crustaceans found by us north of the ridge being *Hymenodora glacialis* and species of *Pasiphæa*.

In the upper layers, however, different scopelids have been found both by us and by others, and on the Norwegian coast the silvery species of *Argyropelecus*, which inhabit depths of about 300 metres in the Atlantic, have occasionally been met with. It seems tolerably certain, therefore, that *the Wyville Thomson Ridge shuts out the whole of the Atlantic pelagic deep-sea fauna from the Norwegian Sea*, and that it is only in the superficial layers from the surface down to 400 or 500 metres that pelagic forms are able to wander in from the Atlantic.

Benthos of the Faroe Channel.

That the bottom-fauna is different on either side of the ridge is well known. Our trawlings, both on this occasion and previously, have merely helped to confirm the fact; still we secured a very large amount of material, which in itself is of

FIG. 107.
Paraliparis bathybii, Coll. Nat. size, 23 cm.
(Taken in pelagic haul in Norwegian Sea, May 1911.)

considerable interest. At Station 101 (south of the ridge), in 1000 fathoms (1853 metres) of water, a haul of two hours' duration yielded a barrel-full of lower animals, most of which were echinoderms, and ninety fishes (*Macrurus*, *Antimora*, *Alepocephalus*, *Harriotta*, and Synaphobranchi), representing a fauna that may be said to characterise the north-east Atlantic from the Wyville Thomson Ridge southwards, far along the coast of Africa. The remarkable fish, *Harriotta raleighana*, which we captured at Station 101, a few miles from the deep water of the Norwegian Sea, had been previously taken by us at Station 35, to the south of the Canary Islands. On the other hand, fish that exist only a few miles farther north, on the northern side of the ridge, never enter the Atlantic, though in the deep water of the Norwegian Sea they may be met with as far north as Spitsbergen, and perhaps even still farther north.

Extent of the cruise.

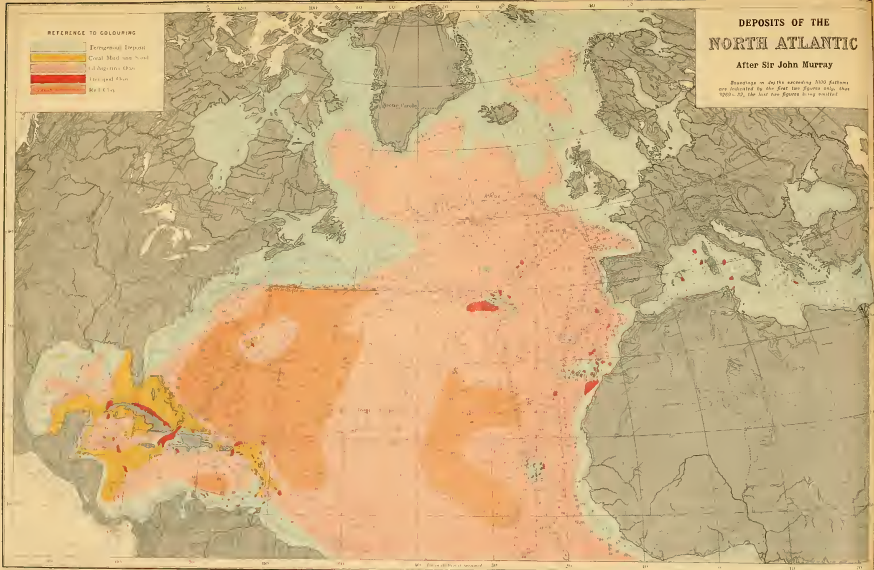
The "Michael Sars" anchored at Bergen on 15th August. During her four and a half months' cruise she had traversed 11,500 miles, and occupied 116 research stations; on a rough estimate we had lowered and hauled in about 1500 kilometres of wire with our four winches. Only the greatest attention and energy on the part of the crew could have made this possible. Thanks to them we have probably opened up a new way for ocean research, by showing what a little vessel can accomplish, which is by no means the least valuable result of our expedition. The following chapters aim at giving the results of our scientific observations from a more general and systematic point of view than was possible in this brief account of the actual cruise.

J. H.

S.S. "MICHAEL SARS" TOWING OTTER TRAWL.

Track of H M S Challenger shown thus

Track of H.M.S. Challenger shown thus



Track of H.M.S. Challenger shown thus

Sifting Deposits on board the "Challenger."

CHAPTER IV

THE DEPTHS AND DEPOSITS OF THE OCEAN

1. The Depths of the Ocean

In the opinion of astronomers the earth is the only planet of our solar system which has oceans on its surface. If Mars and the moon once had oceans, these have apparently disappeared within their rocky crusts. Our earth is in what is called the terraqueous stage of a planet's development. The ocean is less than the hydrosphere, which is regarded as including all lakes and rivers, the water-vapour in the atmosphere, and the water which has penetrated deep into the lithosphere.

The earth as a planet.

If the whole globe were covered with an ocean of uniform depth, and if there were no differences of density in the shells of the rocky crust, the surface of the ocean would be a perfect spheroid of revolution. But, as every one knows, the surface of the earth is made up of land and water, and at all events the superficial layers of the lithosphere are heterogeneous. The figure of the earth departs from a true spheroid of revolution, and is called a geoid. The surface of the ocean is, therefore, farther removed from the centre of the earth at some points

Figure of the earth.

than at others; the gravitational attraction of emerged land causes a heaping-up of the sea around continental and other coasts. The extent of this heaping-up near elevated continents, and consequent lowering of the sea-surface far from land, appear to have been much exaggerated. The difference of level due to this cause has sometimes been estimated at thousands of feet. Recent researches indicate that the differences of level at different points of the sea-surface do not depart more than 300 or 400 feet from a true spheroid of revolution.

Attraction of the land-masses.

The other causes which, in addition to the tides, may affect the level of the ocean are meteorologic, such as barometric pressure, temperature, the action of wind, evaporation, precipitation, the inflow of rivers, but in no cases do these affect the level of the ocean more than a few inches or a few feet.

Measurements of depth.

All depths recorded by the sounding-line in the open sea are referred to the surface of the ocean, and near coasts to mean sea-level. The first method of ascertaining the depth of the ocean was by means of the hand line and lead, armed with tallow, used by ordinary sailors. A great advance was made when Lieutenant Brooke, of the United States Navy, devised the apparatus for detaching the weight or sinker when it struck the bottom, the line bringing up only a small tube with a sample of the bottom-deposit. During the "Challenger" Expedition the line used was a fine hempen rope, and the time when each 100-fathoms mark passed over the ship's side was carefully noted. When a great change of the rate was observed, the lead was known to have reached the bottom. It is believed that even the deepest soundings taken in this way are correct to within 100 feet.

Hand line.

Brooke's sounding machine.

Hemp line for sounding.

Wire for sounding.

Another advance was made when fine wire was used for the soundings, and the machine recorded automatically the moment when the sinker struck the bottom. There are many types of wire deep-sea sounding machines now in use, but the most compact and practical of these is the Lucas sounding machine. Sounding instruments are referred to in greater detail in another chapter (see p. 30).

Number of deep-sea soundings.

To give the total number of deep soundings recorded by British and other ships up to the present day, even in depths exceeding 1000 fathoms, would be difficult. An approximation has been made by counting the number of soundings in depths exceeding 1000 fathoms laid down on the latest charts. It must be remembered that not all the recorded soundings can be laid down on small scale charts where they are at all numerous.

In 1886 Sir John Murray had three hemispheres drawn on

Lambert's equal-surface projection, one to show the Atlantic Ocean, one the Pacific, and one the Indian Ocean, on which all the soundings recorded up to that time, in depths exceeding 1000 fathoms, were laid down in position, and contour-lines of depth drawn in. Since then these hemispheres have been kept up to date by Dr. Bartholomew by the inclusion from time to time of new soundings recorded in depths greater than 1000 fathoms, and the contour-lines have been redrawn. The North Atlantic from one of these hemispheres is shown on Map III., where practically all soundings recorded in depths greater than 1000 fathoms are placed in position, the two last figures being omitted.

Equal-surface projection hemispheres.

The total number of soundings laid down on these charts is 5969, of which 2500 are in the Atlantic (1873 in the North Atlantic and 627 in the South Atlantic), 2466 in the Pacific (1266 in the North Pacific and 1200 in the South Pacific), and 1003 in the Indian Ocean. These figures show that proportionately a great many more soundings have been taken in the Atlantic than in the Pacific, which covers an area so much larger. Of these 5969 soundings, 2516 were taken in depths between 1000 and 2000 fathoms, 2962 in depths between 2000 and 3000 fathoms, and only 491 are laid down in depths exceeding 3000 fathoms, of which 46 exceed 4000 fathoms, and only 4 exceed 5000 fathoms. It may be added that though only four soundings over 5000 fathoms have been laid down on the charts, in reality seven have been recorded, three in the South Pacific in the Aldrich Deep, and the other four taken by the U.S.S. "Nero" in the Challenger Deep in the North Pacific, near the island of Guam, but in such close proximity to one another that only the deepest, 5269 fathoms, could be laid down on the map.

Number of soundings in depths greater than 1000 fathoms.

The deepest sounding hitherto recorded is that of 5269 fathoms just mentioned. This is equal to 9636 metres, or 31,614 feet, or 66 feet less than six English miles, and it exceeds the greatest known height above the level of the sea (Mount Everest in the Himalaya Mountains, 29,002 feet) by 2612 feet. The known range of variation in the level of the earth's crust, from the greatest height above sea-level to the greatest depth below sea-level, is thus 60,616 feet, or about $11\frac{1}{2}$ English miles, but this range is very small when we remember that the diameter of the earth is nearly 8000 miles; in fact, on a six-feet globe a mere scratch one-tenth of an inch deep would represent the extreme variation in the irregularities of the earth's surface.

Deepest recorded sounding.

Range of variation of level of the earth's crust.

Deepest soundings in the Atlantic and Indian Oceans.

The second deepest sounding on the ocean-floor is 5155 fathoms in the Aldrich Deep in the South Pacific, depths exceeding 5000 fathoms being limited to the Pacific Ocean. The deepest sounding recorded in the Atlantic is 4662 fathoms in the Nares Deep to the north of the West Indies, and the deepest in the Indian Ocean 3828 fathoms in the Wharton Deep to the south of the East Indies.

Superficial area of the earth.

In 1886 Professor Chrystal calculated for Sir John Murray the superficial area of the earth, regarded as a spheroid of revolution, as equal to 196,940,700 square English miles, of which the land-surface was estimated at 55,697,000 square miles, and the water-surface at 141,243,000 square miles.[1] At that time the area of land surrounding the south pole was estimated at 3,565,000 square miles, but the results of all the recent south polar expeditions seem to indicate that the Antarctic continent covers a larger extent than was supposed. The latest measurements by Sir John Murray give a probable area of about 5,122,000 square miles for Antarctica, so that the total land-surface of the globe may now be estimated at 57,254,000 square miles, which may be supposed to include all lakes and rivers, leaving about 139,686,000 square miles for the waters of the ocean and seas directly connected therewith.

Area of Antarctic continent.

Area of land on the globe.

Area of water on the globe.

Planimeter measurements of the most recent depth hemispheres gave 139,295,000 square English miles for the area of the whole ocean, and this figure will be adopted throughout this publication.

Areas of the ocean-floor at different depths.

The approximate areas between the consecutive contour-lines drawn in at equal intervals of 1000 fathoms worked out as follows for the whole ocean :—

Fathoms.	Square English Miles.	Percentage.
0–1000	21,725,000	15.59
1000–2000	26,915,000	19.34
2000–3000	81,381,000	58.42
3000–4000	9,058,000	6.50
Over 4000	216,000	0.15
	139,295,000	100.00

[1] *Scottish Geographical Magazine*, vol. ii. p. 550, 1886.

This table shows at a glance that the greater portion of the ocean-floor is covered by deep water, *i.e.* by water exceeding 1000 fathoms in depth, equal to more than four-fifths of the entire superficies of the ocean, two-thirds being occupied by water exceeding 2000 fathoms in depth, while only one-fifteenth of the entire sea-floor is covered by water exceeding 3000 fathoms in depth.

"Deeps."

Those parts of the ocean in which depths greater than 3000 fathoms have been recorded are called "deeps," and have had distinctive names conferred upon them, just as mountain ranges and peaks on the dry land (Mount Everest, for example) are distinguished by names. These deeps are shown on Map II., and will presently be dealt with in some detail.

Areas of the continental shelf and continental slope.

The table also shows that a comparatively large area, about one-sixth of the ocean-floor, is covered by water less than 1000 fathoms in depth, of which by far the greater proportion is covered by still shallower water. Thus if we divide this area into two portions by the 500-fathoms line, we find that the area within that line is about 17 million square miles (or over 12 per cent of the entire ocean) compared with only $4\frac{1}{2}$ million square miles (or 3 per cent of the entire ocean) beyond that line, *i.e.* having depths between 500 and 1000 fathoms. Again, of the area covered by less than 500 fathoms of water, more than one-half is occupied by the continental shelf or continental plateau lying between the shore-line and the 100-fathoms line, which has elsewhere[1] been estimated at 7 per cent of the whole ocean. The relatively large area covered by the gentle slopes of the continental shelf in depths less than 100 fathoms, as compared with the relatively small area covered by the steeper gradients of the continental slope in depths greater than 100 fathoms, is strikingly shown by these figures, for while about 7 per cent of the ocean-floor lies within the 100-fathoms line, only about 5 per cent occurs within the next succeeding 400 fathoms (between the 100- and 500-fathoms lines), and only about 3 per cent within the next succeeding 500 fathoms (between the 500- and 1000-fathoms lines).

Continental edge and mud-line

The position occupied by the junction of the continental shelf with the continental slope, as indicated by the change of gradient, has been called the continental edge (see Fig. 144, p. 198), and varies in depth according to circumstances, but on the average all over the world is not far from the 100-fathoms

[1] Sir John Murray, Presidential Address to the Geographical Section of the British Association, Dover, 1899.

line, coinciding generally with what we have designated the mud-line.[1]

Let us now consider the distribution of depth in the three great oceans (the Atlantic, the Pacific, and the Indian Oceans), regarding them as extending in each case as far south as the shores of the Antarctic continent.

Area of the Atlantic sea-floor at different depths.

Atlantic Ocean.—The Atlantic may be looked upon as including the Arctic Ocean and Norwegian Sea, the Mediterranean, Caribbean, and Gulf of Mexico, and as being separated from the Pacific in the south at the meridian of Cape Horn (long. 70° W.) and from the Indian Ocean at the meridian of the Cape of Good Hope (long. 20° E.). As thus defined the Atlantic Ocean covers an area of about 41,321,000 square English miles, the distribution of depth being shown in the following table:—

Fathoms.	Square English Miles.	Percentage.
0–1000	11,388,000	27.56
1000–2000	7,531,000	18.22
2000–3000	19,539,000	47.29
3000–4000	2,848,000	6.89
Over 4000	15,000	0.04
	41,321,000	100.00

Continental shelf and slope in the Atlantic.

These figures show that nearly three-fourths of the Atlantic sea-floor are covered by water exceeding 1000 fathoms in depth, and over one-half by water exceeding 2000 fathoms in depth, but the most characteristic feature of this ocean when compared with the Pacific and Indian Oceans is the large proportion covered by water less than 1000 fathoms in depth. The table shows that this shallowest zone (from 0–1000 fathoms, which includes both the continental shelf and the continental slope) covers about 11½ million square miles, while the succeeding zone (1000–2000 fathoms) covers only 7½ million square miles. If again we divide the shallowest zone into two portions by the 500-fathoms line, the predominance of the area covered by shallow water is still more pronounced, the area less than 500 fathoms being nearly 10 million square miles as compared

[1] Murray and Renard, Deep-Sea Deposits Chall. Exp. p. 185, 1891; Murray, Summary of Results Chall. Exp. p. 1433, 1895.

with $1\frac{1}{2}$ million square miles between 500 and 1000 fathoms. This is due to the large expanses of shallow water in the Arctic regions and Hudson Bay, on the Banks of Newfoundland, off the east coasts of North and South America, between Greenland and the British Isles, around the British Isles, and in the Baltic.

Mid-Atlantic ridge.

The most striking feature of the Atlantic Ocean is certainly the low central ridge (dividing the ocean into eastern and western deep basins), which was until recently supposed to be continuous from Iceland through both the North and South Atlantic as far as lat. 40° S., but is now known to be discontinuous in the neighbourhood of the equator; on the other hand, it has been extended farther south by the soundings taken on board the "Scotia" in 1904 by Dr. W. S. Bruce, so that the southern limit of the ridge now extends as far south as lat. 53° S. At the position of the break in the ridge on the equator the floor of the ocean seems to be more than usually irregular, for depths less than 2000 fathoms alternate with depths exceeding 3000 and even 4000 fathoms. On this ridge, with the exception of the Azores group, the only islands are St. Paul's Rocks, Ascension, Tristan da Cunha, and Gough Island. The northern extremity of the ridge between lat. 50° and 60° N. is peculiar because of the number of isolated soundings exceeding 2000 fathoms apparently surrounded by shallower water.

Shore-slopes of the Atlantic.

Another point that strikes one in the Atlantic is the gentle slope off the American coasts and off the coasts of the British Isles, as compared with the slopes off Africa and off Spain and Portugal. This is still more remarkable when compared with the slopes off the Pacific coasts of America. The wide shore platform off the coast of the southern half of South America is especially noteworthy, as well as that off the coasts of the United States and Newfoundland. The shallow area surrounding Rockall Bank also attracts attention.

Submarine banks of the Atlantic.

The series of banks made known as a result of the work of telegraph ships, off the north-west coast of Africa to the north of the Canary Islands, is another striking instance of the irregularity of the floor of the Atlantic. In the same neighbourhood the area with depths less than 2000 fathoms surrounding Madeira and extending northwards towards the coast of Portugal is remarkable. In the South Atlantic, besides the central ridge, three smaller shallow areas should be noted, two neighbouring ones to the east of the South American coast in lat. 30° S., and the third midway between the ridge and the Cape of Good Hope.

Atlantic area exceeding 2000 fathoms in depth.

The principal area exceeding 2000 fathoms in depth is continuous throughout the Atlantic, although much broken up by areas of shallower water; there are besides in places isolated areas in which the depth exceeds 2000 fathoms, as in the Gulf of Guinea, near the Canary Islands, at the northern extremity of the Mid-Atlantic ridge (as already mentioned), as well as in the Norwegian Sea, the Mediterranean Sea, the Carribbean Sea, and the Gulf of Mexico.

The areas exceeding 3000 fathoms in depth ("deeps") will be referred to under a later heading.

Area of the Pacific sea-floor at different depths.

Pacific Ocean.—The Pacific may be looked upon as extending southwards from the Arctic circle in Behring Strait to the Antarctic continent, including the fringe of partially enclosed seas along its western border, and as being separated from the Atlantic in the south at the meridian of Cape Horn (long. 70° W.), and from the Indian Ocean at the meridian of Tasmania (long. 147° E.). As thus defined the Pacific Ocean covers an area of about 68,634,000 square English miles, the distribution of depth being shown in the following table:—

Fathoms.	Square English Miles.	Percentage.
0–1000	7,174,000	10.45
1000–2000	12,214,000	17.80
2000–3000	44,633,000	65.03
3000–4000	4,412,000	6.43
Over 4000	201,000	0.29
	68,634,000	100.00

These figures show that nearly nine-tenths of the Pacific sea-floor are covered by water exceeding 1000 fathoms in depth, and nearly three-fourths by water exceeding 2000 fathoms in depth. Unlike the Atlantic, the shallowest zone in the Pacific (0–1000 fathoms) is smaller than the succeeding zone (1000–2000 fathoms), indicating that the Pacific land-slopes are on the average steeper than those of the Atlantic, and this is strikingly shown by the near approach to the land of the deep contours in certain regions, as off the coasts of South America, North America, Japan, the Philippine Islands, and South-East Australia. The ratio between the two areas on either side of the 500-fathoms line is not so striking as in the case of the Atlantic, the area

Continental shelf and slope in the Pacific.

less than 500 fathoms in the Pacific being about 5 million square miles, as compared with 2 million square miles for the area between 500 and 1000 fathoms.

The Pacific Ocean differs from the Atlantic in having much more steeply sloping shores both on the east and west sides, greater depths, and very many small islands, chiefly of volcanic and coral formation. This gives a very irregular appearance to the depth-map of the Pacific, and shows sharper contrasts in rises and depressions of the ocean-floor than are found in either of the other great ocean basins. Along the west coasts of both North and South America the steep slopes are most remarkable, the land descending from the great heights of the Rocky Mountains and the Andes to depths of 2000 fathoms and more in a comparatively very short horizontal distance. This is particularly striking off the coast of South America between the latitudes of 10° and 35° S., where depths of over 3000 fathoms (in three cases over 4000 fathoms) are found within a very short distance from the shore-line. It is noteworthy that all the soundings recorded in depths of over 4000 fathoms are taken comparatively near land, viz. off South America (as just mentioned), off the Aleutian Islands, the Kurile Islands and Japan, the Philippines, the Ladrone Islands, the Pelew Islands, between the Solomon Islands and New Pommerania, and to the north of New Zealand, east of the Kermadec and Friendly Islands.

Shore-slopes of the Pacific.

Very deep soundings comparatively near land.

The greater part of the area with depths less than 1000 fathoms lies in the western Pacific, in the fringe of partially enclosed seas which lie between the continents of Asia and Australia and the islands fringing their eastern shores, such as the Behring Sea, the Sea of Japan, the Yellow Sea, China Sea, Java and Arafura Seas, and around the New Zealand plateau.

The area covered by depths between 1000 and 2000 fathoms lies mostly south of the equator, that part north of the equator consisting of detached areas in the Behring Sea, Sea of Okotsk, Sea of Japan, and China Sea, narrow bands round the various island groups and along the western shores of North America, widening greatly off the coast of Central America, and nine small areas where the floor of the ocean rises from surrounding depths of over 2000 fathoms. The area in the South Pacific with depths between 1000 and 2000 fathoms was formerly supposed to extend from the Southern Ocean between Auckland Islands and the Antarctic continent in a wide band north-eastwards towards the coasts of Central America without a break, but recent investiga-

Pacific area with depths between 1000 and 2000 fathoms.

tions by the late Alexander Agassiz on board the U.S.S. "Albatross" showed that this rise from the general depth of over 2000 fathoms was not continuous. This has led to a great decrease in the figures given for the area with depths between 1000 and 2000 fathoms, and a corresponding increase in the area with depths between 2000 and 3000 fathoms.

Pacific area exceeding 2000 fathoms.

The area exceeding 2000 fathoms in depth in the Pacific is connected with the corresponding area in the Atlantic by a comparatively narrow trench running to the south of Cape Horn between South Georgia and South Orkney, and is continuous throughout the Pacific except for detached areas in several of the fringing seas on the west, one in the Coral Sea, and one large and six small areas in the South-West Pacific, where the soundings are very numerous and the contour-lines of depth are very sinuous.

The areas exceeding 3000 fathoms in depth will be referred to under a later heading.

Area of the Indian Ocean sea-floor at different depths.

Indian Ocean.—The Indian Ocean may be looked upon as extending southwards from the Bay of Bengal and Arabian Sea to the Antarctic continent, including the Red Sea and Persian Gulf, and as being separated from the Atlantic in the south at the meridian of the Cape of Good Hope (long. 20° E.) and from the Pacific at the meridian of Tasmania (long. 147° E.). As thus defined the Indian Ocean covers an area of about 29,340,000 square English miles, the distribution of depth being shown in the following table :—

Fathoms.	Square English Miles.	Percentage.
0–1000	3,163,000	10.78
1000–2000	7,170,000	24.44
2000–3000	17,209,000	58.65
Over 3000	1,798,000	6.13
	29,340,000	100.00

These figures show that, like the Pacific, nearly nine-tenths of the Indian Ocean sea-floor are covered by water exceeding 1000 fathoms in depth, while nearly two-thirds are covered by more than 2000 fathoms of water. The shallowest zone in the Indian Ocean (0–1000 fathoms) is much smaller than the succeeding zone (1000–2000 fathoms), indicating that the average

Continental shelf and slope in the Indian Ocean.

land-slopes throughout the basin are, as in the Pacific, steeper than those of the Atlantic. The ratio between the two areas on either side of the 500-fathoms line is again much less than in the case of the Atlantic, the area less than 500 fathoms in the Indian Ocean being over 2 million square miles, as compared with less than 1 million square miles for the area between 500 and 1000 fathoms.

The Indian Ocean, unlike the other two, is completely land-locked to the north. The area with depths less than 1000 fathoms forms a zone of varying width along the main land-masses, a fairly wide zone round the various island groups, and extends into the Red Sea and Persian Gulf. The area with depths between 1000 and 2000 fathoms is made up of the greater part of the Bay of Bengal and the Arabian Sea, a fairly wide belt along the east coast of Africa, a much narrower one along the western shores of the Sunda Islands and Australia, a large expanse between Tasmania and the Antarctic continent which narrows considerably towards the west, and a large tract extending from lat. 30° to 55° S. and long. 35° to 94° E., forming a plateau on which are situated the islands of Prince Edward, Crozet, Kerguelen, M'Donald, Heard, St. Paul, and Amsterdam, as well as one or two small isolated areas.

Indian Ocean area with depths between 1000 and 2000 fathoms.

With the exception of a comparatively small area in the Southern Ocean, about lat. 60° S. to the south of Australia, the area with depths between 2000 and 3000 fathoms is a continuous one, though interrupted by areas of deeper and shallower water; it is continuous with the corresponding area of the Atlantic, but distinct from that of the Pacific, being separated from it by the rise that runs southwards from Tasmania to the Antarctic continent.

Indian Ocean area exceeding 2000 fathoms.

The areas exceeding 3000 fathoms in depth are referred to under the next heading.

Deeps.—As already indicated, those areas of the ocean-floor covered by more than 3000 fathoms (5486 metres) of water have been called Deeps, and, though occupying a relatively small proportion of the ocean-floor, estimated in the aggregate at about 9 million square miles, they are extremely interesting from an oceanographical point of view. Map II. shows the distribution of these deeps throughout the great ocean basins, according to the present state of our knowledge, and it will be seen that the total number is fifty-seven, of which thirty-two occur in the Pacific, five in the Indian Ocean, nineteen in

Deeps.

Number of known deeps.

the Atlantic, and one partly in the Atlantic and partly in the Indian Ocean. From the point of view of depth the Challenger Deep in the North Pacific and the Aldrich Deep in the South Pacific are the most important, for only these two include depths exceeding 5000 fathoms, while in eight other deeps depths exceeding 4000 fathoms have been recorded. On the other hand, in some cases the deeps enclose low rises, on which the depth is less than 3000 fathoms. The deeps vary in form and size to a most extraordinary degree, and future soundings may show that some of them should be subdivided into two or more portions, or that two or more deeps as now laid down should be united into a single deep.

Deepest deeps.

From the point of view of superficial area, the most important deeps are the Valdivia, Murray, Tuscarora, Wharton, Nares, Aldrich, and Swire Deeps, which are estimated to cover in each case an area exceeding 500,000 square miles. In the following paragraphs the principal deeps of the world are briefly characterised, arranged in the order of magnitude :—

Largest deeps.

Valdivia Deep.

Valdivia Deep lies in the far south, partly in the Atlantic and partly in the Indian Ocean. It is based principally on soundings taken by the German Deep-Sea Expedition on board the "Valdivia," and has a maximum depth of 3134 fathoms. It is estimated to cover a total area of 1,136,000 square miles, nearly one-half of which (523,000 square miles) lies to the west of long. 20° E., *i.e.* within the Atlantic basin, while the remaining half (613,000 square miles) lies to the east of that meridian, and is therefore in the basin of the Indian Ocean. The outline of this deep, especially in its western portion, is largely hypothetical, and future soundings may modify the area assigned to it at present.

Murray Deep.

Murray Deep, situated in the Central North Pacific between lat. 25° and 40° N., is estimated to cover an area of about 1,033,000 square miles, and is founded on soundings taken partly by the "Challenger" Expedition. The maximum depth recorded in it is 3540 fathoms, and there is a small area within the deep in the vicinity of this deepest sounding where depths of only 2800 and 2900 fathoms are recorded.

Tuscarora Deep.

Tuscarora Deep lies in the North-Western Pacific, and is of elongated form, extending from the Tropic of Cancer north-eastwards to near the Aleutian Islands in lat. 52° N., approaching to within a comparatively short distance of the shores of Japan and the Kurile Islands. Its area is estimated at 908,000 square miles, and the maximum depth is 4655 fathoms, recorded by the U.S.S. "Tuscarora" in 1874. A considerable portion of this deep is covered by depths exceeding 4000 fathoms, including one large elongate area founded on eight soundings, and two small areas founded each on single soundings—one towards the southern end of the deep and the other in the extreme north.

Wharton Deep lies in the eastern Indian Ocean, extending from lat. 10° S. to the Tropic of Capricorn, and is estimated to cover an area of 883,000 square miles; it includes the two deepest soundings yet recorded in the Indian Ocean, viz. 3828 and 3703 fathoms, taken in 1906 by the German ship "Planet" in what is called by the Germans the "Sunda Graben" at no great distance from the coast of Java. Wharton Deep.

Nares Deep is the largest deep lying wholly in the Atlantic Ocean, and at the same time the deepest. Its outline is most irregular, extending from lat. 18° N. to 34° N., and in the neighbourhood of the West Indies the floor of the deep sinks to depths exceeding 4000 fathoms over a limited area, the maximum depth being 4662 fathoms, recorded by the U.S.S. "Dolphin" in 1902. This deep is estimated to cover an area of 697,000 square miles. Nares Deep.

Aldrich Deep lies in the Central South Pacific, extending from lat. 15° to 47° S., and is estimated to cover an area of about 613,000 square miles. It includes seven small areas lying along its western border in which the depth exceeds 4000 fathoms. In three of these the depth exceeds 5000 fathoms, viz. 5022, 5147, and 5155 fathoms, recorded by Commander Balfour on board H.M.S. "Penguin" in 1895. Numerous soundings have been taken round these seven deepest areas, and seem to prove that they are all separated from one another by ridges covered by water between 3000 and 3700 fathoms in depth. The outline of this deep is remarkable, and it is possible that future soundings will show it to be two distinct deeps, for a rise, on which soundings in 2000 to 2900 fathoms have been recorded, interrupts the sequence of great depths. Aldrich Deep.

Swire Deep lies in the North-West Pacific in close proximity to the Philippines, and extends from about lat. 4° N. to lat. 25° N., covering an area of about 550,000 square miles. It is broken up by several rises on the ocean-floor where depths of 2700, 2800, and 2900 fathoms have been recorded; on the other hand, at remarkably short distances from the coasts of Mindanao and Samar Islands in the Philippines are two areas with depths exceeding 4000 fathoms, a similar depth being Swire Deep.

recorded also at the northern end of the deep. The maximum depth, which occurs off Samar Island, is 4767 fathoms.

Tizard Deep. *Tizard Deep* in the South Atlantic is estimated to cover an area of about 468,000 square miles, extending southwards from the equator to lat. 22° S. on the western side of the Mid-Atlantic ridge. The greatest depth recorded in it is 4030 fathoms, just south of the equator. In the southern portion of the deep two low rises occur, where depths rather less than 3000 fathoms have been recorded.

Buchanan Deep. *Buchanan Deep* lies to the east of the Mid-Atlantic ridge in the South Atlantic, between lat. 6° and 22° S., and covers an estimated area of 298,000 square miles. This deep appears to be somewhat flat-bottomed, because the numerous soundings recorded within it do not reach 3100 fathoms though exceeding 3000 fathoms, the maximum depth being 3063 fathoms.

Brooke Deep. *Brooke Deep* lies in the North-West Pacific between the latitudes of 12° and 19° N., and covers an area estimated at about 282,000 square miles. Its greatest depth is 3429 fathoms. Several elevations of the ocean-floor, rising to within 1400, 1100, and even 1000 fathoms of the surface, are situated close to the western and northern borders of this deep, separating it from the Challenger Deep on the west, and from the Bailey Deep on the north.

Moseley Deep. *Moseley Deep* lies in the North Atlantic to the east of the Mid-Atlantic ridge between lat. 9° and 18° N., and is estimated to cover an area of about 279,000 square miles; the deepest sounding recorded within it is 3309 fathoms.

Bailey Deep. *Bailey Deep* lies in the North-West Pacific, between the Brooke and the Murray Deeps, on the Tropic of Cancer. It is estimated to cover an area of about 241,000 square miles, and the deepest sounding recorded in it is 3432 fathoms.

Jeffrey Deep. *Jeffrey Deep*, in the eastern Indian Ocean, extends in a narrow band round the southern and western coasts of Australia, and as laid down on the map at present is estimated to cover an area of about 228,000 square miles. It is based on nine widely scattered soundings in the southern portion and four soundings closer together at the northern end, leaving a long stretch where no soundings have been taken. Further investigation may show that what is now regarded as one continuous deep is really two distinct deeps.

Belknap Deep. *Belknap Deep* lies in the Central Pacific, extending from about lat. 12° to 17° N., and covering an area estimated at about 165,000 square miles. Near the centre of the deep a rise based on a sounding in 2600 fathoms occurs between two soundings in 3100 fathoms, and the floor of the deep sinks from this rise towards the east to the maximum depth of 3337 fathoms.

Chun Deep lies in the North Atlantic between lat. 20° and 29° N., and is very peculiar in outline; it is estimated to cover an area of about 159,000 square miles, and the greatest depth is 3318 fathoms. Chun Deep.

Challenger Deep lies to the east of the Ladrone Islands in the western Pacific, and extends from lat. 11° to nearly 20° N., covering an area estimated at about 129,000 square miles. In 1875 the "Challenger" recorded a depth of 4575 fathoms between Guam and the Pelew Islands, and in 1899 the United States steamer "Nero" took a sounding in 5269 fathoms to the south-west of Guam, which is the deepest sounding hitherto recorded. The 4000-fathoms area extends in a narrow trench as far to the north-east of the "Nero" sounding as the "Challenger" sounding is south-west of it, and a small isolated area occurs still farther north, based on a single sounding in 4204 fathoms. At a comparatively very short distance from this deep trench is a pronounced rise within the deep based on three soundings: one in 1800 fathoms and two in 1000 fathoms; another slight rise is based on a sounding in 2900 fathoms. Challenger Deep. Deepest sounding.

The remaining deeps are smaller, and need not be referred to in detail, their position being clearly shown on the accompanying map (Map II.). Attention may be drawn, however, to the great depth of the Planet Deep, situated in the tropical Pacific between the Solomon Islands and New Pommerania, in which a sounding in 4998 fathoms was recorded in 1910 by the German survey ship "Planet" a short distance to the west of Bougainville Island.

2. Deep-Sea Deposits

The systematic investigation of deep-sea deposits was first undertaken by Sir John Murray during the "Challenger" Expedition, and the only standard work dealing with the whole subject is Murray and Renard's "*Challenger*" *Report on Deep-Sea Deposits*, published in 1891. That Report was not based merely on the deposit-samples brought home by H.M.S. "Challenger," though the detailed descriptions were limited to those samples, but included the results of the examination of samples collected by many other ships, received at the First systematic study of marine deposits.

"Challenger" Office from the British Admiralty and from many other British and foreign sources. Since the publication of the "Challenger" Report, deposit-samples collected by H.M. surveying ships and by British cable ships, as well as by many ships belonging to other nations, have been forwarded to the "Challenger" Laboratory for study, so that nearly all the samples of deposits procured from deep water over the ocean's floor have passed through our hands, and are available for the preparation of maps showing the distribution of the different types of deposits, and for the determination of the various constituents entering into the composition of deep-sea deposits.

Number of deposit-samples examined.

How extensive this material is may be surmised from the fact that nearly 12,000 deposit-samples have been examined in the "Challenger" Office. Some of these samples were very small, in a few cases insufficient even to indicate the type of deposit; but the great majority sufficed for the determination of the deposit-type, and of the percentage of calcium carbonate, while a very large number were available for detailed study and description. The samples have all been dealt with in a uniform manner, the methods of examination and description fully explained in the "Challenger" Report having been adopted throughout, for, notwithstanding the large amount of sounding-work carried on since that Report was published, the general results, the classification, and the nomenclature given therein have been fully substantiated and found quite adequate in every respect, no new types having been discovered.

Composition of marine deposits.

In this place we are dealing only with *deep-sea deposits*, *i.e.* those occurring in depths greater than 100 fathoms, the littoral and shallow-water deposits found in depths less than 100 fathoms being excluded. It may be stated, however, that these shallow-water and shore deposits near land are principally made up of relatively gross materials directly derived from the adjacent coasts, and from rivers pouring their waters and detritus into the ocean. Coral sands prevail near coral reefs, Volcanic sands off volcanic islands, and continental detritus near the embouchures of great rivers. All these materials become finer in texture with increasing distance from land, and in the greater depths of the ocean.

The constituents entering into the composition of deep-sea deposits may conveniently be divided into two classes: (A) those of organic origin, precipitated by organisms from the dissolved constituents of sea-water, and (B) those of inorganic origin, derived from (1) the decomposition of terrestrial and submarine rocks, (2) extra-terrestrial sources, (3) products synthesized at the bottom of the sea.

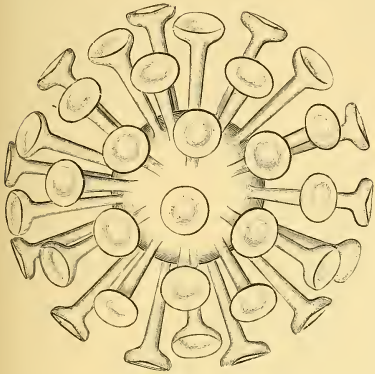


FIG. 108.
Discosphæra thomsoni, Ostenfeld. From the surface ($\frac{2000}{1}$).

Materials of organic origin.

Organic remains belonging to the vegetable kingdom are on the whole comparatively rare on the sea-floor, when compared with those belonging to the animal kingdom; still, in the neighbourhood of land, vegetable matter, branches of trees, leaves, fruits, etc., may be carried into deep water through the agency of large rivers, storms, off-shore winds, etc., along with the remains of sea-weeds growing in shallow water. Similarly in coral-reef regions, the remains of algæ which lived on the reefs, such as *Lithothamnium* and *Corallina*, occur in the deposits in the vicinity. But the most constant components of vegetable origin are the remains of algæ, which secreted either calcium carbonate or silica from the surface waters of the ocean to form their hard parts, viz. the calcareous coccospheres and rhabdospheres (see

Plant remains in marine deposits.

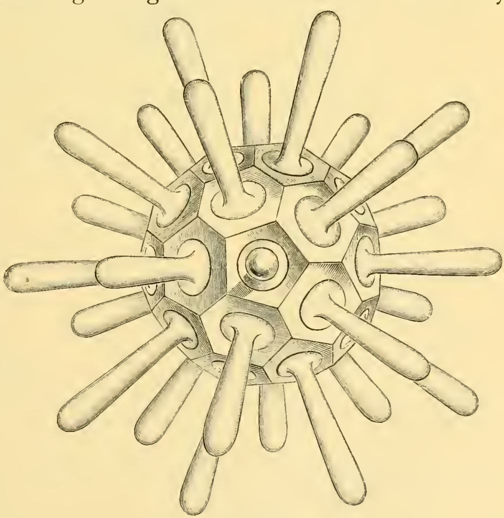


FIG. 109.
Rhabdosphæra claviger, Murray and Blackman. From the surface ($\frac{2000}{1}$).

Figs. 108 and 109) characteristic of tropical and sub-tropical regions, and the siliceous diatoms characteristic of extra-tropical regions. While the diatom remains are so abundant in the deposits of the Southern Ocean and of the North Pacific as to form a distinct deposit-type (Diatom ooze), the remains of the pelagic calcareous algæ are always overshadowed by the abundance of

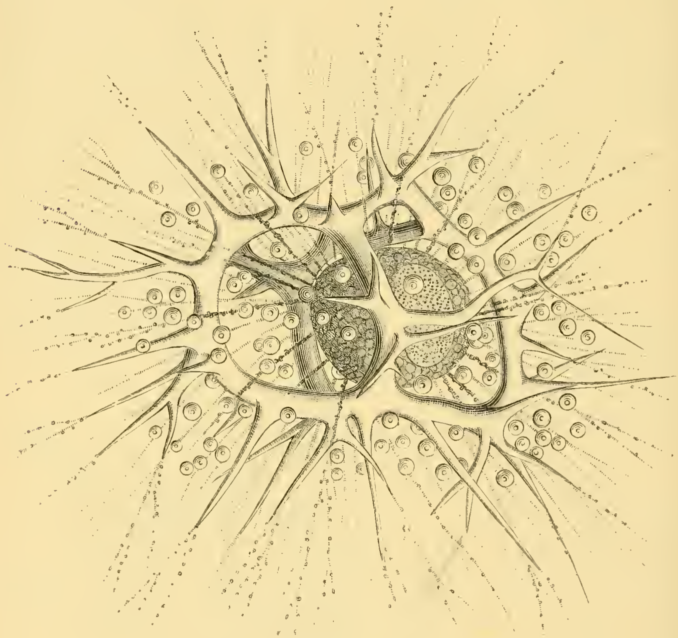


FIG. 110.
Eucoronis challengeri, Haeckel. From the surface (magnified).

the remains of pelagic foraminifera and mollusca in the deposits of the warmer regions of the ocean. These pelagic calcareous algæ are so fragile in texture, that it is principally their broken-down parts (coccoliths and rhabdoliths) that occur in the deposits; in certain favourable localities coccospheres of small size may be fairly numerous, but rhabdospheres are practically unknown in deep-sea deposits, being apparently easily dismembered, and the same remark seems to apply to the large-sized coccospheres.

Traces of albuminoid organic matter may be found in most Albuminoid matter.

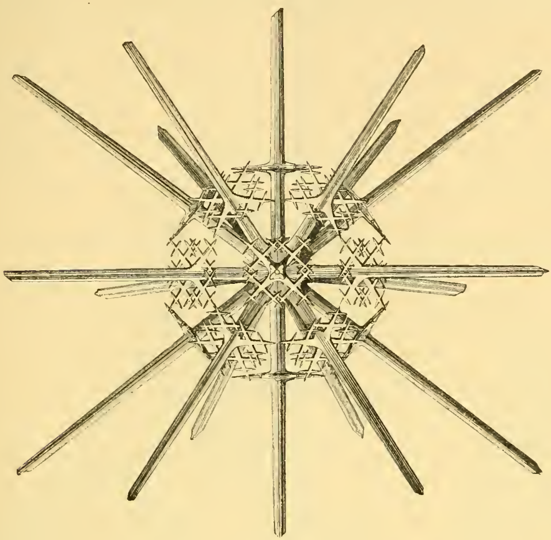


FIG. 111.
Stauracantha murrayana, Haeckel. From the surface (magnified).

deep-sea deposits, especially in the neighbourhood of land, and

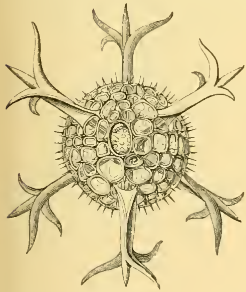


FIG. 112.
Hexancistra quadricuspis, Haeckel.
From the surface (magnified).

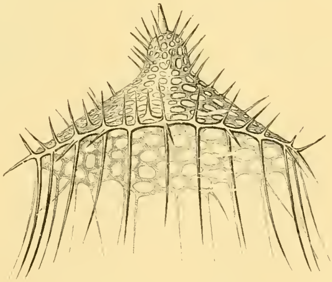


FIG. 113.
Lampromitra huxleyi, Haeckel.
From the surface (magnified).

may be either of animal or vegetable origin ; a greenish organic matter is generally associated with the glauconite in the Green sands. The benthonic deep-sea animals live by eating the mud or ooze covering the ocean-floor, and appear to find all the

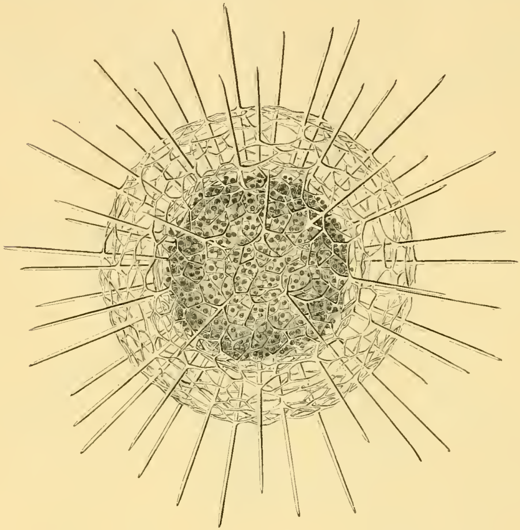


FIG. 114.
Haliomma wyvillei, Haeckel. From the surface (magnified).

nourishment they require therein. The excreta of these animals are associated with a certain amount of slimy albuminoid matter, and in certain localities these excreta become so numerous that the term "coprolitic mud" has been proposed for the deposits containing them.

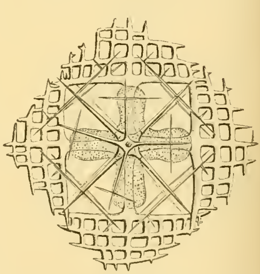


FIG. 115.
Lithoptera darwinii, Haeckel. From the surface (magnified).

Animal remains in marine deposits.

The animal remains found in deep-sea deposits are either siliceous or calcareous, those of a chitinous character being extremely rare, if not entirely absent.

Siliceous remains.

The siliceous remains of radiolaria (see Figs. 110 to 117) and the spicules of siliceous sponges are widely distributed over the ocean-floor, the radiolarian skeletons being so abundant in certain regions as to make up a very large part of the deposit, which is then called Radiolarian ooze; sponge spicules, though present in nearly every bottom-sample examined by us from deep and shallow water, very seldom take any considerable part in the formation of the deposits.

The calcareous remains of foraminifera, corals, alcyonaria, annelids, crustacea, echinoderms, bryozoa, molluscs, tunicates, and fishes seem to bulk more largely in deep-sea deposits than the siliceous remains. The Globigerina and Pteropod oozes and the Coral muds and sands owe their names to the abundance in

Calcareous remains.

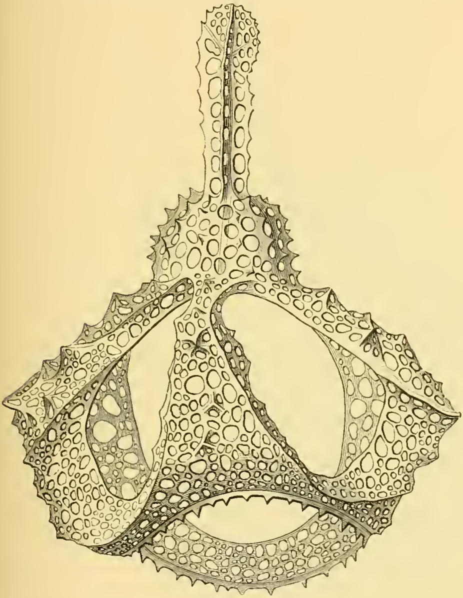


FIG. 116.
Clathrocanium reginæ, Haeckel. From the surface (magnified).

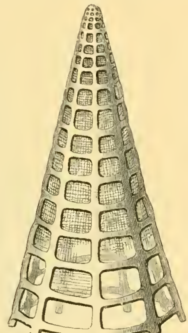


FIG. 117.
Cinclopyramis infundibulum, Haeckel. From the surface (magnified).

them of the remains of pelagic foraminifera (see Figs. 118 to 121), of pelagic molluscs (Figs. 122 and 123), or of coral fragments, while the valves of ostracods (Figs. 124 and 125), the spines of echinoids, the spicules of alcyonaria and tunicates, and the otoliths of fishes are among the most constant of the calcareous remains occurring in the deposits, though rarely found in any great abundance. Reference may also be made to the teeth of sharks (see Figs. 126 and 127) and the earbones of whales (see Figs. 128 and 129) found occasionally in all deposits, but characteristically in the Red clay areas especially of the

Pacific Ocean, which have evidently lain there for a long period

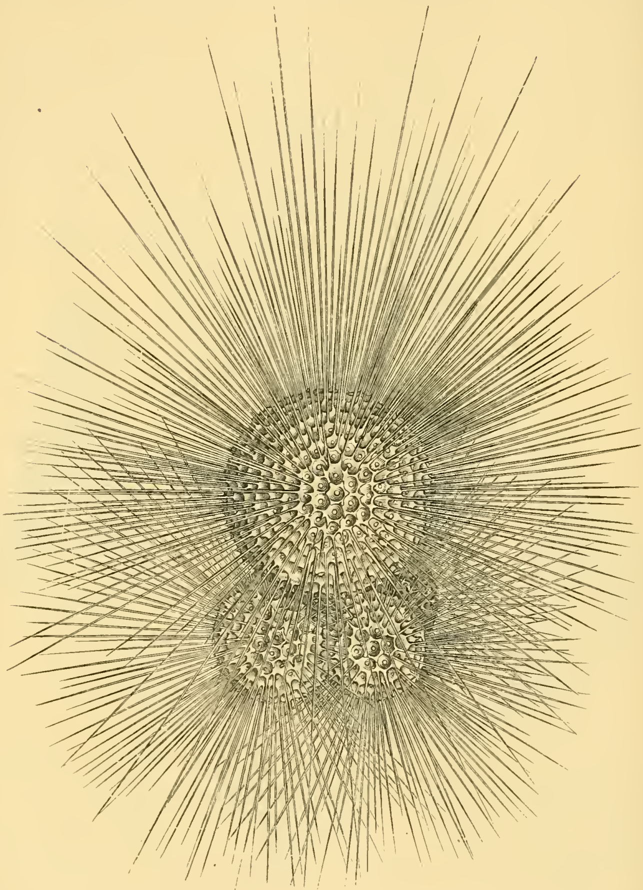


FIG. 118.

Globigerina bulloides, d'Orbigny. From the surface (magnified).

of time, having become much decomposed or deeply impregnated, and in many cases thickly coated, by the peroxides of manganese and iron. It is remarkable how very few fish bones other than teeth and otoliths occur in marine deposits.

Materials of inorganic origin.

The inorganic materials entering into the composition of deep-sea deposits may be conveniently considered under three

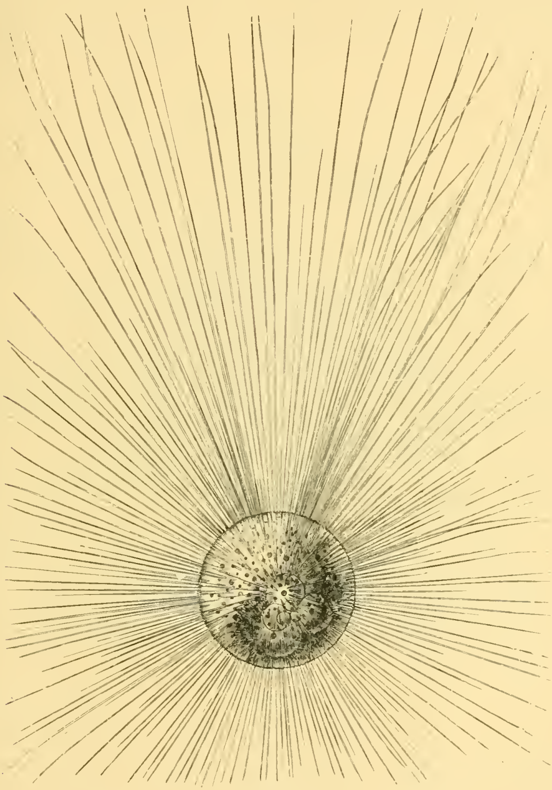


FIG. 119.
Orbulina universa, d'Orbigny. From the surface ($\frac{50}{1}$).

heads: (1) terrestrial, (2) extra-terrestrial, and (3) secondary or chemical products.

Terrestrial materials.

The terrestrial materials are either of volcanic or continental origin, the former being derived from submarine and subaerial eruptions, and, by reason of their areolar structure, widely distributed over the ocean-floor, the latter being derived from the disintegration of continental land through atmospheric and physical agencies and distributed in comparatively close proximity to that land. Of volcanic products the most characteristic is pumice, which may float for a long time in the surface waters of

Volcanic products.

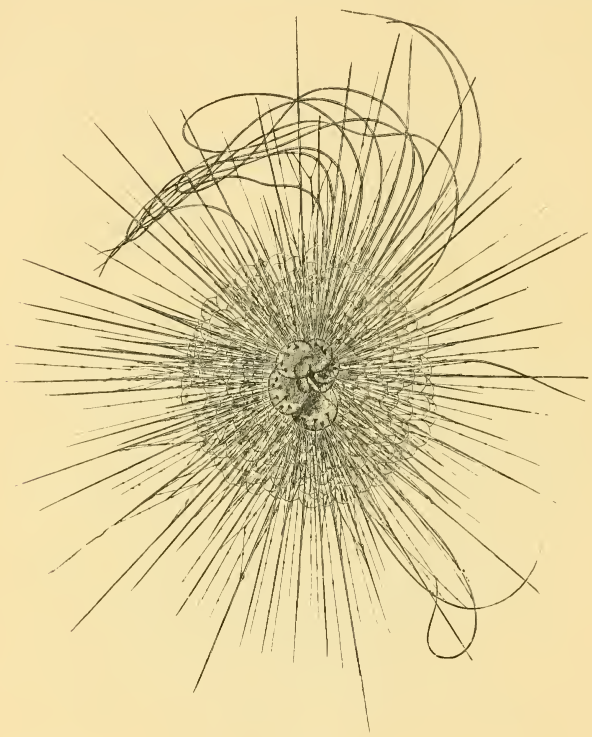


FIG. 120.
Hastigerina pelagica, d'Orbigny. From the surface ($\frac{10}{1}$).

the ocean and may be carried far from its original source before finally becoming water-logged and sinking to the bottom. While floating on the surface these stones are knocked against one another by the waves, and the broken-off fragments fall to the bottom. Three varieties of pumice have been recognised among the fragments from the sea-bottom: liparitic, basaltic or basic, and andesitic. After pumice, the most striking volcanic products are fragments of basic volcanic glass (sideromelan) nearly always partly, sometimes entirely, decomposed and altered into palagonite, together with palagonitic tufas, generally associated with the deposition of the peroxides of manganese and iron, besides basaltic and other lapilli and volcanic ashes. Great slabs have been dredged showing sometimes distinct

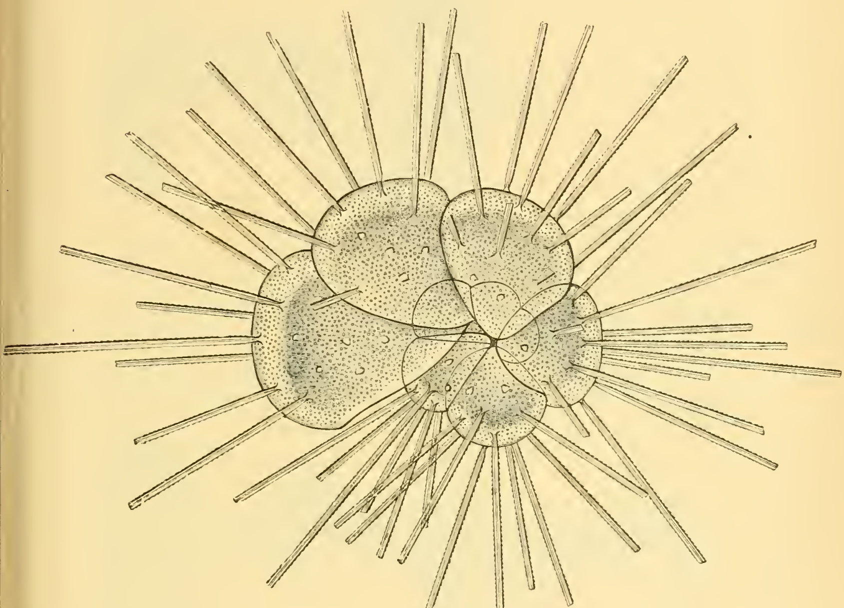


FIG. 121.
Hastigerina pelagica, d'Orbigny. From the surface ($\frac{50}{1}$).

layers produced by showers of volcanic ashes. Minerals of volcanic origin (volcanic dusts) may be carried great distances by the winds, and ultimately find a resting-place on the bottom of the sea.

Continental products.

The continental products consist of fragments of continental rocks and the minerals derived from their disintegration, the characteristic mineral species being quartz. The rock-fragments are usually found only in close proximity to the continental land-masses, though exceptionally found in deep water far from land in those regions of the ocean affected by floating icebergs. The dust from deserts, like volcanic dusts, may be carried by wind to great distances from land, and can be detected in deep-sea deposits, for instance, off the west coast of Africa.

Extra-terrestrial materials.

The materials of extra-terrestrial origin, though extremely interesting, do not bulk largely in marine deposits; indeed they are rather of the nature of rarities, and are noticed most abundantly in Red clay areas where, for many reasons, it is believed the rate of deposition is at a minimum. They consist of minute black metallic spherules and brown chondritic spherules, which may be extracted by the aid of a magnet when the Red clay deposit is reduced to a fluid condition by admixture of water. The black spherules (see Figs. 130 and 131) sometimes have a shining metallic nucleus of native iron (or an alloy of iron, cobalt, and nickel), surrounded by a shell of brilliant magnetic oxide of iron, to which the magnetic properties of the spherules are due. The brown spherules (see Figs. 132 and 133) have the lustre of bronze externally, and have a finely lamellated crystalline structure, with blackish-brown inclusions of magnetic iron, which account for their extraction by the magnet. A cosmic

Cosmic spherules.

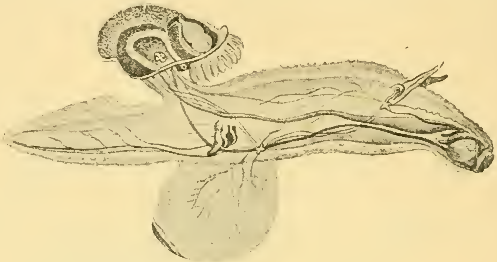


FIG. 122.
Carinaria lamarckii, Pèr. and Les. (From Steuer.) The fragile shells of this species are occasionally met with in deep-sea deposits.

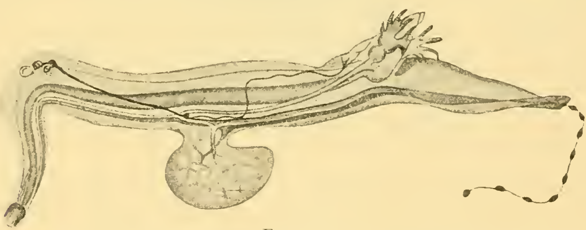


FIG. 123.
Pterotrachea coronata, Forsk. (From Leuckart, after Steuer.) This species has no shell, and therefore does not enter into the composition of deep-sea deposits.

origin is attributed to both forms of magnetic spherules, which are supposed to have been thrown off by meteorites, or falling stars, in their passage through our atmosphere.

Secondary products.

The secondary products entering into the composition of deep-sea deposits are (1) clay, (2) manganese nodules, (3) barium and barium nodules, (4) glauconite, (5) phosphatic concretions, and (6) zeolites.

FIG. 124.
Krithe producta, Brady. From the bottom-deposits (magnified).

Clay.

The clayey matter in the deposits near land may have been transported by rivers, etc., from the land, but most of the clayey matter present in the deposits far from land is believed to have been derived from the decomposition under the action of water of eruptive and metamorphic rocks and minerals, especially pumice and volcanic glass. The deep-sea clays, some of which are mostly made up of these decomposing volcanic materials, are usually coloured a reddish-brown by the oxides of manganese and iron—products of the decomposition of the same rocks that gave rise to the clayey matter—and a comparatively small amount of clay may give a clayey character to the deposit.

FIG. 125.
Cythere dictyon, Brady. From the bottom-deposits (magnified).

Manganese nodules.

The oxides of iron and manganese are widely distributed in marine deposits, and especially in deep-sea deposits. They occur in minute grains, and act as colouring matter in nearly all deep-sea clays, and in certain abyssal regions of the ocean they form concretions of larger or smaller size, which are among the most striking characteristics of the oceanic Red clay. Sometimes the oxides cover consolidated masses of tufa, fragments of rocks, portions of the deposit, branches of coral and other calcareous remains, or form irregular concretionary masses, though the commonest form is that of more or less rounded nodules (see Figs. 134 and 135), which at any one station have a general family resemblance and differ in form and size from those taken at another station, looking like marbles at one place, like potatoes or like cricket balls at other places. Generally the nodules are concretions formed around a nucleus, con-

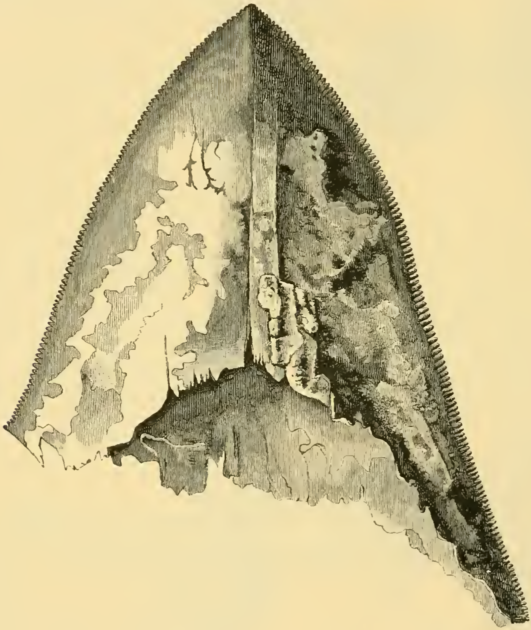


FIG. 126.—TOOTH OF *CARCHARODON MEGALODON*.
"Challenger" Station 281, South Pacific, 2385 fathoms.

sisting of a shark's tooth or whale's earbone, or portions of teeth or bone, a piece of pumice or fragment of volcanic glass, etc., though sometimes no nucleus could be detected. These nodules of iron and manganese are classed with the impure variety of manganese known as wad or bog manganese ore, and the greater part of the manganese and iron is believed to have been derived directly, along with clay, from the alteration of the rock-fragments and mineral particles containing manganese and iron, especially of those of volcanic origin, which are spread over the ocean-floor. Where basic volcanic rocks are in process of decomposition, manganese nodules may be relatively abundant in shallow water, and they are never numerous in Globigerina oozes, except where volcanic material is present in some abundance in the deposit.

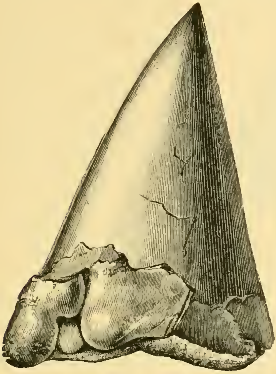


FIG. 127.—TOOTH OF *OXYRHINA TRIGODON*.
"Challenger" Station 276, Tropical Pacific, 2350 fathoms.

Sulphate of barium has been found to be present in most marine deposits and in manganese nodules in small quantities; in terrigenous deposits up to about 0.1 per cent, in manganese nodules slightly more, and in Red clays up to about 1 per cent. Small round nodules have been trawled off Colombo, in 675 fathoms, containing 75 per cent of barium sulphate. Barium.

Glauconite occurs in the terrigenous deposits typically in the form of minute rounded grains of a greenish colour, usually associated with greenish or brownish casts of calcareous organisms (foraminifera, etc.); in fact, the rounded Glauconite.

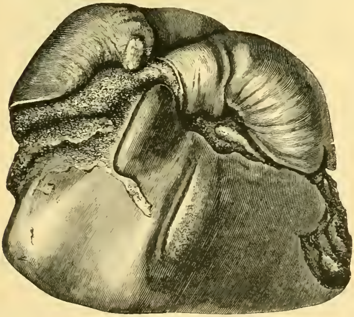


FIG. 128.—PETROUS AND TYMPANIC BONE OF *ZIPHIUS CAVIROSTRIS*.
"Challenger" Station 286, South Pacific, 2335 fathoms.

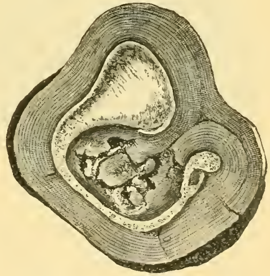


FIG. 129.—SECTION OF A MANGANESE NODULE, SHOWING A TYMPANIC BONE OF *MESOPLODON* IN THE CENTRE.
"Challenger" Station 160, Southern Ocean, 2600 fathoms.

green grains are supposed to be casts which have lost all trace of the enveloping calcareous chambers. The individual grains of glauconite do not exceed one millimetre in diameter, though occasionally they are cemented into nodules, several centimetres in diameter, by a phosphatic substance; the grains are always rounded, often mammillated, hard, dark green, or nearly black, with sometimes a dull and sometimes a shining surface. Mixed with the rounded grains are pale green, pale grey, white, yellow and brownish internal casts of the cavities and chambers of calcareous organisms, often associated with an amorphous organic matter of a brownish-green colour.

FIG. 130.—BLACK SPHERULE WITH METALLIC NUCLEUS ($\frac{60}{1}$).
"Challenger" Station 285, South Pacific, 2375 fathoms.

FIG. 131.—BLACK SPHERULE WITH METALLIC NUCLEUS ($\frac{60}{1}$).
"Challenger" Station 9, North Atlantic, 3150 fathoms.

Glauconite is principally developed in the interior of foraminiferous shells and other calcareous structures, the initial stages in the formation of glauconite being probably due to the presence of organic matter in the interior of these shells. Glauconite is

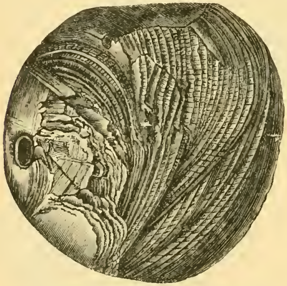


FIG. 132.—SPHERULE OF BRONZITE ($\frac{25}{1}$).
"Challenger" Station 338, South Atlantic, 1990 fathoms.

FIG. 133.—A LAMELLA OF A SPHERULE OF BRONZITE (highly magnified).
"Challenger" Station 338, South Atlantic, 1990 fathoms.

always associated with terrigenous mineral particles and rock-fragments, the decomposition of which, under the action of sea-water, would yield the chemical elements subsequently deposited in the form of glauconite in the chambers of foraminifera and other calcareous organisms. The excreta of echinoderms appear sometimes to be converted into glauconite.

Phosphatic concretions.

Associated with the glauconite in certain localities, more especially off the Cape of Good Hope and off the Atlantic coast of the United States, irregular concretions, largely made up of phosphate of lime, have been dredged. The concretions vary greatly in size and form, with a greenish or brownish glazed external surface, and are made up of heterogeneous fragments derived from the deposit containing the concretions (grains of glauconite and other minerals or remains of organisms), cemented by phosphatic material, which constitutes the principal part of the concretions. When the cemented particles are purely mineral, the phosphatic matter acts simply as a cement, but when the remains of calcareous organisms are included in the concretions, the phosphatic material plays a more important part, filling the internal chambers, and often the calcium carbonate of the shell is pseudomorphosed into calcium phosphate. When the filling up of a foraminifer, for example, and the pseudomorphism of its shell, are complete, the phosphate, attracted around this little centre continues to be added at the surface, and thus a phosphatic granule is formed, the external appearance of which no longer recalls that of the organism around which the phosphate has grouped itself. These phosphatic concretions occur chiefly along coasts bathed by waters subject at times to great and rapid changes of temperature, which cause the destruction on a large scale of marine life, the decomposition of the organic remains, sometimes thickly covering the sea-floor in such localities, giving rise to the phosphate of lime to be permanently fixed in the phosphatic nodules.

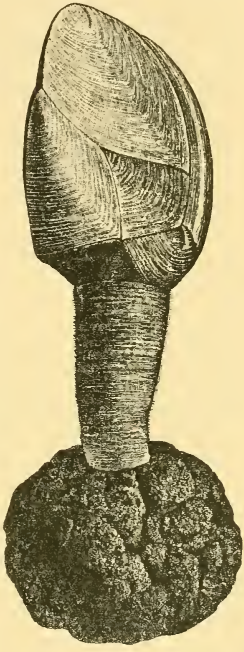


FIG. 134. — MANGANESE NODULE WITH *SCALPELLUM DARWINII* GROWING ON IT.
"Challenger" Station 299, South Pacific, 2160 fathoms.

Phillipsite.

Just as the silicate glauconite occurs in the terrigenous deposits, and is supposed to be a secondary product derived from the decomposition of continental rock fragments, so the silicate phillipsite occurs in the pelagic deposits, and is supposed to be a secondary product derived from the decomposition of volcanic rock fragments. Phillipsite is found in the various kinds of deposits in the deep water of the Central Pacific and Central Indian Ocean far from land, and is most abundant in some Red clay areas. It occurs in crystalline form, either as simple isolated microliths, crossed twins, irregular groups, or aggregated into spherolithic groups in which these zeolitic crystals are entangled together so as to form crystalline globules of sufficient size to be distinguished by the naked eye. The distribution of these crystals of phillipsite coincides with that of basic volcanic glasses and basaltic lapilli over the ocean-floor, the decomposition of which, under the action of sea-water, would give rise to the materials afterwards deposited in a free state as zeolitic crystals and aggregates.

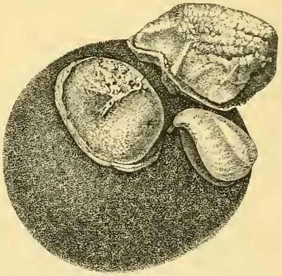


Fig. 135.—Manganese Nodule with two Tunicates and a Brachiopod attached.

"Challenger" Station 160, Southern Ocean, 2600 fathoms.

Radio-active substances.

Professor Joly has examined for their radium contents a number of deposit-samples supplied by Sir John Murray. He finds that the deep-sea deposits are much richer in radium than the average terrestrial rocks. The Red clays and the Radiolarian oozes, which are laid down in deep water far from land, contain much more radium than the calcareous deposits like the Pteropod and Globigerina oozes. The radio-activity and percentage of calcium carbonate in the deposits stand in an inverse ratio to each other, and the Blue muds contain less than the calcareous oozes, though more than the continental rocks. It seems evident that the quantity of radio-active substances, of manganese nodules, with earbones of whales and sharks' teeth, of zeolitic crystals and cosmic spherules, is greatest where, for other reasons, we believe the rate of deposition to be least.

Deep-sea deposit types.

In the neighbourhood of emerged land the material derived from that land is spread over the sea-floor, becoming finer and finer in texture with greater distance and depth, whereas in the central regions of the great ocean basins land-detritus may be almost totally absent from the deposits, while the calcareous and siliceous shells and skeletons of pelagic or plankton organisms may greatly predominate. This fact affords a ready means of dividing marine deposits into two main classes, viz. *Terrigenous Deposits*, largely made up of detritus derived directly from emerged land, with the remains of benthonic organisms, and *Pelagic Deposits*, containing little if any land-detritus, but largely made up of the remains of pelagic organisms. The former class of deposits must therefore form a border, varying in extent according to circumstances, around all the land-masses and islands of the world, while the latter class of deposits occurs in those regions so far removed from the land-masses and islands that very little material derived directly from the land can reach the position where they are found. The dividing lines between these two classes of deposits, and between the various types included in them, are not sharply defined, but the different kinds of deposits merge gradually the one into the other, so that frequently two names, and in some cases even three names, might equally well be applied to the same sample. It is the terrigenous deposits laid down in close proximity to the land, and in enclosed seas like the Mediterranean, that are represented in the geological series of rocks, but it is extremely doubtful whether the pelagic deposits laid down in deep water far from land have any analogues among the geological strata.

Classification.

After a careful study of all the available samples, Murray and Renard gave the following classification of marine deposits :—

MARINE DEPOSITS

1. Deep-Sea Deposits, beyond 100 fathoms.	Red clay Radiolarian ooze Diatom ooze Globigerina ooze Pteropod ooze	I. Pelagic Deposits formed in deep water removed from land.
	Blue mud Red mud Green mud Volcanic mud Coral mud	II. Terrigenous Deposits, formed in deep and shallow water close to land-masses.
2. Shallow-Water Deposits, between low water mark and 100 fathoms.	Sands, gravels, muds, etc.	
3. Littoral Deposits, between high and low water marks.	Sands, gravels, muds, etc.	

Terrigenous deposits.

The Terrigenous Deposits are characterised, as already stated, by the abundance of land-detritus, and are subdivided into the following types, viz. :—

Blue mud.

Blue Mud.—This is the predominant type of deposit in the neighbourhood of continental land, and is principally made up of land-detritus (quartz being the characteristic mineral species), which becomes less and less abundant with increasing distance from the land, until the Blue mud passes gradually into one of the types of pelagic deposits.

Green mud and sand.

Green Mud is a variety of Blue mud, distinguished by the abundance of grains of glauconite usually associated with phosphatic concretions, and is found most characteristically on the continental slopes off high and bold coasts where currents from different sources alternate with the season, as off the Cape of Good Hope, off the east coast of Australia, off Japan, and off the Atlantic coasts of the United States. In the lesser depths the amount of clayey and muddy matter decreases and the deposits are called *Green Sands.*

Red mud.

Red Mud is a local variety of Blue mud found in the Yellow Sea and off the coast of Brazil, where the great rivers bring down a large amount of ochreous matter, to which the deposit owes its colour and its name.

Volcanic mud and sand.

Volcanic Mud occurs off those coasts and islands where volcanic rocks prevail ; the volcanic mineral particles are larger and more abundant in the shallower water near the land, and the deposits there are called *Volcanic Sands.*

Coral mud and sand.

Coral Mud is found in the vicinity of coral reefs and islands ; fragments derived from the disintegration of the reefs are larger and intermixed with less fine material in the lesser depths, and the deposits are then called *Coral Sands.*

Pelagic deposits.

The Pelagic Deposits are characterised by the fact that, with the exception of Red clay, their composition is largely determined by the pelagic or plankton organisms, which secrete hard shells either of calcium carbonate or of silica, the predominance of the remains of one or other of these classes of organisms giving the names to the deposits. In fact, the deposits may be divided into those that are calcareous and those that are siliceous, the calcareous deposits (Globigerina ooze and Pteropod ooze) being characteristic of tropical and subtropical regions, where there is abundant secretion of calcium carbonate by plankton organisms, the siliceous deposits (Diatom ooze and Radiolarian ooze) being characteristic of polar and other regions, where there is a large admixture of clayey matter in the surface waters, and where there is abundant secretion of silica by the plankton organisms. Over wide areas in very deep water, however, neither calcareous nor siliceous remains predominate; the basis of the deposit then becomes Red clay, consisting of clayey matter derived from the decomposition of volcanic materials; quartz particles, so abundant in terrigenous deposits, are rare or absent.

FIG. 136.—PTEROPOD OOZE.
"Valdivia" Station 208, Indian Ocean, lat. 6° 54′ N., long. 93° 28′.8 E., 162 fathoms (magnified).

The pelagic deposits are subdivided into the following types, viz. :—

Pteropod ooze.

Pteropod Ooze.—In the shallower waters, usually far from continental land, on oceanic ridges and cones, especially within coral reef regions where warm water with small annual range occupies the surface, almost every surface organism which secretes a hard shell or skeleton is represented in the deposit, the dead shells of pteropods and heteropods being characteristic, and the deposit is hence called Pteropod ooze (see Fig. 136). About 35 species of pteropods and 32 species of heteropods, as well as pelagic gasteropods (see pp. 172-173), are known to live in the surface waters of the tropics, and

FIG. 137.—GLOBIGERINA OOZE.
"Valdivia" Station 45, Atlantic, lat. 2° 56′.4 N., long. 11° 40′.5 W., 2728 fathoms (magnified).

the shells of all these species may occur in the Pteropod ooze, but the extent of this type of deposit is not great. Shelled pteropods, except *Limacina*, are not found in the polar oceans.

Globigerina ooze.

Globigerina Ooze.—The average depth of the ocean is about 2000 fathoms, and the most widely distributed of the deposits in these average depths is Globigerina ooze (see Figs. 137 to 139), which is made up largely of the dead shells of surface foraminifera, the genus *Globigerina* often greatly predominating, hence the name. About twenty species of pelagic foraminifera (see p. 172) inhabit the surface waters of the tropical oceans, and their dead shells are found in the Globigerina ooze[1] and also in the Pteropod ooze, but towards the Arctic and Antarctic regions only one or two dwarfed species occur in the surface and subsurface waters. In very deep water, even within the tropics, the calcareous shells do not accumulate on the bottom,

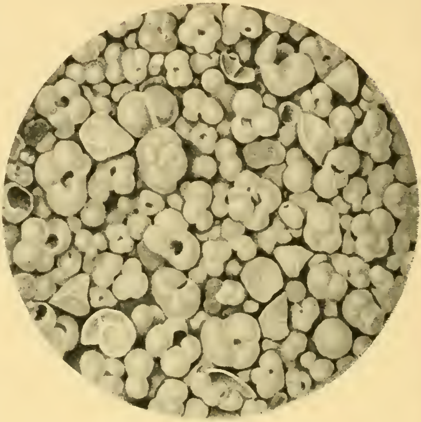


FIG. 138.—GLOBIGERINA OOZE.
"Valdivia" Station 162, Southern Ocean, lat. 43° 44'.4 S., long. 75° 33'.7 E., 1878 fathoms (magnified).

FIG. 139.—GLOBIGERINA OOZE.
"Valdivia" Station 154, Southern Ocean, lat. 61° 45'.2 S., long. 61° 15'.9 E., 1940 fathoms (magnified).

[1] The names "Biloculina clay" and "Orbulina ooze" will be found in the literature of marine deposits, but these have been described from samples which had been passed through fine sieves, the larger shells having been retained while the smaller ones had passed through the meshes.

being apparently removed through the solvent action of sea-water, and with increasing depth the Globigerina ooze passes gradually into another pelagic type, usually Red clay.

FIG. 140.—DIATOM OOZE.
"Valdivia" Station 140, Southern Ocean, lat. 54° 2′ S., long. 22° 13′.2 E., 2207 fathoms (magnified).

Diatom ooze.

Diatom Ooze.—We have indicated that in the colder regions of the ocean, as in the great circumpolar Southern Ocean and along the northern border of the Pacific, diatoms flourish abundantly in the surface waters, and where detrital matters are not very large in amount their dead frustules, falling to the bottom, make up a large part of the deposit called Diatom ooze (see Fig. 140).[1]

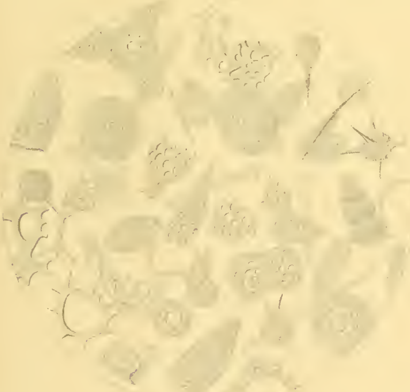


FIG. 141.—RADIOLARIAN OOZE.
"Valdivia" Station 237, Indian Ocean, lat. 4° 45′ S., long. 48° 58′.6 E., 2772 fathoms (magnified).

Radiolarian ooze.

Radiolarian Ooze (see Fig. 141) has not been recorded from the Atlantic Ocean, but is characteristic of deep water in the tropical regions of the Pacific and Indian Oceans, where the surface waters have rather a low salinity and carry clayey matter in suspension. It may be regarded as a variety of Red clay containing

[1] It may be noted that Flint has recorded Diatom ooze from the tropical Pacific, but his samples have since been examined and classed by us as Radiolarian ooze.

many radiolarian skeletons. The frustules of diatoms and skeletons of radiolarians may occur in all deposits, but generally they do not become characteristic or predominant when calcareous shells are present in large numbers.

Red clay.

Red Clay is characteristic of great depths, say beyond 2700 fathoms (as Globigerina ooze is characteristic of moderate depths, between 1000 and 2500 fathoms), and is the most widely distributed of all the deep-sea deposits, covering a larger area of the sea-floor than any other deposit type. The basis of the deposit is the hydrated silicate of alumina, or clay, derived principally from the decomposition and disintegration of pumice and other volcanic products long exposed to the action of sea-water, often associated with secondary products derived from the same source, such as manganese-iron nodules and phillipsite crystals. Calcareous remains may be totally absent in the greatest depths, while in lesser depths the percentage of calcium carbonate may approach 30, and the deposit then passes gradually into Globigerina ooze. If the calcium carbonate in a Globigerina ooze or a Pteropod ooze be removed by weak acid, the residue resembles closely a Red clay. In other places the siliceous remains of radiolaria may increase to such an extent that the Red clay merges gradually into Radiolarian ooze. The rate of accumulation is evidently at a minimum in the Red clay areas, for the calcareous shells falling from the surface waters have been gradually removed in solution either before, or immediately after, reaching the bottom; the ear-bones of whales and teeth of sharks (some of them belonging to extinct species) are there found in the greatest profusion, impregnated with and coated by the peroxides of manganese and iron; and there also occur in greatest abundance (though always rare) minute metallic and chondritic spherules supposed to have fallen from interstellar space, and found there more abundantly simply because of the sparse deposition of other materials. Radio-active substances are also found more abundantly in Red clay than in any other marine deposit, or in any continental rocks.

Horizontal distribution.

A few facts relating to the horizontal distribution of marine deposits may now be indicated. The terrigenous deposits include a number of varieties, but as a whole they surround all continents and islands in all latitudes, and extend to varying distances from the shore. The Coral muds and sands included in this class are limited to the coral-reef regions of tropical and subtropical latitudes, and the presence of the calcareous shells of pteropods and heteropods and pelagic foraminifera in terrigenous deposits indicates approximately temperate or tropical latitudes; in the Arctic and Antarctic regions these shells are absent from the deposits. Green muds and sands appear to be limited to regions where there is a wide range of temperature in the surface waters of the ocean, while Red muds are limited to those localities where a large amount of ochreous matter is carried into the sea by rivers, and Volcanic muds and sands are limited to the neighbourhood of volcanic centres, both subaerial and submarine. But the most widely distributed of all the terrigenous types is Blue mud, which occurs in both the Arctic and Antarctic regions, and along the shores of continents and continental islands throughout the world, where not displaced by one or other of the varieties just mentioned.

Broadly speaking, the terrigenous deposits close to land in shallow water contain more and larger mineral fragments than those farther removed from the land and in deeper water. Where great rivers enter the sea the terrigenous deposits may extend very far seaward, and a Blue mud may occupy the whole of the continental slope, extending perhaps some distance out over the deep bed of the ocean. On the other hand, along high and steep coasts oceanic conditions may approach close to the shore, and a Blue mud may pass into a Green mud or into a Pteropod ooze, and finally into a Globigerina ooze along the continental slope.

Turning to the pelagic deposits, we find that Pteropod ooze is limited to the tropical and subtropical regions, usually in the neighbourhood of oceanic islands and on the summits and sides of submarine elevations; it is found in relatively shallow water, and covers a relatively small extent of the ocean-floor.

Globigerina ooze is much more widely distributed; in fact, it covers an area of the entire sea-floor second only to that occupied by Red clay, extending as far north as lat. 72° N. in the Norwegian Sea and as far south as lat. 60° S. in the South Atlantic. A Globigerina ooze from a tropical locality differs greatly from one taken towards the polar regions, for the tropical sample may contain the representatives of more than twenty species of pelagic foraminifera as well as many species of pelagic molluscs, whereas the polar sample would include only one or two species of pelagic foraminifera and no pelagic molluscs. Globigerina ooze is the predominant type of deposit in the North Atlantic, covering all the deeper parts of that ocean except for two areas of Red clay, and it is there found in much deeper water than in any other of the great ocean basins.

Diatom ooze occurs typically only in extra-tropical regions, forming a broad almost circumpolar band in the great Southern Ocean, outside the zone of Blue mud bordering the Antarctic continent, and a smaller band along the extreme northern border of the Pacific Ocean, along the Alaskan and British Columbian coasts of North America, and the Kamtchatkan and Japanese coasts of Asia and the intervening Aleutian Islands.

Radiolarian ooze covers the sea-floor in certain portions of the tropical regions of the Pacific and Indian Oceans, being apparently entirely unrepresented in the Atlantic; it occurs in a band of varying width in the equatorial eastern Pacific, approaching comparatively close to the shores of Central America, and in other smaller isolated areas.

Red clay is the most characteristic and most extensive of the pelagic deposits, occupying the deepest portions of the great ocean basins except in the polar regions, extending beyond lat. 50° N. and S. in the Pacific, and between lat. 40° N. and S. in the Atlantic. It is the typical deposit of the great Pacific Ocean, attaining there its maximum development, and being associated over wide areas with the characteristic manganese nodules; in the Indian Ocean it is also associated with much manganese, and therefore usually of a dark chocolate colour, while in the Atlantic it is generally intermixed with less manganese and usually of a light red-brown colour.

Vertical distribution.

As regards the vertical distribution of the deposits, we have already indicated how gradual is the transition between the various types and classes, so that frequently two or more names might be used to characterise samples from the border regions. It is therefore evident that no definite limits of depth can be assigned to the different types of deposits, but their general distribution may be broadly outlined.

The terrigenous deposits have for their upper limit the shore-line, while their lower limit varies according to local conditions. We have already pointed out that in certain localities Blue mud may be restricted to the continental slope within depths less than 1000 fathoms, while in other localities it may extend far into the abysmal area in depths exceeding 2000 fathoms, and in some places approaching 3000 fathoms. Coral mud may extend into depths approaching 2000 fathoms before passing gradually into a Globigerina ooze, but sometimes it merges into Pteropod ooze in depths less than 1000 fathoms, while in the lagoons of coral islands it may be found in a few feet of water. Volcanic mud may be found extending into very deep water—in fact, some of the deepest Red clays might be called Volcanic muds, so abundant are the minute fragments of pumice and volcanic glass—but in the neighbourhood of volcanic islands the material from the land is generally masked by the accumulation of pelagic shells, and the Volcanic mud may pass into Pteropod ooze in depths of about 1000 fathoms, or into Globigerina ooze in depths of 1500 or 2000 fathoms. Green mud and Red mud generally occur in depths less than 1000 fathoms, the seaward limit being about 1300 or 1400 fathoms.

Of the pelagic deposits, Pteropod ooze is found in shallower water than any of the other types—from about 400 fathoms to about 1500 fathoms, its seaward limit being reached in about 1700 or 1800 fathoms. Globigerina ooze may be found in all depths from about 400 fathoms to over 3000 fathoms, but occurs typically in depths between about 1200 and 2200 fathoms, its deeper limit in the Pacific and Indian Oceans occurring at about 2800 or 2900 fathoms, while in the North Atlantic it is known in depths approaching 3500 fathoms. Diatom ooze occurs usually in depths of about 600 to over 2000 fathoms, but in the North Pacific it is found in depths of 4000 fathoms. Radiolarian ooze is a characteristically deep-water deposit, hardly known in depths less than 2000 fathoms, and covers the bottom at the greatest depths recorded by the "Challenger" and "Nero" in 4500 to over 5000 fathoms. Radiolarian ooze may, however, be regarded as a mere variety of Red clay, containing a notable proportion of these siliceous remains as a result of the favourable conditions in the surface waters. Red clay is the typical deep-water deposit, and covers wide areas in depths exceeding 2000 fathoms, occupying the sea-floor in all the "deeps" except in one or two cases in the North Atlantic, being displaced in certain parts of the Pacific and Indian Ocean by its variety, Radiolarian ooze.

Rate of deposition.

The rate of deposition of materials on the sea-floor is naturally beyond the range of direct measurement, at all events in deep water. The only observations bearing on this point have been recorded by Mr. Peake, who in 1903 on board the S.S. "Faraday" raised and repaired a telegraph cable lying in 2300 fathoms in lat. 50° N. and long. 31° W. in the North Atlantic. This same cable had been lifted from a depth of 2000 fathoms about 200 miles to the eastward in 1888 by

Mr. Lucas on board the S.S. "Scotia," and on portions of the cable recovered in 1903 being submitted to Mr. Lucas, he was quite convinced that no deterioration had taken place during the interval of fifteen years. This is ascribed to the fact that the cable when lifted in 1888 was covered by Globigerina ooze, which is believed to act as a preservative upon cables in contact with it. As in 1888 the cable had been submerged for thirteen years, this implies a rate of deposition of one inch of the deposit in some period less than thirteen years; but as the deterioration noted in the cable, especially in the hemp serving, had probably taken some years to effect, it is perhaps fair to assume a period of ten years for the accumulation of a layer of the deposit one inch in thickness, in the position referred to. Another cable lifted from the bed of the equatorial Atlantic (lat. 2° 47′ N., long. 30° 24′ W.) from a depth of 1900 fathoms in 1883, after having been submerged for nine years, was found to be in much better condition than the North Atlantic cables examined after having been laid for a similar period, and this is supposed to be due to the more rapid deposition of the Globigerina ooze in the warmer waters of the equatorial Atlantic than in the colder waters of the North Atlantic, so that the cable became more rapidly covered over by the Globigerina ooze.[1]

While, therefore, it may be assumed that the Globigerina ooze accumulates at the rate of about one inch in ten years in the central part of the North Atlantic in lat. 50° N., and at a still more rapid rate in the central part of the equatorial Atlantic, it would appear from the recent observations of the "Michael Sars" Expedition that the rate of deposition of sediment may be almost *nil* even at depths of 1000 fathoms in certain parts of the North Atlantic, where glaciated stones have been dredged in considerable quantities. Possibly, however, these glaciated stones may have been deeply covered by the ooze since the close of the glacial period, and may have been subsequently exposed by the action of deep tidal currents sweeping away the Globigerina shells from the top of a low ridge perhaps recently elevated by earth-crust displacements in the deep sea. We now know that tidal currents prevent the formation of muddy deposits on the top of the Wyville Thomson Ridge in depths of 250 to 300 fathoms, while just below the summit of the ridge on both sides mud is deposited.

[1] See Murray and Peake, *On Recent Contributions to our Knowledge of the Floor of the North Atlantic Ocean*, extra publication of the Royal Geographical Society, London, 1904, pp. 21 and 22.

As to the relative rate of accumulation of the different types of deposits, it may be assumed that the terrigenous deposits accumulate at a much more rapid rate than the pelagic deposits. Of the terrigenous deposits, the Blue muds situated near the mouths of large rivers may be supposed to accumulate at a relatively very rapid rate, for the various constituents of the mud show little trace of alteration, while the rate of deposition in the case of Green muds and sands must be much slower, since the mineral particles are generally profoundly altered, and there is an extensive formation of secondary products, like glauconite and phosphate of lime; Coral muds and sands appear to accumulate rapidly under certain conditions, and the same may be said of Volcanic muds and sands in the neighbourhood of active volcanoes, where the volcanic minerals are fresh and unaltered, but most of the deep-sea volcanic deposits far from land appear to accumulate at a relatively slow rate, for the volcanic particles show abundant traces of alteration accompanied by the deposition of manganese peroxide.

Of the pelagic deposits, the Globigerina and Pteropod oozes of tropical regions probably accumulate the most rapidly, from the greater variety of tropical pelagic species of foraminifera and molluscs, and the larger and more massive shells secreted in tropical as compared with extra-tropical regions. Diatom ooze appears to accumulate at a more rapid rate than Radiolarian ooze, since in addition to the siliceous remains it usually contains a considerable admixture of calcareous remains, but from all points of view it seems reasonable to suppose that the minimum rate of deposition of materials on the ocean-floor is reached in those characteristic Red clay areas farthest removed from continental land and in very deep water. The greater abundance of cosmic spherules, sharks' teeth, and ear-bones of whales, some of them belonging to extinct species, in the Red clays than in any other type of deposit, is ascribed to the fact that few other substances there fall to the bottom to cover them up. The state of profound alteration of the volcanic materials in the Red clay, accompanied by the secondary formation of clay, manganese nodules, and zeolitic crystals, is ascribed to the fact that these materials have lain for a long time exposed to the solvent action of sea-water. The presence of radio-active substances in this deposit, in much larger quantity than in other deposits, apparently also points to a very slow rate of deposition.

It may be stated generally, with reference to the horizontal

Distribution of calcareous remains in pelagic deposits.

distribution of calcium carbonate organisms, that they are most abundant both at the surface and at the bottom in warm tropical regions where the annual range of surface temperature is least. In the tropics the following genera and species of foraminifera are known to have a pelagic habitat, three or four of the species being rather doubtful :—

Pelagic species of foraminifera.

Globigerina sacculifera, Brady.
,, *æquilateralis*, Brady.
,, *conglobata*, Brady.
,, *dubia*, Egger.
,, *rubra*, d'Orbigny.
,, *bulloides*, d'Orbigny.
,, *inflata*, d'Orbigny.
,, *digitata*, Brady.
,, *cretacea*, d'Orbigny.
,, *dutertrei*, Brady.
,, *pachyderma* (Ehrenberg).
,, *marginata* (Reuss).
,, *linnæana* (d'Orbigny).
,, *helicina*, d'Orbigny.
Orbulina universa, d'Orbigny.
Hastigerina pelagica (d'Orbigny).
Pullenia obliquiloculata, Parker and Jones.
Sphæroidina dehiscens, Parker and Jones.
Candeina nitida, d'Orbigny.
Cymbalopora (*Tretomphalus*) *bulloides* (d'Orbigny).
Pulvinulina menardii (d'Orbigny).
,, *tumida*, Brady.
,, *canariensis* (d'Orbigny).
,, *micheliniana* (d'Orbigny).
,, *crassa* (d'Orbigny).
,, *patagonica* (d'Orbigny).

The following genera and species of shelled pteropods and heteropods are pelagic :—

PTERORODS

Pelagic species of pteropods.

Limacina inflata (d'Orbigny).
,, *triacantha* (Fischer).
,, *helicina* (Phipps).
,, *antarctica*, Woodward.
,, *helicoides*, Jeffreys.
,, *lesueuri* (d'Orbigny).
,, *australis* (Eydoux and Souleyet).
,, *retroversa* (Fleming).
,, *trochiformis* (d'Orbigny).
,, *bulimoides* (d'Orbigny).
Peraclis reticulata (d'Orbigny).
,, *bispinosa*, Pelseneer.
Clio (*Creseis*) *virgula* (Rang).
,, ,, *conica* (Eschscholtz).
,, ,, *acicula* (Rang).
,, ,, *chierchiæ* (Boas).
,, (*Hyalocylix*) *striata* (Rang).
Clio (*Styliola*) *subula* (Quoy and Gaimard).
,, *andreæ* (Boas).
,, *polita* (Craven).
,, *balantium* (Rang).
,, *chaptali* (Souleyet).
,, *australis* (d'Orbigny).
,, *sulcata* (Pfeffer).
,, *pyramidata*, Linné.
,, *cuspidata* (Bosc).
Cuvierina columnella (Rang).
Cavolinia trispinosa (Lesueur).
,, *quadridentata* (Lesueur).
,, *longirostris* (Lesueur).
,, *globulosa* (Rang).
,, *gibbosa* (Rang).
,, *tridentata* (Forskål).
,, *uncinata* (Rang).
,, *inflexa* (Lesueur).

HETEROPODS

Pelagic species of heteropods.

Carinaria cristata (Linné).
,, *fragilis*, St. Vincent.
,, *lamarckii*, Péron and Lesueur.
Carinaria depressa, Rang.
,, *australis*, Quoy and Gaimard.
,, *galea*, Benson.

Carinaria cithara, Benson.
,, *punctata*, d'Orbigny.
,, *gaudichaudii*, Eydoux and Souleyet.
,, *atlantica*, Adams and Reeve.
,, *cornucopia*, Gould.
Atlanta peronii, Lesueur.
,, *turriculata*, d'Orbigny.
,, *lesueurii*, Eydoux and Souleyet.
,, *involuta*, Eydoux and Souleyet.
,, *inflata*, Eydoux and Souleyet.
,, *inclinata*, Eydoux and Souleyet.
,, *helicinoides*, Eydoux and Souleyet.
,, *gibbosa*, Eydoux and Souleyet.
Atlanta gaudichaudii, Eydoux and Souleyet.
,, *fusca*, Eydoux and Souleyet.
,, *depressa*, Eydoux and Souleyet.
,, *rosea*, Eydoux and Souleyet.
,, *quoyana*, Eydoux and Souleyet.
,, *mediterranea*, Costa.
,, *violacea*, Gould.
,, *tessellata*, Gould.
,, *primitia*, Gould.
,, *cunicula*, Gould.
,, *souleyeti*, Smith.
Oxygyrus keraudrenii (Lesueur).
,, *rangii*, Eydoux and Souleyet.

The gasteropod genus *Ianthina* is also pelagic, while the species of coccolithophoridæ are very numerous.

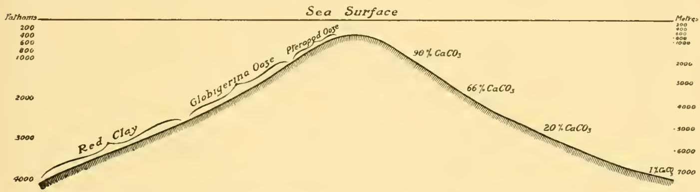


FIG. 142.—DIAGRAM SHOWING GRADUAL DISAPPEARANCE OF CALCIUM CARBONATE WITH INCREASING DEPTH.

The distribution of the dead shells of these pelagic organisms in different depths is peculiar and remarkable. If we suppose a cone to rise from a depth of 4000 fathoms up to within half a mile of the surface far from land in the warmer regions of the ocean (see Fig. 142), we shall find on the upper surface of this cone, and down its sides to about 1000 fathoms, nearly every shell of pelagic organisms represented in the deposit, even the smallest and most delicate. At about 1500 fathoms many of the thinnest and smallest shells will have disappeared, and the Pteropod ooze passes gradually into Globigerina ooze. At 2000 fathoms there may not be a trace of pteropods, and some of the more delicate foraminifera will also have disappeared. At 2500 fathoms the larger and thicker foraminifera shells still remain, and the deposit becomes a Red clay with some carbonate of lime. At 4000 fathoms not a trace, or little more than a trace, of these shells can be found, and chemical analysis does not show 1 per cent of calcium carbonate.

Disappearance of calcium carbonate with increase of depth.

Now it has been shown by hundreds of observations that in the surface waters the living animals are as abundant over the Red clay areas, where not a trace of their shells can be detected in the deposits, as over the Pteropod ooze areas, where every one of them may be found.

At about 2500 fathoms the percentage of calcium carbonate in the deposits apparently falls off more rapidly than at other depths. In some areas, as, for example, in the North Pacific, calcareous shells are not found in 2500 fathoms, while in the North Atlantic they are at the same depth sufficiently numerous for the deposit to be called a Globigerina ooze. Where the living organisms are most numerous in the surface waters, the dead shells are to be found at greater depths on the ocean's floor than elsewhere. Where cold and warm currents intermingle, shelled organisms are killed in large numbers, and the dead shells may be found in deeper water than in neighbouring regions.

Evidences of movements of the ocean-floor.

It must be remembered that while we know the crust of the earth on the continental areas to the depth of several thousands of feet, our knowledge of the crust under the oceanic areas is limited to one or two feet. Only in a few exceptional instances can we say that the sounding-tube has penetrated more than eighteen inches or two feet into the deposit. Sometimes, when the sounding-tube brings up a section over a foot in length, there are distinct indications of stratification.[1] Even in great depths there may be a Globigerina ooze overlying a Red clay in the deeper part of the section. This arrangement may be explained by supposing that the calcareous shells have been slowly dissolved from the deeper layers, but this explanation will not suffice when a Red clay occupies the upper and a Globigerina ooze the deeper layer of the section. This latter arrangement appears to indicate that a large block of the earth's crust may have subsided to the extent of several hundreds of feet—from a depth at which a Globigerina ooze had been formed in normal circumstances to a depth at which a Red clay is laid down at the present time.

Stratification in marine deposits.

There are not many cases on record of one type of deposit being superposed upon another distinct type, examples being more numerous of differences in colour and in composition in the different layers of the same type of deposit. Thus, in Blue

[1] From his examination of the samples collected during the German South Polar Expedition on board the "Gauss," Philippi believed that stratification on the sea-floor of to-day is not the exception but the rule, and that, where it seems to be wanting, the upper layer is probably thicker than the depth to which the sounding-tube penetrated.

muds it seems to be the rule that the upper portion should be thin and watery and reddish-brown in colour, in striking contrast with the stiff compact blue lower portion, and this is apparently due to the ferric oxide or ferric hydrate being transformed into sulphide and ferrous oxide in the deeper layers. Among our records there are seven cases of Red clay overlying Globigerina ooze, eight cases of Globigerina ooze overlying Red clay, three cases of Globigerina ooze overlying Blue mud, two cases of Globigerina ooze overlying Diatom ooze, and four cases of Diatom ooze overlying Blue mud; in twenty other cases the percentage of calcium carbonate was considerably higher in the upper portion of the deposit-samples than in the lower portion, while in six cases the lower portion was richer in calcareous remains than the upper portion.

Subsidence in oceanic areas.

Elevation in continental areas.

The examples of Red clay overlying Globigerina ooze point to subsidence in the region where they occur, and, indeed, there are many reasons for believing that the great earth-blocks in the oceanic areas for the most part undergo subsidence, while similar earth-blocks on the continents are, on the whole, subject to elevation.

3. Some Chemical Reactions in the Deep Sea

In Dittmar's well-known analysis of ocean-water[1] the acids and bases are arbitrarily combined, but it is now known that the dissolved substances in sea-water are not accurately represented by that table, inasmuch as they are present mainly as ions. The aggregate degree of ionic dissociation may be calculated from the freezing and boiling points of sea-water to be about 90 per cent. That is, only one-tenth of the total solids are present as salts pure and simple; but these must comprise not only those named by Dittmar but all the possible combinations of bases with acids, among which calcium and magnesium sulphates will be relatively in largest proportion. The bulk of the solutes, however, consists of ions, and it would be more rational to write the composition of sea-water thus:—

[1]

Sodium chloride	27.213 grams per litre.
Magnesium chloride	3.807 ,, ,,
Magnesium sulphate	1.658 ,, ,,
Calcium sulphate	1.260 ,, ,,
Potassium sulphate	0.863 ,, ,,
Calcium carbonate	0.123 ,, ,,
Magnesium bromide	0.076 ,, ,,
	35.000

Dissolved solids in sea-water as ions.

	Parts per 1000.	Percentage.
Na . .	10.722	30.64
Mg . .	1.316	3.76
Ca . .	0.420	1.20
K . .	0.382	1.09
Cl . .	19.324	55.21
SO_4 . .	2.696	7.70
CO_3 . .	0.074	0.21
Br . .	0.066	0.19
	35.000	100.00

Dittmar's item $CaCO_3$, which was presumably included in order to express the fact that there is on the whole an excess of bases over acids, is obviously incomplete as it stands. From the most recent measurements we gather that a 3 per cent sodium chloride solution, in equilibrium, as regards CO_2-tension, with air (which holds good approximately for sea-water), dissolves at 25° C. about 0.07 gr. of calcium carbonate per litre. Hence there cannot be as much as 0.13 gr. per litre in sea-water. The surplus base should rather be regarded as a mixture of calcium and magnesium bicarbonates, existing in equilibrium with a certain amount of free CO_2, and of the products of their hydrolytic dissociation, viz. calcium and magnesium hydroxides. It is the two latter which impart to sea-water its alkaline reaction.

On considering sea-water in its relation to submarine deposits we note that, of all possible combinations of cation with anion, there are three which are much less soluble than any others, and are therefore closest upon saturation and precipitation : these are calcium sulphate, calcium carbonate, and magnesium carbonate.

Calcium sulphate.

From what is known of the solubility of gypsum in brines, and allowing for the excess of SO_4, one would suppose that sea-water is very nearly saturated for this salt, and that addition of, for instance, a sulphate would precipitate it. But gypsum is unknown as a constituent of deep-sea deposits (unless of extraneous origin), so that its solubility-limit is evidently never exceeded under submarine conditions.

Calcium carbonate.

Calcium carbonate, on the other hand, occurs, as already stated, in enormous quantities at the bottom of the sea over wide areas. All the lime in it has been derived, by the aid of organic agencies, from the calcium held in solution by sea-water, whilst the carbonic acid owes its origin more or less indirectly to the atmosphere and to infra-oceanic respiration.

In considering by what agencies calcium carbonate may be precipitated from the sea, we can at once set aside two which are of importance in terrestrial geology, viz. removal of solvent by evaporation and change of temperature; neither are operative in adequate degree in the hydrosphere. Turning to chemical processes we note, in the first place, that the solubility of calcium carbonate in water is nearly proportional to the cube root of the CO_2-tension,[1] *i.e.* the amount of free CO_2 present in solution. Calcium carbonate as such is scarcely soluble at all, but in presence of CO_2 the bicarbonate $Ca(HCO_3)_2$ is formed, and this is soluble to a considerable extent. Hence, if CO_2 be abstracted, calcium carbonate will tend to come out of solution. Here we have what seems to be the *modus operandi* of calcareous algæ. The plant absorbs CO_2 by way of nutrition, precipitates calcium carbonate, and thus builds its skeleton. That this process takes place in fresh water, where the bicarbonate is the chief salt of calcium present, may be considered as established. The mosses *Hypnum*, *Eucladium*, *Trichostoma* are cases in point, as also *Chara*. These plants deposit coral-like growths, known to mineralogists as tufa and travertine. Many occurrences have been noted in the Yellowstone Park and other American localities. In some instances the calcium carbonate is aragonitic, as at Carlsbad. The calcareous algæ, which are well represented at the surface and at the bottom of the warmer oceans (coccolithophoridæ), no doubt secrete their skeletons in the same way as the fresh-water algæ enumerated.

But there is another far more important agency at work. Calcium carbonate must separate out if the product of the concentrations of its ions $Ca^{\cdot\cdot}$ and CO_3'' happens to exceed a certain definite limit. Small increases in the concentration of $Ca^{\cdot\cdot}$ ions may be disregarded, since their concentration is already considerable; but small local accessions of CO_3'' ions, which, in the shape of alkaline carbonate, may and do occur, are more effective. Marine animals generate, as ultimate products of the metabolism of their proteid food, ammonia and carbon dioxide. These combine to form ammonium carbonate, which in aqueous solution is largely dissociated into $NH_4^{\cdot}$ and CO_3'' ions; thus calcium carbonate is precipitated with liberation of ammonia, and a shell or coral growth may be formed. The reaction here described,

[1] Schloesing, *Comptes Rendus Acad. Sci. Paris*, vol. lxxv. p. 70, 1872; Bodländer, *Zeitschr. Phys. Chem.*, vol. xxxv. p. 23, 1900.

which, according to the older chemical notions, was expressed by the equation

$$(NH_4)_2CO_3 + CaSO_4 = CaCO_3 + (NH_4)_2SO_4,$$

seems to have been first suggested in this connection by Forchhammer, and was fully proved and worked out experimentally, with respect to marine organisms, by Murray and Irvine.[1] It accounts for the enormous amount of calcium carbonate at the bottom of the ocean, which once formed part of the tests or skeletons of living organisms. A limited amount of purely inorganic precipitation does, indeed, take place in coral reefs and some shallow-water deposits and in the Black Sea. In the Mediterranean, for instance, stone-like crusts are plentiful, consisting of clay cemented by calcium carbonate, which latter is produced by ammonium carbonate arising from the decay of organic matter in the mud below bottom-level meeting with fresh sea-water from above. We have further the lime-concretions of the Pourtales, Argus, and Seine banks, the "Challenger" casts of shells from the Great Barrier Reef,[2] and so on. But all these must be regarded as rarities. A great many of the reactions here referred to are believed to be ruled by enzymes and catalytic substances.

Whilst a great deal of calcium is thus being taken out of solution throughout the ocean, conversely the carbonate is continually being redissolved. Calcium and magnesium carbonates are held in solution mainly as bicarbonates; but since these compounds are incapable of existence in the solid state, questions of precipitation and dissolution, so far as they can be approached on theoretical grounds, must be decided by the solubilities of the normal carbonates. The solubility of $CaCO_3$ in water (foreign salts being absent), and the equilibrium of the various molecules and ions concerned, have been fairly thoroughly elucidated.[3] When $MgCO_3$ is also present and sea-water is the solvent, matters become so complicated that we cannot calculate, from first principles, how near sea-water is to saturation for calcium carbonate. There are, however, direct empirical data on this point. From the experiments of Anderson with natural, and of Cohen and Raken with artificial, sea-water, it would appear that with regard to $CaCO_3$, in the final stable modification of calcite, sea-water is saturated and incapable of taking up more, under conditions of stable equilibrium. Nevertheless the ocean does unquestionably dis-

[1] *Proc. Roy. Soc. Edin.*, vol. xvii. p. 79, 1889.

[2] Deep-Sea Deposits Chall. Exp., pp. 170, 172, 1891.

[3] Bodländer, *loc. cit.*

solve such calcium carbonate as it comes in contact with, especially dead shells and skeletons. Three reasons for this may be adduced :—

(1) There may be local accessions of CO_2, the dissolving power of which has already been referred to. The sarcode of molluscs and the albuminous binding material of their shells are decomposed, on the death of the animal, to CO_2 and ammonia, the former being much in excess. The solvent thus provided, in the case of any given shell-forming organism, can only, however, be small relatively to the calcareous matter present.

(2) The carbonate may be in a less stable, and therefore more soluble, form than calcite. This is eminently true of corals, which are mainly aragonitic. Some shells also are wholly or partially aragonitic, and marine aragonitic algæ occur, such as *Halimeda*. Sea-water saturated for calcite would, needless to say, be unsaturated for aragonite.

(3) It is a familiar fact that freshly precipitated calcium carbonate is much more soluble than the stable macrocrystalline modification. The older theory, which supposed the former to be basic or hydrated $CaCO_3$, seems open to doubt, since there is no sort of evidence that such compounds exist. More probably the abnormal solubility is due to the exceedingly small size of the particles. Above a certain limit of size, the concentration of saturated solutions of a solid is constant, whether the particles be large or small; below this limit the concentration becomes greater the smaller the particles, these stronger solutions being in perfectly stable equilibrium with solid particles of a definite magnitude. Experimental observations of this phenomenon, which may be an effect of surface-tension between solid and liquid, have in recent times been made on a variety of substances.[1] The limiting size for abnormal solubility is about 2μ diameter for gypsum, and will hardly be very different for calcium carbonate. It may be that what is called amorphous calcium carbonate is often merely calcite or aragonite in a state of extremely fine subdivision, whence the higher solubility. Abnormal solutions thus produced are of course supersaturated for larger particles, but there is evidence that they part with their surplus solute with extreme reluctance.

In all probability, then, the particles of calcium carbonate of organic origin in the sea, which are protected, during life, by albuminoid matter, go into solution, in the course of their post-mortem descent, by virtue of their minute size, and leave trails

[1] See Hulett, *Zeitschr. Phys. Chem.*, vol. xxxvii. p. 385, 1901.

of sea-water surcharged with lime. This lime, though in a metastable condition, finds no nuclei to deposit upon and remains in solution, being carried about until it reaches an area impoverished of lime by precipitation, when its condition becomes stable, or until it is itself reprecipitated by coming into the sphere of action of an ammonia-producing organism. Thus the ocean as a whole remains just about saturated for calcium carbonate.

Oceanic calcium undergoes extensive circulation between the dissolved and undissolved states. When calcareous fragments fall on a clayey or muddy bottom, they fall into water which can take up lime, and are dissolved as the water passes over them, while on falling on distinctively calcareous deposits like Pteropod ooze they fall into water-layers, immediately above the bottom, which can dissolve no more lime. In either case the lime depends for its redistribution on the slow processes of diffusion by convection and other currents. In those areas covered by Globigerina and Pteropod oozes lime is being steadily withdrawn from the ocean. Over Red clay areas, on the other hand, lime is being returned to the ocean. From the state of saturation of sea-water we may infer that the aggregate accessions of lime to the bottom exactly balance the aggregate supply from land and from the direct decomposition of submarine rocks. On the whole, lime at the present time appears to be accumulating towards the equator.

Magnesium carbonate.

Another element present in the sea, magnesium, shares the vicissitudes of calcium, but in a very minor degree. Magnesium, in contrast with calcium, is very prone to form hydrated and basic carbonates, and when the carbonate is precipitated from solutions of magnesium salts, it comes down not in the anhydrous crystalline form, but mainly as a trihydrate. Now solubility-determinations in pure water and in salt-solutions indicate that $MgCO_3$ as bicarbonate, in equilibrium with trihydrate, is of the order of ten times more soluble than $CaCO_3$. Hence the former is far less likely to be precipitated than the latter, even though there is about three times as much magnesium in the sea as calcium. Moreover, it is well known that magnesium carbonate is not readily brought down in presence of ammonia. Thus we find that in living shells, corals, and algæ the proportion of $MgCO_3$ to $CaCO_3$ is usually below 1 per cent. It is observed, however, that in dead carbonates, *e.g.* Coral sands and muds and calcareous oozes which have been for a long time at the bottom, there are markedly greater admixtures of magnesium.

This enrichment in magnesium is a familiar phenomenon at shallow depths, notably in and about coral reefs. It has also been shown on the basis of the "Challenger" analyses that bottom-deposits contain more $MgCO_3$ in proportion to $CaCO_3$ the less calcareous they are. Granted that accumulation of magnesium does take place, there are two explanations which have been offered, viz. (1) that deposited lime is dissolved away in preference to magnesia, and (2) that a kind of pseudomorphosis by the interaction of calcium carbonate and dissolved magnesium salts sets in. Both assume $MgCO_3$ to be less soluble than $CaCO_3$, and both may well hold good. Even if $MgCO_3$ were precipitated as trihydrate, it would sooner or later change into the anhydrous form, or rather into dolomite, that being the most stable and final form. Perhaps this transformation has already been effected in the shell. But dolomite is well known to be less soluble in carbonated water than calcite. As regards enrichment by accession of magnesia, this could only take place if sea-water were nearly saturated for $MgCO_3$, a matter which has not hitherto been put to the test; sea-water is certainly not saturated for the trihydrate, but it is conceivable that anhydrous calcium carbonate would determine the deposition of magnesium carbonate in the anhydrous form, which is relatively very insoluble. Now when calcium carbonate goes into solution, the concentration of CO_3'' ions in its neighbourhood is increased, whereby the solubility of any other carbonate is lowered; thus a precipitation of $MgCO_3$ might ensue. However, if this action were capable of taking place generally, we should expect a far larger percentage of magnesia in the purer calcareous oozes. On the whole, therefore, the enrichment in magnesia in deep-sea deposits proper is rather to be sought in preferential dissolution of lime.

The total magnesium carbonate at the bottom of the sea only amounts to a small percentage of the total calcium carbonate. Since the proportion of Mg to Ca, primarily in rocks and secondarily in river-waters, is much larger than this, it is clear that dissolved magnesium is accumulating in the ocean.

Another of the more important constituents of sea-water, Sulphur. sulphur, suffers transference, on a modest scale, from the sea to the bottom. Nowhere in the deposits of the open ocean has sulphur been found to occur as sulphate, but in those very extensive landward areas where Blue muds form the deposit there is always a small percentage of ferrous sulphide and of free sulphur, which are directly or indirectly derived from sea-water sulphates. In all deep-sea muds there is a certain amount of decaying animal and vegetable matter fallen from the hydrosphere, the proteids of which leave their sulphur, so far as it escapes oxidation, combined with the iron of the surrounding mud. But apart from this rather insignificant item, there are bacteria which, whilst living on sarcodic matter, seize on the dissolved sulphates of sea-water and reduce them to sulphides ; the latter react with whatever ferruginous material is present, and produce the highly insoluble compound ferrous sulphide. Free sulphur, when found, is to be accounted for by the partial oxidation of sulphides, either by dissolved oxygen or at the expense of ferric iron. The retention of sulphur in bottom-deposits can only occur where there is plenty of decaying organic matter, where the bottom-waters are stagnant, or nearly so, and not well aerated, and where there is not a copious hail of calcareous tests ; that is, mainly in the lower layers of muddy bottoms at shallow and medium depths. The sea-water imprisoned below the upper layer of mud becomes poorer in sulphate and richer in carbonic acid,[1] whilst the mud is darkened in colour by very finely-divided and easily oxidizable ferrous sulphide. Under suitable conditions the ferrous sulphide may, as in Black Sea muds,[2] combine with free sulphur and attain a condition of higher stability in the form of pyrites. The essential chemical factor which renders possible the retention of sulphur is the power of the colloidal ferric hydroxide in clay to react with sulphides. A small quantity of ammonium sulphide added, in the laboratory, to ordinary Red clay from the deep sea, at once goes into reaction: the clay is darkened to a tint resembling that of Blue mud ; the original tawny colour is restored by atmospheric oxidation ; the darkened clay evolves sulphuretted hydrogen with dilute acid. At the same time it is well to remember that many Blue muds owe their colour to quite other causes than the presence of sulphur.

The reduction of sulphates occurs only where there is a continuous deposition of detritus, and takes place, in the submarine muds, in the deeper layers. Consequently under normal conditions precipitated sulphur does not perform a cycle between bottom and sea, but remains irrevocably buried, accumulating as the deposit accumulates. No attempt seems hitherto to have been made to determine the ferrous sulphide in marine muds, but it is probably very minute in amount.

[1] Murray and Irvine, *Trans. Roy. Soc. Edin.*, vol. xxxvii. p. 481, 1893.
[2] Murray, *Scott. Geogr. Mag.*, vol. xvi. p. 673, 1900.

Free sulphur has been found in a maximum of 0.003 per cent in oceanic deposits,[1] although inland and estuarine deposits may contain rather more. We may therefore take it that the aggregate influx of oxidized sulphur into the ocean greatly exceeds the fixation of reduced sulphur at the bottom.

The elements silicon (as hydrated silica) and phosphorus (as calcium phosphate) are transported by biological agencies from the sea to the bottom, the former in large, the latter in small, quantities. The compounds referred to are capable of existing in solution in sea-water only to an infinitesimal extent, so that all the silicic and phosphoric acids carried into the ocean must eventually find their way to the bottom.

The silica of organic origin in deep-sea deposits, which of Silica.
course represents but a tiny fraction of the total silica present, is peculiar in having been derived not only from dissolved, but also from suspended, silicates.[2] It takes the form of tests and skeletons characterising the important Diatom ooze and Radiolarian ooze areas, and of sponge spicules, which are ubiquitous but nowhere concentrated enough to give rise to a definite deposit. Chemically, this silica is in the hydrated colloidal condition not unlike opal. By what process the siliceous organisms convert their intake of dissolved silica and floating clay into structural silica is not clearly known; as regards the former, it is evident that the organisms possess some means of coagulating to a hydrogel the silica which they receive either as SiO_3'' ions or as a hydrosol of silicic acid; whilst their argillaceous food is probably decomposed by some acid juice with elimination of alumina in solution and eventual deposition of coagulated silica. During life, siliceous tests are protected from dissolution by an admixture of albuminoid matter, which rots away after death. The hydrogel of silica then undergoes peptisation (that is, so much of it as does not fall to the bottom), probably by virtue of the free alkali in sea-water, and returns to the dissolved state. The conditions of dissolution of silica and, for instance, calcium carbonate are very different. Silica, as being a colloid, has not a definite solubility; its existence as a hydrosol is limited only by the coagulating action of the electrolyte solutes of sea-water or by its precipitation in combination with a base. As to the former effect, we have no data except that sodium chloride is comparatively feeble as a coagulant. It is remarkable that no silica seems ever to reach the bottom as a chemical precipitate

[1] Buchanan, *Proc. Roy. Soc. Edin.*, vol. xviii. p. 17, 1891.
[2] Murray and Irvine, *Proc. Roy. Soc. Edin.*, vol. xviii. p. 229, 1891.

of calcium or magnesium silicate, although magnesium silicate is known to be soluble to only 1 part in 100,000 of sea-water.[1] This perhaps indicates that the silica in solution in the sea is always below saturation-point, so that a local concentration large enough to determine precipitation never occurs. Or again, excess silica perhaps combines with what little alumina there is in sea-water and is deposited as clay; if that were the case, the limit of dissolved silica would be set by the solubility of this substance, which may well be less than that of magnesium silicate. At any rate, the quantity of silica really dissolved in sea-water is extremely small. According to the most recent and trustworthy determinations,[2] there is on the average about one part, and never more than two parts, per million in North Sea and Baltic waters.

Although for obvious reasons vastly less silica is produced, by biological agencies, in the waters of the sea than calcium carbonate, the former, like the latter, is found in almost all submarine deposits. When siliceous remains fall into a calcareous deposit, the silica has little tendency to combine with lime, since silicic at low temperatures is an even weaker acid than carbonic; but, the process of peptisation being accelerated by the higher alkalinity of the superjacent waters, we should expect the predominance of lime to favour the dissolution of silica. This seems to be borne out by the fact that silica is least abundant in the most calcareous bottoms of the open sea, and also by the almost total absence of silica in coral reefs and muds.[3] Again, essentially siliceous accumulations (Radiolarian ooze) are characteristic of the very deepest parts of the ocean, where calcareous remains have such enormous columns of sea to fall through that they may fail to reach the bottom. There is thus a tendency for silica and calcium carbonate to be mutually exclusive. In terrestrial calcareous deposits (chalk) we find imprisoned silica going into solution, migrating to centres of coagulation and forming nodular segregations (flint). No such phenomenon is observed at the bottom of the sea, where the silica brought into solution has probably no difficulty in diffusing into the hydrosphere out of the comparatively loose deposit.

The soluble silica of the sea is derived ultimately from felspathic minerals, and the greater bulk is introduced from

[1] Murray and Irvine, *Proc. Roy. Soc. Edin.*, vol. xviii. p. 238, 1891.
[2] Raben, *Wissensch. Meeresuntersuchungen*, Kiel, vol. viii. pp. 99 and 277, 1905.
[3] The Atoll of Funafuti: Report of Coral Reef Committee of the Royal Society; Chemical Examination of the Materials from Funafuti, by J. W. Judd, p. 370, 1904.

land by means of rivers. Since the ocean cannot retain in solution more than a trace, all this silica must eventuate as organic deposits, especially Radiolarian and Diatom oozes. Furthermore, a certain quantity of suspended terrigenous clay is being continually converted into the hydrated silica of these deposits. Neglecting the latter source of biological silica and the comparatively inconsiderable radiolarian areas, we can say that the dissolved silica yielded by the continents is tending to accumulate on the frontiers of the temperate and polar zones, especially in the Antarctic Ocean.

The amount of phosphorus in sea-water is comparable in its tenuity to that of silica. Raben's determinations for North Sea and Baltic waters show a seasonal variation ranging from 0.14 to 1.46 parts of P_2O_5 per million. Phosphorus originates as calcium phosphate in the form of apatite, passes through the ionized condition, and is deposited on the bottom of the sea as calcium phosphate. In the deposits this compound is of universal distribution; all samples of whatever character contain from a trace to about 3 per cent of tricalcium orthophosphate. The clays and muds no doubt retain traces of undecomposed mineral phosphate. On the other hand, calcium phosphate is secreted to a greater or less extent by the living denizens of the sea, whence its presence in calcareous and siliceous deposits; here we have the phosphorus withdrawn from aqueous solution and partly going through a cycle between the sea and the bottom, like lime and silica. Phosphorus.

If there were no organic life in the ocean, the deposit everywhere would consist of a mud or clay, composed of mineral detritus. As it is, this detritus is nowhere wholly absent, and large areas consist of little else. Whether the mud be brought into the sea by rivers or through the agency of tidal erosion, or whether it be formed *in situ* at the bottom, it is always of a dual nature. The one ingredient is more or less finely powdered original mineral matter produced by mechanical comminution; the other is a mixture of substances resulting from the chemical decomposition of rocks. It has not been found possible to disentangle these components quite satisfactorily by chemical analysis, but it is safe to state that the proportion of one to the other ranges from one quarter to three quarters. Decomposition of minerals.

In chemically-produced mud we have the result of the action of water on crystalline silicates without the intervention of any solute except dissolved gases. Qualitatively, therefore, it is of the same composition whether formed in fresh water or in the sea. Quantitatively, it might be expected to show a difference for terrigenous and pelagic origin respectively, since the mother-rocks are in general not the same. Nevertheless, a remarkably close similarity is revealed by analyses, such as the "Challenger" analyses of Blue muds and Red clays, or still better, of Clarke's ultimate analyses of averaged "Challenger" deposits.[1] One notable point of difference is brought out, viz. the greater manganese-content of pelagic deposits.

The action of unlimited water, oxygen, and carbonic acid on the earth's crust tends to lead to certain definite end-products, the nature of which is dictated by the abundance and the affinities of the elements concerned, and by their habit as regards solubility. All minerals, given time, succumb to these agencies. Reviewing the chief elements, we find the final conditions of stability under subaqueous influences to be as follows. The alkalies, being of a highly soluble tendency, go into solution and accumulate in the hydrosphere. Calcium and magnesium are rendered soluble by the presence of carbonic acid and become sea-water constituents, the former being ultimately redeposited by organic processes. Phosphorus behaves similarly. Ferric iron is very feebly basic, and therefore tends to the condition not of a salt but of a hydrated oxide ($Fe_2O_3.Aq$) which, being very insoluble, remains in the residuum. Ferrous iron, which is a much stronger base, is leached out by the aid of carbonic acid, but is soon oxidized to ferric iron and rendered insoluble. Much the same holds good of manganese, which exists in minerals almost exclusively in the manganous state: it is dissolved as bicarbonate, undergoes oxidation, and comes to rest as hydrated peroxide ($MnO_2.Aq$). Aluminium forms only one base, which is very weak, but has the property of combining with silica to form a highly insoluble substance, ideal clay ($Al_2O_3.2SiO_2.2H_2O$), which represents its final stable condition. Silicon exists as a weak acid (SiO_2) of insoluble tendencies, which, after having been brought into solution, partly joins the residuum as clay and is partly redeposited as hydrated silica through organic agency.

The ultimate mineral residuum, then, consists, if we pass over the rarer elements, of aluminous clay, hydrated ferric oxide, and hydrated manganese peroxide. In all probability the two former substances should be considered together and submarine clay regarded as an ill-defined colloidal compound in which

[1] *Proc. Roy. Soc. Edin.*, vol. xxxvii. pp. 167 and 269, 1907.

silica and alumina play the chief part, but ferric hydroxide and even lime, magnesia, and alkalies are also represented. These minor constituents are, at any rate, so combined as to resist leaching out by dilute acids. Vast areas of the lowest depths of the sea are covered by such a clay in a state of considerable mechanical purity, a product of almost exclusively submarine disintegration, known as Red clay.

The chemical action by which pelagic clay is derived from its volcanic mother-rocks must proceed, as compared with subaerial weathering, with the utmost sluggishness. The fundamental question, indeed, whether fresh or salt water exerts the more powerful action upon rocks must be regarded as not yet answered. Great experimental difficulties are encountered, and we find the results of Thoulet, who concluded that fresh water is a better disintegrant than salt, diametrically opposed to those of Joly.[1] But several other considerations must be taken into account, and it cannot be doubted that rock silicates are degraded more slowly in the sea than on land. For instance, the clastic action of frost is never brought into play. There is no comminution of the minerals by moving water. The soluble by-products are removed, and the supply of oxygen and carbonic acid maintained, by diffusion only.

At this stage the state of rest of the deep-sea residuum is not even yet necessarily final, but is capable of being disturbed locally by organic agencies. Aluminous clay, indeed, is permanent once it is at the bottom, but, whilst floating, it is to some extent decomposed, as we have seen, by siliceous algæ for purposes of nutrition. Iron and manganese oxides are susceptible to reduction by purifying sarcodic matter, whence result the ferrous iron of the Blue muds, and also many of the concretionary forms of these oxides.

The Blue mud areas, which are of vast extent, afford a most important example of the reduction of submarine clay after deposition. We may indeed divide the floor of the sea, according to the relative abundance or paucity of dissolved oxygen in the bottom-waters, into oxidizing and reducing areas. Reducing conditions will prevail wherever there is a larger excess of putrefiable organic matter than can be coped with by whatever supply of oxygen (depending on the circulation of the area) may be available. In general, therefore, the coast-lines of continents are girdled by reducing areas, and it is here that

[1] It may be mentioned that the methods of leaching adopted by these experimenters are somewhat different, and that Thoulet measures his effects by loss in weight, whereas Joly determined the amounts taken up in solution.

Blue muds characteristically occur. Oxidation of the organic matter is here effected at the expense of ferric iron, probably by bacterial agency. A special case of this, viz. the bacterial production of ferrous sulphide and free sulphur, has already been referred to. It may be that sulphur plays an intermediate part in the formation of Blue muds, but the end-product is simply a clay, in which some or most of the iron has been reduced to the ferrous state, containing 1 or 2 per cent of amorphous black organic substance. To these two factors the distinctive dark colour is due. The organic substance is associated with but little nitrogen and hydrogen, and it no doubt represents the final refuse of bacterial and higher forms of life. Blue muds are produced out of the deposit from the top downwards, as is evidenced by the reddish unreduced layer overlying the deeper Blue ones. Since Blue mud is of terrigenous origin, the undegraded silicate which it contains consists of continental minerals.

From the general conditions obtaining in reducing areas it follows that carbonic acid must be unusually plentiful in the mud-waters. A consequence of this is that calcium carbonate, if deposited, is readily redissolved. Hence the Blue muds are on the whole poor in lime. It further follows that lime is tending to accumulate in the deposits of the moderate depths of the ocean, between the reducing areas and the abysses where it is dissolved before reaching the bottom.

Doubtless the decay of minerals on the floor of the sea follows much the same course as subaerial weathering. Intermediate products, however, are comparatively rare, since the general conditions are not (as on land) subject to variation. The only substances of this category which form in any profusion are zeolites, especially the one known as phillipsite. Here and there intermediate products are arrested by being surrounded with concretions. A notable instance is the mineral

Palagonite.

palagonite, which is frequently found at the centre of ferro-manganic nodules. Basic volcanic glass (an amorphous fused silicate of calcium, magnesium, and ferrous iron) has the property of combining with water continuously from the periphery inwards without crumbling, giving what is virtually a hydrated aluminium-iron silicate in a medium of opal. A coating of concretionary matter prevents the gelatinous silica from breaking away and dissolving, but offers no resistance to the diffusion of calcium and magnesium, which are leached out. Meanwhile the colloidal silica exerts its absorbing power on the potash and soda of sea-water, and these oxides enter to the extent of about 4 per cent each. The iron becomes ferric, and can no longer get away as bicarbonate. The resulting palagonite is a more or less homogeneous and transparent amorphous mineral. Exposed naked to the action of bottom-waters it rapidly breaks down to clay.

Deep-sea conditions are, on the whole, more favourable to the degradation of mineral matter than to the generation of new minerals. Nevertheless a few syntheses are being continually carried on in the muddy parts of the bottom and in the immediately superjacent layers of water; they fall into two groups, viz. true chemical syntheses of new classes of silicates, and mineralogical syntheses of concretionary minerals. The first group comprises glauconite and phillipsite, the second group ferromanganic and phosphatic concretions. Synthetic products.

Glauconite is a hydrous double silicate of potassium and trivalent iron, occurring in rounded grains said to be composed of minute felted crystals. The ideal composition ($KFe\ Si_2O_6 . Aq$) is claimed for it, but actually the purest marine glauconite hitherto analysed contains 1.5 per cent of Al_2O_3, 3.1 per cent of FeO, and 2.41 per cent of MgO, with only 7.7 per cent of K_2O.[1] The chemistry of its genesis is still a complete mystery; all that can be said is that it appears to result from a metamorphosis of ferruginous clay, and that, in view of its frequent formation inside the shells of foraminifera (and of its absence in the Red clay and Red mud areas), decomposing organic matter probably plays a part in its formation. On the score of abundance glauconite is a mineral of considerable importance in bottom-deposits, being the characteristic component of the Green sands and Green muds. Glauconite is a mineral belonging essentially to the reducing areas of the deep sea. Glauconite.

The most notable geochemical change associated with glauconite is the withdrawal of potassium out of solution in the sea. This element has a remarkable tendency to be held in loose combination in amorphous and colloidal minerals (like palagonite), and all submarine muds and clays contain a small amount (less than 1 per cent) of absorbed potash; the quantities thus progressively entangled at the bottom will be roughly proportional to the aggregate accessions of clayey matter, and can only be a tiny fraction of the total potassium imported into the ocean. In glauconite-producing areas, on the other hand,

[1] Collet and Lee, *Proc. Roy. Soc. Edin.*, vol. xxvi. p. 238, 1905.

the fixation of potassium must reach formidable dimensions, since the purest Green sands may contain 7 to 8 per cent of K_2O. Nevertheless over the whole ocean it is hardly probable that deposition keeps pace with supply, and potassium may be regarded as one of those elements which are slowly concentrating in sea-water.

Phillipsite.

The zeolite phillipsite is the only substance produced in well-developed crystalline forms at the bottom of the sea, where it is peculiar to the deepest Red clay regions. Marine phillipsite is a hydrated calcium-aluminium silicate in which the principal minor bases are potash and soda (4 to 5 per cent each of K_2O and Na_2O), with insignificant amounts of lime and magnesia. Like all zeolites, it must have been deposited out of a solution of its constituents, and it represents an intermediate stage in the degradation of rock-silicates to clay. Why should the process of degradation have been arrested at this stage? In all probability because solutions containing silica, alumina, and the other elements in just the right proportions were imprisoned in interstices of the Red clay, secure from diffusion, and therefore available for the slow process of crystallisation. It is worthy of note that in point of percentage quantity the minor bases of marine phillipsite differ widely from those of the terrestrial mineral, in which latter calcium plays the chief part. Taking into account the well-known faculty possessed by zeolites of exchanging bases with solutions with which they are in contact we have here (especially in the high percentage of Na_2O) an interesting effect of sea-water as a medium in the mineralogical world, comparable with its far-reaching biological effects. Why the crystallographical species phillipsite should be favoured rather than any other zeolite, we cannot in the present state of knowledge imagine.

Concretionary substances.

The chief submarine concretionary substances are, in descending order of abundance, manganese and iron peroxides, calcium phosphate, calcium carbonate, and barium sulphate. A tendency to assume concretionary forms argues proneness to supersaturation and feebly crystalline habit on the part of the substance concerned. The former property is very characteristic of the peroxides and of calcium phosphate, and is evidently connected with the reluctance to come to equilibrium in solution which so often goes hand in hand with high valencies.[1] Wherever concretions are found, we must suppose that there has at one time been a layer, or a chronological series of layers,

[1] See Van t'Hoff, *Sitzungsber. K. Akad. Wiss. Berlin*, vol. xxxiv. p. 658, 1907.

of water surcharged with the substance, whence deposits have taken place on whatever nuclei offered, forming a hard radial aggregation, which would continue to grow until either the solution was exhausted or the supersaturation was relieved by external causes. The shape of the concretion must depend on the shape and number of its nuclei and the evenness of concentration in the surrounding solution; in the ideal case of a small single nucleus and a uniform supply of substance from all sides, the concretion becomes an almost perfect sphere, like the manganese nodules met with in certain localities.

Concretions of iron and manganese.

Iron and manganese depend for the formation of supersaturated solutions in bottom-waters on the change of valency of which these elements are capable. Iron is brought into solution as ferrous bicarbonate by the decomposition of minerals; or again a solution of the bicarbonate may be produced locally by the action of decaying organic matter on ferric compounds. Now ferrous oxide is a base of strength comparable to, but rather less than, that of calcium oxide, and is subject to analogous conditions of solubility as bicarbonate. If oxygen were absent, and if the solubility were diminished, *e.g.* by withdrawal of carbonic acid, we should expect a deposition of ferrous monocarbonate (such as has often taken place on a large scale on land). As it is, the ferrous solution, diffusing out of the mud, meets with dissolved oxygen, and the change of valency to ferric iron rapidly supervenes. Ferric oxide, however, is a much weaker base, and the hydrolytic dissociation of its salts with a weak acid like carbonic is so complete as to render a ferric carbonate practically incapable of existence in presence of water. That is, the substance now in solution is ferric hydroxide. But this is a vastly less soluble body than ferrous bicarbonate; therefore the iron in solution is now supersaturated.

Non-manganiferous ferric concretions are comparatively rare, and have been reported only from the North Atlantic and the polar seas,[1] where the terrigenous bottoms are poor in manganese. They attain no great size or hardness, contain much silica, and are rather balls of clay cemented with hydrated ferric oxide.

As for manganese, the manner in which supersaturated solutions come into being is the same, *mutatis mutandis*, as in the case of iron. The deposited peroxide has approximately the composition MnO_2 in deep-sea nodules, but shows notable

[1] Schmelck, Norwegian North Atlantic Expedition, No. IX. p. 52, 1882; Böggild, Norwegian North Polar Expedition, Scientific Results, vol. v. No. XIV. p. 38, 1906.

admixtures of lower oxides of manganese when laid down in landward waters,[1] where the supply of oxygen is competed for by much organic matter. The hydration $MnO_2.\frac{1}{2}H_2O$ is assumed by Murray and Renard, and $Fe_2O_3.1\frac{1}{2}H_2O$ (limonite) for the accompanying ferric oxide. Deep-sea nodules are never purely manganic, but contain inclusions of clayey and other matters, and always a considerable proportion of iron. The mean of forty "Challenger" analyses works out at 29.0 per cent of MnO_2 and 21.5 per cent of Fe_2O_3, soluble in hydrochloric acid. As a rule, then, surcharged waters hold both iron and manganese ready to be deposited simultaneously. The mode of formation of these nodules and the origin of the manganese from volcanic minerals have been thoroughly elucidated by Murray and Irvine.[2]

It should be noted that these oxides need by no means necessarily assume a concretionary form. They are very commonly found as thin incrustations on granular and fragmentary objects. Furthermore many, if not most, of the pelagic clays contain intimate admixtures of finely-divided brown manganese and occasionally of limonitic iron. Here the supersaturation would seem to have been so high as to transgress the metastable limit, whereupon the oxides have precipitated themselves without the intervention of nuclei; they certainly must have been precipitated from solution.

Manganese originates in the form of silicates and comes to rest exclusively in the form of peroxide. It is imported, on the one hand, from land as detritus or in solution; but in the terrigenous areas of the bottom, where reducing conditions prevail, as a rule, it tends to exist in the suboxidized, *i.e.* soluble, form. Hence much of the terrigenous manganese will be carried on to the deeper oxidizing waters before it can deposit. There is thus a constant accession of manganese from land to the pelagic deposits. In the second place, manganese comes into the floor of the ocean from certain basic volcanic minerals of vitreous habit, and these are to be regarded as the principal source of ferromanganic nodules. These basic glasses are the only primary minerals in the deep sea which contain important amounts of manganese. It so happens that they are common in the Pacific, less common in the Indian Ocean, and rare in the Atlantic. Consequently the greatest abundance of manganese peroxide, pulverulent and nodular, is met with in mid-Pacific.

Phosphatic concretions are of very localised occurrence and

[1] Buchanan, *Trans. Roy. Soc. Edin.*, vol. xxxvi. p. 459, 1892.

[2] *Trans. Roy. Soc. Edin.*, vol. xxxvii. p. 721, 1894.

Phosphatic concretions.

are, in the last resort, of biological origin. The phosphoric acid in sea-water is derived chiefly from the skeletons and tissues of the marine fauna. At certain spots great masses of these skeletons are heaped up at the bottom, and here or hereabouts phosphatic nodules are presently formed. In order to explain why the phosphate of decaying bones goes into solution it is not necessary to postulate exceptional conditions in the surrounding sea-water. The solubility of tricalcium orthophosphate in water is a matter which bristles with complications, and experimental difficulties have hitherto proved too great for its exact measurement; but it seems to be of the order of decigrammes per litre. The solubility is much enhanced by the presence of $H^{\cdot}$ ions, *i.e.* of acids. The solvent action of carbonic acid which has been suggested seems, however, to be merely hypothetical. Carbonic acid is so weak that at best it can produce only a negligible concentration of $H^{\cdot}$ ions; moreover, there is experimental evidence that so long as excess of lime (as bicarbonate) is present, calcium phosphate is no more soluble in carbonated than in pure water. In all probability the rapid dissolution of the calcium phosphate and carbonate in fish-bones is simply due to the fine state of division. This effect has already been discussed with reference to sea-shells. The extreme fineness of the inorganic particles disseminated in the gelatinous matter of fish-bones is attested by the translucency of the mass. Or it may even be that the carbonate and phosphate are present in a colloidal form. In either case they will readily yield supersaturated solutions when the enclosing ossein rots away, and as soon as a nucleus presents itself the formation of concretions is ready to begin. Since phosphatic concretions usually occur, as already indicated, in positions where organic remains accumulate on the bottom at a rapid rate, as in areas having a great range of surface temperature, the transference of matter from bones to nodules must have taken place without much delay. Consequently there has been little opportunity for differential diffusion of carbonate and phosphate, so that these calcium salts are invariably found to have been deposited simultaneously. The "Challenger" analyses show $1\frac{1}{2}$ to 3 parts of tricalcium orthophosphate to one of calcium carbonate. Magnesium phosphates being considerably more soluble than those of calcium, the phosphate of bones is re-deposited unchanged after its passage through sea-water; only a trifling percentage of magnesium is shown by the analyses, and this is probably present as carbonate.

4. Depth and Deposits of the North Atlantic Ocean

The North Atlantic may be called a circumscribed ocean, being practically land-locked except towards the south. Its superficial area is small compared with the other ocean basins, but the area draining into it is enormous, since the Arctic Ocean, the Mediterranean Sea, the Baltic Sea, the Gulf of Mexico, and the Caribbean Sea all communicate with it. Indeed, it has been estimated that nearly one-half of the entire world drains directly or indirectly into the Atlantic Ocean[1] as a whole, or about four times the area draining into the great Pacific Ocean, and of this by far the larger portion drains into the North Atlantic as distinct from the South Atlantic; the largest river of South America, the Amazon, enters the Atlantic just on the equator, and its outflowing waters, with their burden of sediment, are carried mostly into the North Atlantic. It has further been estimated that more than one-half of the total rainfall of the globe falls on the Atlantic drainage area, equal to more than three times the amount falling on either the Pacific or Indian Ocean drainage area.[2] Remembering these facts, and the relatively large area occupied by the continental shelf and continental slope, it is easy to understand why the deposits covering the floor of the North Atlantic partake more of a terrigenous character than those of the other ocean basins, and this character is further emphasised by the floating icebergs met with in the northern part of the ocean, and by the proximity to the southern part of the ocean of the great desert of the Sahara, the sand grains from which are sometimes carried far out to sea by the wind. The North Atlantic is also remarkable for the relatively high temperature of its waters at all depths from surface to bottom, as compared with the other oceans, and this is due partly to the influence of the dense warm water flowing out from the Mediterranean at the Straits of Gibraltar, and partly to the downward movement of the dense surface water of the Sargasso Sea. Another characteristic of the North Atlantic is the permanent anticyclonic area in the Sargasso Sea region, which largely determines the direction of the prevailing winds over a large part of that ocean, and hence of the great surface currents like the Gulf Stream.

The bathymetry of the North Atlantic, according to the

[1] *Scott. Geogr. Mag.*, vol. ii. p. 554, 1886.

[2] *Ibid.* vol. iii. p. 67, 1887.

present state of our knowledge, is shown in Map III. On this chart the soundings in depths greater than 1000 fathoms are indicated by the first two figures, and they show that the North Atlantic is now well sounded — in fact, probably the best sounded of all the ocean basins. The recent soundings by the "Michael Sars" did not bring to light many new facts as to depth, and it is not likely that any great changes in the contour-lines will be revealed by future soundings, though it is possible that further submarine cones, like the Seine Bank and Dacia Bank and the Coral Patch, may yet be discovered. Depths of the North Atlantic.

A comparison of this map with the depth map published by Maury in 1854, which is reproduced in Map I., brings out at a glance the strides that have been made in our knowledge regarding the depth of the North Atlantic since that time — a progress from comparative simplicity to great complexity. Maury's 4000-fathoms area in the North-West Atlantic, based upon some doubtful soundings (two of them exceeding 5000 fathoms and another in 6600 fathoms), has disappeared, though the existence of very deep water in the neighbourhood is evidenced by the soundings in the Suhm Deep. These deep soundings laid down by Maury were among the early attempts at deep-sea sounding, and the records of such depths as 6600 fathoms, no bottom, were due to the uncertainty as to when the sounding-tube touched bottom. The only part of the North Atlantic where the depth is now known to exceed 4000 fathoms (in the Nares Deep north of the West Indies) is blank on Maury's map, but the northern portion of the mid-Atlantic ridge, on which the Azores plateau is situated, is correctly indicated, though since modified in outline; the continuation southward of this ridge was, however, unknown in Maury's time. Maury's depth map.

Reference has already been made to the relatively large area occupied throughout the world by the continental shelf, which is equal to about 7 per cent of the entire ocean-floor. The continental shelf apparently attains its maximum development in the North Atlantic basin, if we include the tributary seas (Arctic Ocean, Mediterranean, etc.). The total area of this basin may be estimated at about 23 million square miles, and of this area no less than about 6 million square miles (or 26 per cent) lies between the shore-line and the 100-fathoms line. Continental shelf in the North Atlantic.

While the gentle gradients of the continental shelf cover such an extensive area, the continental slope beyond the 100-fathoms line seems, on the other hand, to be relatively very steep, for Continental slope in the North Atlantic.

the area between the 100-fathoms line and the 500-fathoms line is only a little over 2 million square miles (or 9 per cent), and the area between the 500-fathoms line and the 1000-fathoms line is only about 1 million square miles (or 4 per cent of the total area). It thus appears that the area with depths less than 1000 fathoms within the North Atlantic basin, as already defined, is equal to about 9 million square miles (or 39 per cent of the total area), and of this the continental shelf covered by water less than 100 fathoms in depth occupies 6 million square miles (or 26 per cent).

Abyssal area of the North Atlantic.

Proceeding into the abysmal region, we find that the area of the North Atlantic sea-floor covered by water between 1000 and 2000 fathoms in depth is about 5 million square miles (or 22 per cent), the area covered by water between 2000 and 3000 fathoms in depth is about $7\frac{1}{2}$ million square miles (or 33 per cent), and the area covered by more than 3000 fathoms of water ("deeps") is about $1\frac{1}{2}$ million square miles (or 6 per cent of the total area). These figures show what a large proportion of the North Atlantic sea-floor is covered by shallow water less than 1000 fathoms (equal to two-fifths of the entire area), and by deep water between 2000 and 3000 fathoms (equal to one-third of the entire area).

Deeps of the North Atlantic.

The deeps of the North Atlantic number fourteen, and cover an area of about $1\frac{1}{2}$ million square miles, as already indicated. The larger and more important of these, Nares Deep, Moseley Deep, and Chun Deep, have been briefly described on pages 141, 142, and 143. The smaller ones are: Makaroff Deep in the West Indian seas; Bartlett Deep in the Caribbean Sea; Mill Deep and Keltie Deep in the sea between Bermuda and the American coast; Suhm Deep, Libbey Deep, Sigsbee Deep, and Thoulet Deep, to the south of Nova Scotia and Newfoundland; Peake Deep to the west of Cape Finisterre; Monaco Deep to the south of the Azores; and Hjort Deep immediately to the east of the mid-Atlantic ridge in lat. 20° N.

The Norwegian Sea.

The Norwegian Sea is bounded on the east by Spitsbergen, Bear Island, the banks of the Barents Sea and the Norwegian coast; on the south by the North Sea, the Shetland and Faroe Islands, and the submarine ridges between the Shetlands and Faroes and between the Faroes and Iceland; on the west by Iceland and Greenland; and on the north, about lat. 80° N., by a submarine ridge supposed to separate the two deep basins called the Norwegian Sea and the Polar Sea.

The Norwegian Sea has a superficial area of 2.58 million square kilometres, nearly two-thirds of which consists of a deep

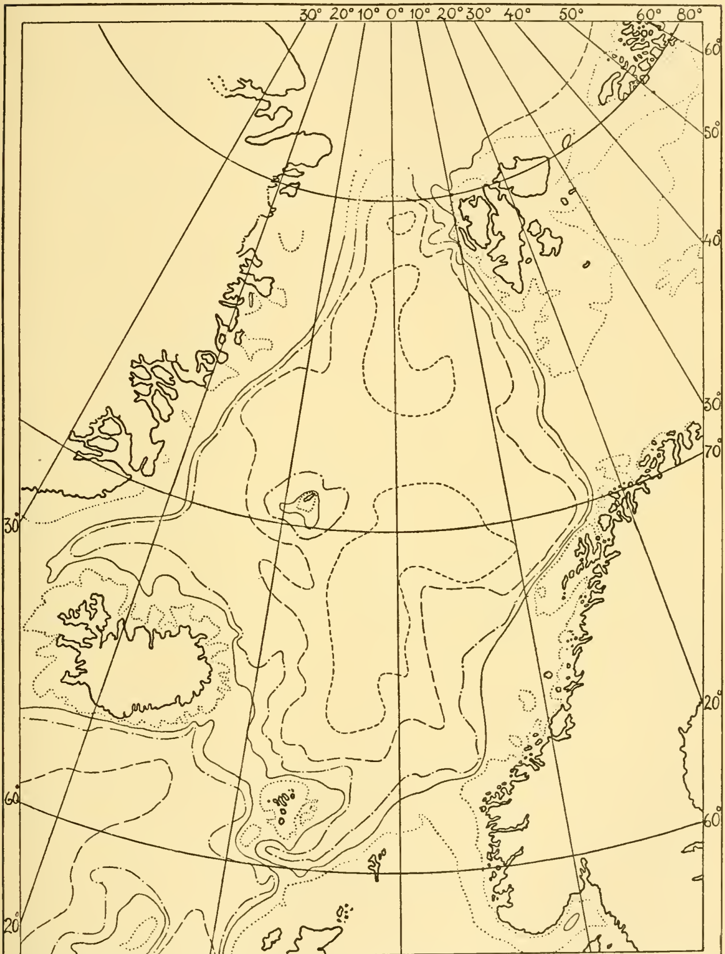


FIG. 143.—THE NORWEGIAN SEA, SHOWING DEPTHS.

············ 200 metres.	—·—·— 1000 metres.
———— 600 ,,	— — — 2000 ,,
- - - - - - 3000 metres.	

basin (see Fig. 143), more than 3000 metres deep in the central portion. From this depth the floor rises gradually towards the continental slope on either side. The main features of the continental slope and shelf along the coast of Norway will be grasped by reference to the accompanying diagram (Fig. 144). The term "coast banks" is usually applied to the higher parts of the submerged continental plateau or continental shelf, which are frequented by fishermen; there is often a marked "edge" between the plateau and the continental slope.

The continental shelf fringes to a greater or less extent the whole of the coasts of the Norwegian Sea, and occupies altogether about a third of its entire superficial area. This shelf is covered by depths down to 200 metres with channels down to 600 metres. In water shallower than 200 metres there are only comparatively small banks, the greatest being at Lofoten and Romsdal and round the Faroes and Iceland. Deeper than 600 metres the continental slope is steep; the bathymetrical curves for 600 and 1000 metres lie everywhere in close proximity to one another, and the area of the sea-bottom between them is no more than 5.4 per cent of the whole extent of the Norwegian Sea.

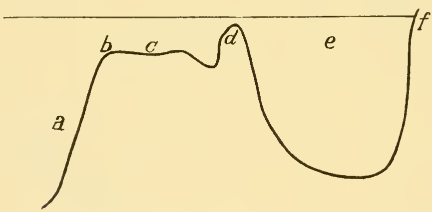


Fig. 144.—Diagrammatic Section off the Norwegian Coast.

a, Continental slope; *b*, continental edge; *c*, continental shelf or plateau; *d*, coast bank; *e*, fjord; *f*, coast.

Deposits of the North Atlantic.

The distribution of the deposit-types over the floor of the North Atlantic is shown on Map IV., an examination of which bears out the statement that the terrigenous deposits are relatively more important in the North Atlantic than in the other oceans, in correlation with the relatively large area covered by shallow water. Thus of the total area of 23 million square miles, one-half, about $11\frac{1}{2}$ million square miles (or 49 per cent), is covered by terrigenous deposits. This area is to a very large extent occupied by Blue mud, no attempt having been made to indicate on the map the small areas occupied by Green mud off the coast of the United States, off the Spanish and Portuguese coasts, and in the vicinity of the Wyville Thomson Ridge, nor the small areas occupied by Volcanic mud in the neighbourhood of the Azores, Madeira, etc. The position of the Coral mud deposits of the West Indies and Bermuda is, however, indicated on the map, and these deposits cover an area of about half a million square miles (or 2 per cent of the total area).

After the Blue mud, the principal type of deposit in the North Atlantic is Globigerina ooze, which covers an area of about 9 million square miles (or 39 per cent of the total area). A glance at the map shows what an extensive area is occupied by this type of deposit in the open ocean, where it is found in greater depths than is usually the case in the other ocean-basins (the "Michael Sars" deepest sounding in 2966 fathoms, for example, gave a Globigerina ooze with 64 per cent of calcium carbonate); it also occurs in the Caribbean Sea, in the Gulf of Mexico, and in the Norwegian Sea in lat. 63° N. to 72° N.

Red clay, which covers such an enormous area of the sea-floor in the great Pacific Ocean, plays a subordinate part in the North Atlantic, being estimated to occupy about 2½ million square miles (or 11 per cent of the total area); it occurs in two areas on either side of the mid-Atlantic ridge: the larger to the west of the ridge, surrounding Bermuda and extending from lat. 13° N. to 40° N., the smaller to the east of the ridge in lat. 8° N. to 28° N., with a subsidiary area in the Caribbean Sea in lat. 13° N. to 15° N.

Pteropod ooze, though widely distributed throughout the basin, covers in the aggregate a comparatively very small area, estimated at about 200,000 square miles (or 1 per cent of the total area); it occurs in the open ocean in the neighbourhood of the Azores, Canaries, Bermudas, and West Indies, as well as in the Mediterranean, Caribbean, and Gulf of Mexico. The other two types of pelagic deposits, Radiolarian ooze and Diatom ooze, are not represented in the North Atlantic.

"Michael Sars" deposit-samples.

Although the "Michael Sars" Expedition did not add greatly to our knowledge either of the depth or of the deposits of the North Atlantic, still both the soundings and the deposit-samples are of value, many of the deposit-samples, indeed, being extremely interesting. A detailed description of all the samples will be reserved for a later publication, but in this place we may refer to the more interesting points brought out by a study of the material.

In the first place, reference may be made to the stones and rock fragments brought up from several stations, which form the subject of a report by Drs. Peach and Horne appended to this chapter; from another station the ear-bone of a whale and two sharks' teeth were obtained.

Of the twenty-seven samples submitted to detailed examination, nineteen were Globigerina oozes, six were Blue muds, one a Pteropod ooze, and one a Globigerina ooze overlying Blue mud. The Globigerina oozes occur over the route followed by the "Michael Sars" as far west as long. 44° W.; the Globigerina ooze overlying Blue mud occurred to the north of the Rockall Bank; the Pteropod ooze near the Canary Islands; and the Blue muds in the Eastern Atlantic from the Faroe Channel to the Straits of Gibraltar. The "Michael Sars" samples show that the Globigerina ooze approaches nearer to the coasts of the British Islands than was previously supposed, having been found at the following depths along the continental slope off the European and African coasts: 547 fathoms (Station 4), 1256 fathoms (Station 25 A), 1122 fathoms (Station 25 B), 1422 fathoms (Station 35), 746 fathoms (Station 41), 688 fathoms (Station 93), 981 fathoms (Station 95), 742 fathoms (Station 98), and 835 fathoms (Station 100). Globigerina ooze and Pteropod ooze were found in the neighbourhood of the Canary Islands in positions where they were previously unrecorded.

An interesting point in connection with the "Michael Sars" deposits is the number of instances where the sounding-tube had plunged deeply into the sediment, bringing up sections varying from two to fourteen inches in length, and in some cases marks observed on the outside of the sounding-tube indicated that it had penetrated still farther into the deposit. Though in most cases the material was apparently uniform throughout, some of these long sections gave distinct evidences of stratification. Thus at Station 10 in the Bay of Biscay, at a depth of 2567 fathoms, the sounding-tube brought up a section about five inches in length, of which the upper portion to the depth of about three inches was of a uniform fawn colour, representing apparently an ordinary Globigerina ooze with 66 per cent of calcium carbonate, while the lower inch or two had a mottled appearance, with light and dark brown patches, the dark brown material giving only 33 per cent of calcium carbonate when analysed. At Station 49 C, from a depth of 2966 fathoms, the sounding-tube brought up a section about fourteen inches in length, showing distinct traces of stratification, especially towards the upper end, although the lower end presented a mottled appearance with patches of lighter and darker brown; towards the upper end there were small patches

Stratification.

of a dark brown colour which proved to be Red clay, with only 25 per cent of calcium carbonate, though the mass of the sample was a Globigerina ooze with 64 per cent of calcium carbonate. At Station 100, in 835 fathoms, the sounding-tube brought up a section about nine inches in length, which was extremely interesting because of the great difference between the upper and lower portions, the upper portion, to the extent of three or four inches, being a Globigerina ooze with 58 per cent of calcium carbonate, while the lower portion was a Blue mud with only 26 per cent of calcium carbonate. At Station 88, in 1703 fathoms, the sounding-tube brought up a section about fourteen inches in length, which showed little difference to the naked eye, although the colour was darker in the lower portion, the upper portion being rather lighter in colour, less coherent, and more granular; the deposit was a Globigerina ooze, containing 83.79 per cent of calcium carbonate in the upper portion, 73.66 per cent of calcium carbonate in the middle portion, and 62.1 per cent of calcium carbonate in the lower portion. It is curious that at this station the trawl brought up a large quantity of empty pteropod shells (chiefly *Cavolinia trispinosa*), while in the samples from the sounding-tube submitted to examination no pteropods were observed. It is possible that the trawl may have worked over shallower depths than where the sounding was taken. Similarly, at Station 23, where the depth was 664 fathoms, the Petersen net sent down with 820 fathoms of line and towed throughout the night of 5th and 6th May brought up a large amount of empty pteropod shells (principally *Cavolinia inflexa*); indeed, the pteropod shells at this station differ strikingly in general appearance from those taken at Station 88, ten degrees farther north. At Station 34, in 1185 fathoms, the middle portion of the section from the sounding-tube, about six inches below the upper surface, showed dark-coloured patches containing a large proportion of volcanic glass splinters, to which the dark colour was due; the volcanic glass was quite fresh and unaltered, as though the products of a volcanic eruption (probably submarine, since the glassy fragments showed no trace of friction or decomposition but were perfectly angular) had been overlain by new material to the depth of six inches.

We append the detailed description of a typical Globigerina ooze taken by the "Michael Sars" to the south of the Azores:—

"Michael Sars" Station 55. 10th June 1910. Lat. 36° 24′ N., long. 29° 52′ W.; depth, 3239 m. (1768 fathoms).

Description of typical deposit sample collected by the "Michael Sars."

GLOBIGERINA OOZE—dirty white colour, coherent, granular.

CALCIUM CARBONATE—78.59 per cent; pelagic and bottom-living foraminifera, ostracods, coccoliths, and rhabdoliths.

RESIDUE, 21.41 per cent:—

Siliceous Organisms—2 per cent; radiolaria, sponge spicules.

Minerals—4 per cent, m. di. 0.09 mm., one angular fragment of volcanic glass exceeded 2 mm. in length; quartz, plagioclase, volcanic glass, augite (?), magnetite, mica.

Fine Washings—15.41 per cent; amorphous clayey matter with minute mineral particles.

Note.—The sounding-tube brought up a roll about 9 inches in length of a creamy white colour throughout.

All the rock fragments dredged during the "Michael Sars" Expedition, as well as those collected by H.M. ships "Knight Errant" and "Triton" in 1880 and 1882, have been carefully examined and studied by Dr. B. N. Peach.[1] Drs. Peach and Horne have prepared the following note on the general results:—

Rock fragments dredged by the "Michael Sars."

The materials collected by the "Michael Sars" Expedition fall under two categories: (1) those whose presence on the sea-floor is due to natural agencies, and (2) those distributed by human agencies. The materials belonging to the first group consist chiefly of rock fragments, the remains of floating or swimming organisms that lived at or near the surface of the sea (such as barnacles and the ear-bone of a whale), and fragments of wood. The members of the second group are mainly furnace clinkers and pieces of coal, small pieces of glazed pottery, and oyster-shells, together with a cannon-bone of a small ox.

By far the most interesting collection of the "Michael Sars" series was obtained from Station 95, which lies about 230 miles south-west of Mizen Head, Ireland, at a depth of 5886 feet, or a little over a mile. The rock fragments, comprising over 200 specimens, included upwards of 100 of sedimentary origin, 58 of igneous origin, and 40 belonging to the metamorphic series. Some of the specimens were referred to the Cretaceous and Carboniferous periods by means of their fossil contents; the remainder were grouped with the Devonian or Old Red Sandstone and Silurian systems solely on lithological grounds.

The fragments regarded as of Silurian age include greywacke-sandstones, dark shales, and black lydian stone identical in lithological characters with rocks that floor a large part of the southern uplands of Scotland and the north of Ireland. Those referred to Devonian time resemble the Glengariff grits of the Dingle peninsula in the south-west of Ireland. The carboniferous specimens comprise encrinital limestones with chert, like those of Galway and Clare. One sandstone fragment was crowded with *Schizodus* and *Edmondia* similar to rocks occurring in places along the Solway shore in Scotland and in Londonderry and Tyrone in Ireland. The specimens of chalk and chalk-flints are like the rocks in the Antrim plateau.

[1] See detailed report in *Proc. Roy. Soc. Edin.*, 1912.

Among the metamorphic series there are representatives of crystalline gneisses and schists which could be matched from the Lewisian gneiss

FIG. 145.—GLACIATED STONE FROM "MICHAEL SARS" STATION 95.

and Moine schist areas in the North-West Highlands of Scotland. Associated with these are specimens indicating a low grade of metamorphism, such as phyllites and sheared greywackes and igneous rocks, which resemble types to be found along the south-eastern border of the Highlands and the north of Ireland. Indeed, some may have been derived from the south of Ireland.

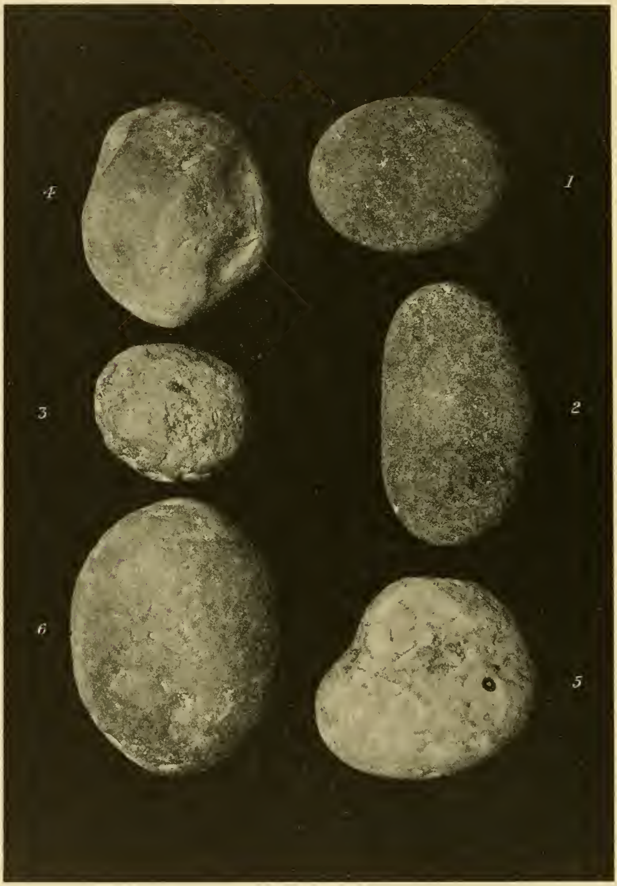


Fig. 146.—Rounded Stones from "Michael Sars" Station 95.

The evidence furnished by the igneous materials is no less remarkable. The plutonic rocks are represented by granites resembling those of Lower Old Red Sandstone age in Scotland and the north of Ireland, and also by a specimen of nepheline-syenite which cannot be matched with any known rock of this type in the North Atlantic basin. The lava-form and intrusive types of the basic materials have marked affinities with the tertiary volcanic rocks of the Inner Hebrides and the north of Ireland.

Of special interest is the evidence pointing to the conclusion that the rock fragments from this station must have been transported by floating ice during some phase of the glacial period. More than half of the specimens are glaciated, the larger part of the remainder are angular, and a number are well rounded. A typical example of one of the glaciated stones is shown in Fig. 145, which is a portion of a larger boulder broken off before being embedded. Irregular striæ appear on this specimen, but on one surface it is facetted and the striæ thereon are more or less parallel. It is noteworthy that the glaciated and ice-

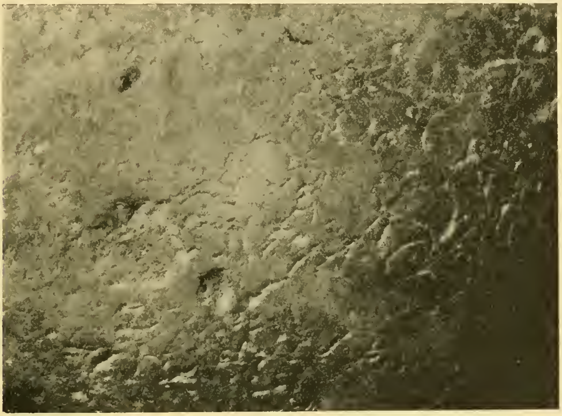


FIG. 147.—SURFACE OF SPECIMEN NO. 4 IN FIG. 146, ENLARGED TO SHOW "CHATTER-MARKS."

moulded specimens include nearly every rock type represented in the collection from this particular station. The stones resemble those found in boulder clay or "moraine profonde," indeed in some instances the clayey matrix of this deposit has been cemented to some of them by calcareous matter.

Some of the rounded specimens, consisting of Silurian greywackes, carboniferous limestone, chalk-flint, dolomite, and vein-quartz, are shown in Fig. 146. These must have been rounded before they reached the position from which they were dredged.

An enlarged part of specimen No. 4 in Fig. 146 (chalk-flint) is represented in Fig. 147, to illustrate the bulbs of percussion or "chatter-marks" which it displays. Such evidence indicates that the stones had originally been dashed against each other by torrent or wave action.

A careful examination of the specimens points to the conclusion that all had been partially embedded in a Globigerina ooze on the sea-floor, as shown by the attached marine organisms and by a slight coating of manganese oxide on the exposed parts. In Fig. 148, which represents a specimen composed of carboniferous limestone and chert, the arrow points to the manganese staining where the exposed and unexposed parts meet.

Fig. 148.—Stone with staining of Manganese, the arrow showing the position of the surface of the deposit in which the specimen had been embedded.

The average size of the stones is about three inches; only a very few reach six inches in length. As the sounding-tube brought up from the sea-floor at this station a core of ooze nine inches long, we may infer that the tube pierced the deposit to a greater depth than that reached by any of the stones. It is therefore clear that none of the stones can be *in situ*. They must have been dropped from above into the ooze.

Many of the specimens, as represented in Fig. 149, must have stood on end in the ooze, which is not the natural position they would have assumed if dropped on the present surface of that deposit. The inference seems obvious that originally they fell into a soft ooze in which they were completely buried. The stones would naturally be arranged along the lines of least resistance to friction, so that many would be entombed end on or edge on, like those illustrated in Figs. 149 and 150. Subsequent current action has removed part of the material in which they were embedded, and has been powerful enough to prevent further accumulation of ooze at the spot where they were dredged. Since the ooze contains 37 per cent of insoluble material, the theory of the removal of the deposit by solution is improbable.

Among the materials distributed by human agency dredged from this station (95) about 200 specimens of furnace clinkers were found, together with fragments of unburnt coal, also a portion of an earthenware jar and a cannon-bone of an ox. This station lies along the route of the Atlantic Liners, from which these specimens were probably dropped. Furnace clinkers, coal, etc.

At Station 10, on the south side of the Bay of Biscay, and nearly 200 miles north of Cape Finisterre, at a depth of over 15,000 feet, an assemblage of stones was obtained, numbering in all 339, most of which were glaciated and almost identical in lithological characters with those just described.

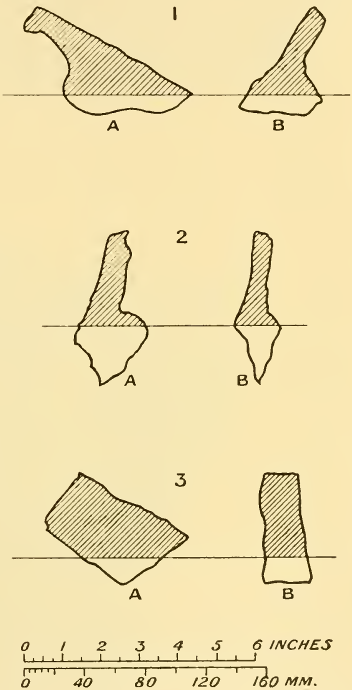


FIG. 149.—DIAGRAMS DRAWN TO SCALE SHOWING POSITIONS OF STONES EMBEDDED IN THE DEPOSIT, THE SHADED PARTS INDICATING THE PORTIONS PROJECTING ABOVE THE DEPOSIT.

At Station 48, lat. 28° 54′ N., long. 24° 14′ W., in about 2800 fathoms, chalk-flints and ice-moulded metamorphic rocks were collected, showing that floating ice had dropped materials over that part of the sea-floor. They were associated with fragments of pumice carried thither by the descending branch of the Gulf Stream. An ear-bone of a finner-whale was also found at this locality.

Just outside the Straits of Gibraltar, at Station 23, in 664 fathoms, a curious assortment of materials was dredged, comprising dead lamellibranch shells (some of them bored by gasteropods), barnacles dropped from whales, furnace clinkers, and an American blue point oyster that had fallen from a passing ship. The dead lamellibranch shells point to subsidence of that part of the sea-floor in recent geological times.

The materials dredged at Station 70, south of the Newfoundland Banks, in 600 fathoms, indicate that this part of the sea-floor is within the range of the present Arctic ice-drift.

The rock fragments obtained from Stations 100 and 101, in 835 and 1013 fathoms, seem to point to the conclusion that they were transported thither by ice that passed over the Orkney and Shetland Isles.

Important evidence was gathered from the Wyville Thomson Ridge

Rock fragments dredged by the "Knight Errant" and "Triton."

at depths ranging from 318 to 3420 feet during the expeditions of H.M. ships "Triton" and "Knight Errant." It suggests that the glaciated stones on the ridge are or have been embedded in a boulder clay. The stones are composed chiefly of Lewisian gneiss and the Moine schists lying to the east of the post-Cambrian displacements in the Highlands of Scotland. A large proportion consists of Caithness flagstones and other Old Red Sandstone rocks, like those occurring in place in the Orkney and Shetland Isles. A considerable number of Jurassic and Cretaceous types occur in the collection, together with two carboniferous specimens, the age of which is determined by their fossil contents. The assemblage of fossiliferous stones are similar to those found by Messrs. Peach and Horne in the boulder clays of Caithness and Orkney.

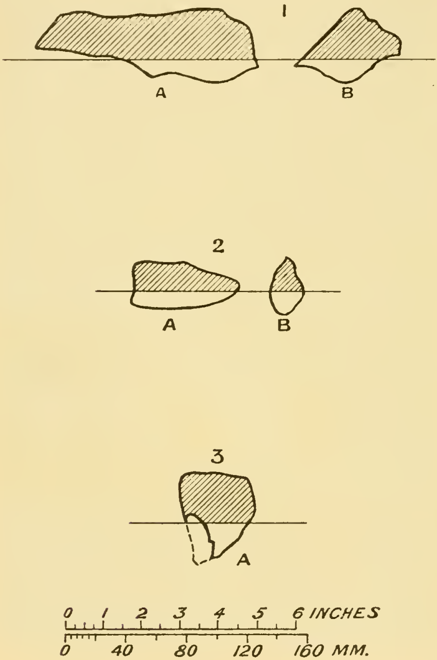


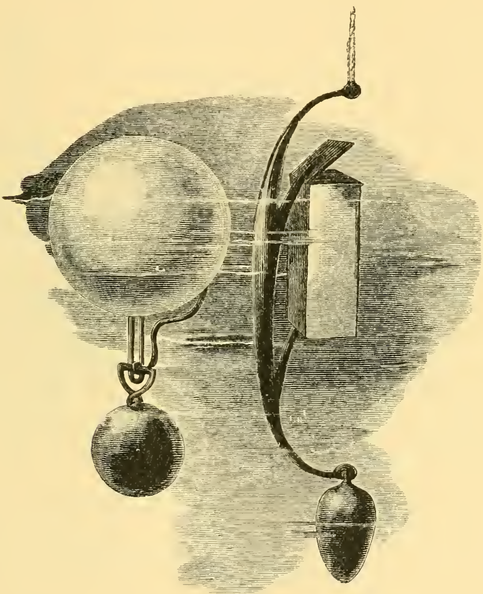
FIG. 150.—DIAGRAMS DRAWN TO SCALE SHOWING POSITIONS OF STONES EMBEDDED IN THE DEPOSIT, THE SHADED PARTS INDICATING THE PORTIONS PROJECTING ABOVE THE DEPOSIT.

On the Faroe Banks the volcanic rocks of the Faroe Isles are not represented among the rock fragments dredged, which would seem to point to the extension of the combined Scottish and Scandinavian ice-sheets over that part of the sea-floor during the glacial period.

Just inside the Rockall Bank, at Stations 100 and 101 ("Michael Sars"), only one Old Red Sandstone boulder was found in the materials collected, but the sand grains occurring in the ooze are either red or green. The ooze also contained fragments of brown glass, resembling the slaggy volcanic rocks of Iceland. Such evidence suggests that some of the material found at this station was distributed by floating ice.

At Station 3 ("Knight Errant"), at a depth of 318 feet, many dead shells of shallow-water habitat were got, which clearly indicate a subsidence of the sea-floor since the glacial period. The absence of raised beaches in Orkney and Shetland, the submerged peat-mosses, the depth and steepness of the sounds between the Faroe Islands, the great depth at which the seaward extension of the fjords in Iceland cut the marine shelf, the submergence of shell banks between Iceland and Jan Mayen referred to by Nansen, all point to the same conclusion. In all probability there was either land connection with Greenland during the glacial period, or a confluent ice barrier which prevented the Gulf Stream from flowing into the Polar basin and deflected it towards the south.

J. M.



Hooke's Sounding Machine and Water-Bottle, 1667.
(See page 2.)

CHAPTER V

PHYSICAL OCEANOGRAPHY

In the middle of last century the idea of "physical oceanography" did not exist, but in the course of a few decades it has become a widespread branch of knowledge, with a copious literature and bulky text-books. A few figures may serve to show how important is the study of the sea. The waters of the globe cover more than two-thirds of its surface, and their volume is about 1300 millions of cubic kilometres, or thirteen times that of all the land above sea-level. The mean height of the land is 700 metres, while the average depth of the sea is 3500 metres. Sea-water contains various salts in solution, the total weight of which is nine times that of the earth's atmosphere.

Difficulties in making oceanic observations.

The reason why the ocean, which plays such an important part in the economy of the earth, has not been investigated until recently is because of the special difficulties which are encountered in making investigations. One great difficulty is, as has been previously mentioned, that it is impossible to observe directly what is going on beneath the surface, and it is necessary to have a special set of apparatus that can be relied upon. The methods have developed with phenomenal rapidity, but the observations are still few in proportion to the extent of the ocean, and consequently it is often difficult to obtain a complete and true image of the actual conditions. Many of the results obtained are therefore merely preliminary, and further study may alter our views on various points; for the solution of

Mechanical appliances necessary.

many important problems we have not yet sufficiently numerous observations. In a rapid sketch like this, only some of the principal facts can be dealt with; we shall first examine the methods employed in physical oceanography, and then endeavour to draw some conclusions from the observations available.

Lines for sending down instruments.

In the first place, one must have a line with which to send down the instruments and draw them up again. Formerly hemp lines were used, but they have now been superseded by wire; steel piano-wire is used for sounding, and wire rope for thermometers, water-bottles, etc. For general use the wire need not be more than 2 to 3 mm. in diameter, and it will, nevertheless, bear the weight of several hundred kilograms without breaking. The old hemp line was marked at regular intervals for the determination of the depth, but this cannot well be done with the wire, which is run out over the metre- or fathom-wheel (see Fig. 151), and this is both a convenient and accurate method. The wheel communicates with a clock-work arrangement with dials and hands, by means of which the length of wire run out can always be read off correct to within a metre. When, however, an observation is to be taken at a depth of 1000 metres, it is not enough to run out 1000 metres of line. The line must be "up and down," and this is not always easily managed, especially in a wind or strong current, when the ship is drifting. Some manœuvring is then required, and the apparatus must either in itself be sufficiently heavy to straighten the line, or an extra weight must be added. Many of the instruments are so constructed that they may be attached to the side of the line as well as at the end, and thus several instruments may be used simultaneously. They are fastened at certain intervals on the line as it is being paid out, and a number of observations are made at the same time at different depths. By this method a comprehensive series of observations from the surface down to two or three thousand metres may be taken in a couple of hours. This method was employed during the "Challenger" Expedition.

Metre-wheel.

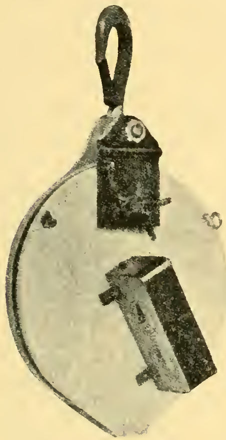


FIG. 151.—METRE-WHEEL.

Several instruments used simultaneously.

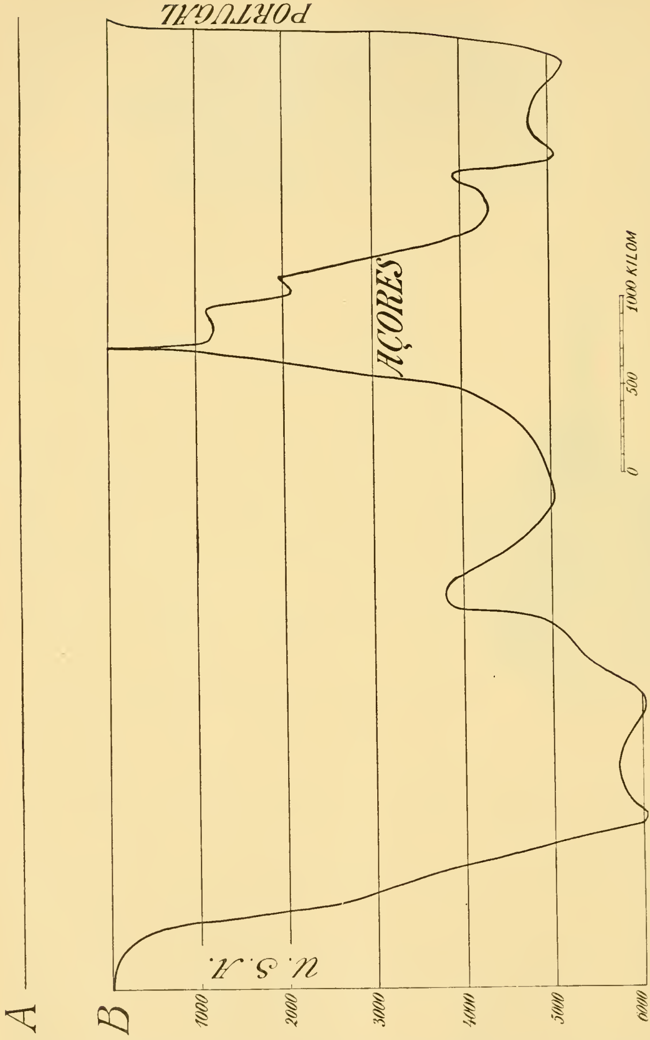


FIG. 152.—SECTION SHOWING THE FORM OF THE BOTTOM OF THE ATLANTIC OCEAN ALONG THE PARALLEL OF 40° N. *B* shows the vertical scale exaggerated 500 times as compared with the horizontal. On the natural scale the section looks like a straight line (*A*).

When several series of observations have been taken in a certain region, they are usually represented for diagrammatic purposes in horizontal plans and vertical sections. It is necessary, in order to be able to see anything in the sections, to exaggerate the scale of depth in comparison with the scale of horizontal distance. This is shown in Fig. 152, which represents the floor of the Atlantic Ocean along the parallel of 40° N. The upper line (A) shows the section drawn to the same scale for depths and horizontal distances; the variations in the depth are represented by a thin uneven line, indicating how relatively small is the depth of the Atlantic Ocean compared with horizontal distances on the earth's surface; the lower diagram (B) shows the section with the depths exaggerated 500 times. Drawing the depth on a larger scale brings out the details of the relief of the ocean-bed: thus off Portugal there is seen a narrow continental shelf, and then a rapid falling-off towards the deep water (the continental slope); farther west (about the middle of the figure) there is a corresponding slope, on the summit of which the Azores appear; then another fall towards the western basin of the North Atlantic, followed by the continental slope on the American side, where again a narrow continental shelf borders the coast. The continental shelf is seen to be wider on the American side than on the European side of the section. This exaggeration of the vertical scale allows of the representation of a number of details, but, of course, the lines look very much steeper than they really are. One must not imagine that the continental slopes are so marked as they appear in the figure, for the angle is usually not so much as two degrees, the slope being similar to that of our common roads and railways; real submarine precipices do occur, but mostly as rare exceptions.

To show physical conditions in diagrammatic sections it is necessary to exaggerate the vertical scale.

Section across the North Atlantic.

At a comparatively early date it was known that the temperature of the sea-surface was strongly influenced by the currents. In the beginning of the seventeenth century, for instance, it was noticed that there was a sudden change of temperature on passing from the cold Labrador current south of the Newfoundland Banks to the adjacent warmer waters of the Gulf Stream. Benjamin Franklin, who made a careful study of the Gulf Stream (see Fig. 153), advised ships' officers to use the thermometer in order to find out when they entered the Gulf Stream, so that they might take advantage of the current when voyaging eastward, and steer clear of it when sailing westward.

The temperature of the sea.

Benjamin Franklin and the Gulf Stream.

The American naval officer M. F. Maury (1806–1873),

Maury.

one of the founders of physical oceanography, used the surface temperatures recorded from different places in the sea in his examination of the currents. He organised an extended collection of temperature-observations for the benefit of navigation; he studied the winds and the drift of vessels, and in the middle of the nineteenth century he published his *Explanations and Sailing Directions to accompany the Wind and Current Charts.* He also wrote an extremely interesting book, *The Physical Geography of the Sea and its Meteorology*, which has appeared in many editions and in several translations. Maury's work had important consequences, for ship-masters following his directions shortened the voyage between North

FIG. 153.—BENJAMIN FRANKLIN'S FIRST CHART OF THE GULF STREAM.

America and England by ten days, that from New York to California by about forty-five days, and that from England to Australia and back by more than sixty days. The profit derived from the use of Maury's charts by British ship-owners on the East India route alone amounted to 10 million dollars yearly.

Log-books for recording observations at sea.

On Maury's suggestion it was decided, at an international congress at Brussels in 1853, that numbers of log-books should be sent out with captains of ships for the purpose of entering observations of wind and weather, of currents, and of temperatures at the sea-surface. This plan has been followed ever since, the notes being as a rule entered once every watch, so that a formidable pile of material has now been amassed. Up to 1904 the Meteorological Office in London had collected 7 millions of these notes, the Deutsche Seewarte in Hamburg more than $10\frac{1}{2}$ millions, the Dutch Meteorological Institute in De Bilt $3\frac{1}{2}$ millions, the Hydrographical Bureau in Washington $5\frac{1}{2}$ millions, and so on. Add to this the surface observations made by scientific and other expeditions, and it will be evident that in the course of the last sixty years a good deal of knowledge regarding the surface of the sea has been gained.

Temperature observations at the surface of the sea.

Making surface-temperature observations is very simple work. All that is necessary is to haul up a bucket of sea-water and measure the temperature by means of an ordinary thermometer. It is a far more difficult thing to record the actual temperature of the deeper layers. In 1749 Captain Ellis brought up water from 1190 metres and from 1645 metres to the south of the Canaries, and, on measuring the temperature of the water inside the water-bottle after it had been hauled up, found it to be 17.2° C. lower than the temperature at the surface. Some investigators coated their water-bottles with an insulating substance, so that the temperature might remain unaltered during the process of hauling up. This principle has recently been developed to a high degree of perfection in one of the water-bottles now most used, viz. the Pettersson-Nansen water-bottle, which will be described later.

Temperature observations beneath the surface.

Insulating water-bottles.

Insulating thermometers.

Attempts were also made to insulate the thermometer itself by surrounding the bulb with a stout sheath of caoutchouc or wax. This insulated thermometer was lowered to the depth desired, where it was left for hours to assume the temperature of the water; it was then hauled up quickly and the temperature read off. In this manner de Saussure was able, in 1780, to determine correctly the temperature in the Mediterranean at 585 metres, finding it to be 13° C. Thermometers made on this principle have been much used until our own times, but they have one serious drawback, for the operation takes a very long time, and this makes them unsuitable for use in expeditions, where the work must be done as quickly as possible; they may, however, do good service in cases where the very greatest accuracy is not required, and where there is unlimited time at disposal, as on light-ships.

Maximum and minimum thermometers.

Nearly a hundred years ago some one thought of employing Six's maximum and minimum thermometer for temperature observations in the sea, various modifications being introduced, until finally in 1868 it became quite serviceable as made by Casella under the direction of Dr. Miller. The Miller-Casella thermometer (see Fig. 154) was the one principally used on board the "Challenger" and during other great expeditions. At the

Miller-Casella.

top there are two glass bulbs, united by a bent capillary tube; the left-hand bulb is filled with creosote, the capillary tube contains some mercury, and the right-hand bulb constitutes a vacuum except for a little creosote. When the thermometer is heated, the creosote on the left side expands, driving the mercury through the tube so that it rises in the right-hand branch; the mercury lifts a small index, a pin that is so constructed that it sticks at the place where the mercury leaves it. When the thermometer is cooled the creosote contracts, and the creosote-vapours in the right-hand bulb propel the mercury farther into the left-hand branch, where there is a similar index. In this way the index on the right shows the maximum temperature, and that on the left the minimum temperature. The thermometer is fastened to a rectangular plate carrying the temperature scale, and the whole instrument is put inside a protecting tube of copper. The maximum and minimum thermometer needs about twenty minutes for adjustment, and is slow enough not to change appreciably during a rapid hauling up from moderate depths, but if it has to be brought from great depths, erroneous results may be recorded, *e.g.* in waters where the temperature does not fall or rise uniformly towards the bottom. In Arctic and Antarctic seas, for instance, the temperature generally falls to a minimum at about 50 or 70 metres below the surface, rising to a secondary maximum at a depth of a few hundred metres, finally falling again towards the bottom, and this implies two maxima and two minima. In such a case Six's thermometer would show only the highest maximum and the lowest minimum encountered, and not the intervening values. This thermometer has, however, done very good service; it is, for instance, astonishing how correct the temperature determinations taken on board the "Challenger" have proved to be. In the great depths of the ocean the variations of temperature from year to year are so small that it is possible to verify now the observations of earlier expeditions.

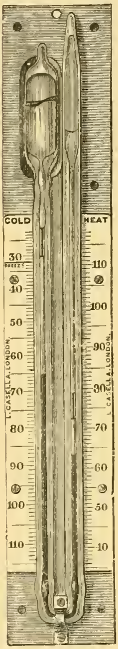


FIG. 154.
MILLER-CASELLA THERMOMETER.

Reversing thermometers

The French physicist Aimé about seventy years ago introduced the reversing thermometer, which is caused—either by a sliding weight ("messenger") or by a propeller-release—to turn upside down at the depth where the temperature is to be determined. The temperature is thereby registered, and can be read off at any time after the instrument has been hauled up. Aimé's instrument was, however, rather intricate. Aimé. In 1878 Negretti and Zambra of London constructed a reversing thermometer, which has played a prominent part in physical oceanography. Negretti and Zambra. In this form there is a narrowing of the tube just above the bulb; the mercury fills the tube above the narrowing to a greater or lesser extent according to the temperature, and when the thermometer is tipped over, the mercury breaks off at the narrowing, the portion which was above that point sinking down to the end of the tube (Fig. 155); the scale on the tube indicates the temperature at the moment of inversion. The thermometer must be able to withstand the pressure of the ocean depths, and is therefore placed inside a strong glass tube, with some mercury round the bulb of the thermometer in order to secure a rapid conduction of heat.

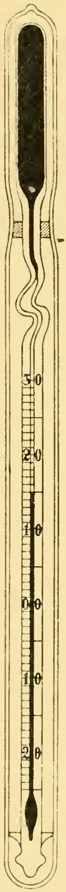


Fig. 155.
Negretti-Zambra Thermometer, after reversing.

The Negretti and Zambra reversing thermometer has latterly been widely used, but it has been found that occasionally the mercury broke off not exactly at the narrowing, but at some other place in the tube, while sometimes additional mercury might overflow during the process of hauling up. Certain improvements have therefore been introduced to remedy these defects, like the recent modifications by C. Richter of Berlin, who altered the breaking-off arrangement so as to render it quite trustworthy, Richter. and formed the tube in such a way that no superfluous mercury could enter it during the ascent (see Fig. 156). The severed column naturally lengthens or shortens somewhat according to the temperature changes to which it is subjected: suppose, for instance, the thermometer to be reversed in water of 2.00° C., and then hauled up through warmer water and read off in the air at a temperature of 20° C., the mercury-thread would have expanded a little, giving a reading perhaps of 2.25° C. instead of 2.00° C. This secondary change is easily calculated when the temperature of the mercury at the reading-off is known, and so inside the protective tube Richter has placed a small auxiliary thermometer (*d*), which gives the reading temperature, and thereby a correction for the reading.

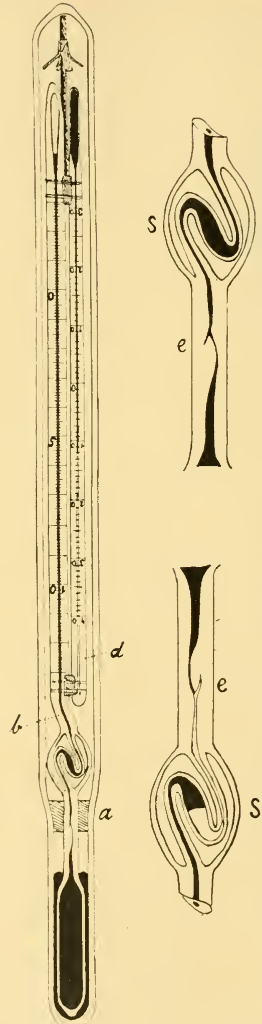


Fig. 156.—Richter's Reversing Thermometer. The mercury breaks at *e*; the figure on the left and the upper one on the right show the position of the mercury before reversing. The lower figure on the right represents part of the thermometer immediately after reversing.

In many cases it is necessary to have the temperature determined with the highest possible degree of accuracy, and Richter's reversing thermometer is very satisfactory in this respect. During the "Michael Sars" Atlantic Expedition the temperature series were taken almost exclusively by the aid of these thermometers, and in most instances two thermometers were used simultaneously, so as to make quite sure of the determinations. When the readings were corrected it was found that the mean difference between the values given by the two thermome-

Two thermometers used simultaneously.

ters in about 600 double determinations was only $\frac{1}{100}$° C., so that the temperature of the greatest ocean depths can now be determined with great accuracy.

Reversing mechanism.

A common form of reversing mechanism is a brass tube which can turn over within a frame. A pin retains the tube (into which the thermometer is placed) in an upright position; when the pin is withdrawn, the tube is tipped over by the aid of a steel spring. The pin is removed either by means of a propeller or by a messenger. The propeller is so adjusted that it does not move during the descent, but when the apparatus is pulled upwards it revolves, drawing out the pin along with it. Formerly this propeller-release was employed with many kinds of oceanographical apparatus, but it is not always reliable, especially in a rough sea, and the apparatus must be hauled up some distance before the propeller works. It is, therefore, gradually being superseded by the messenger, a small weight which is fixed on the line and let down after the apparatus has reached the desired depth. When the messenger reaches the reversing mechanism it knocks out the pin and the thermometer is turned upside down. One of the water-bottles used during the "Michael Sars" Expedition is reversed together with the thermometer; in other words, this water-bottle is a reversing mechanism for taking a temperature and a water-sample at the same time.

Pettersson-Nansen water-bottle.

The Pettersson-Nansen water-bottle has a very high insulating capacity, and the temperature of the water-sample is not affected by conduction even when hauled up from a depth of several hundred metres, though the apparatus may be drawn through water-layers having very different temperatures. Pettersson originally used an ordinary thermometer, which was inserted into the water-bottle after it came up. Then Nansen thought of fixing a thermometer inside the water-bottle, and in this way the temperature at any depth was determined more easily as well as more exactly. The Nansen thermometer is very delicate, and is protected by a strong glass tube against the great pressure.

Effect of great pressure.

In making temperature-observations, however, one special precaution must be taken. When a liquid is exposed to great pressure its volume is slightly diminished, and, some heat being liberated, the temperature of the liquid rises. Lord Kelvin studied this question carefully, and arrived at a formula by which such changes of temperature may be calculated. Conversely, the volume of a liquid released from great pressure increases, and by this process some heat is taken up which is drawn from the liquid, lowering its temperature. When, therefore, a water-sample is drawn up in an insulating water-bottle from a depth of 1000 metres, the temperature of the water-sample sinks a little. Nansen first called attention to this fact, and has drawn up tables for the corrections according to Lord Kelvin's formula. The corrections prove to be quite considerable. When employing an insulating water-bottle, account must be taken, not only of the alteration of volume in the water-sample, but also of that taking place in the solid parts of the water-bottle. A water-sample, for instance, brought up in an ordinary-sized Pettersson-Nansen water-bottle from a depth of 1000 metres in the Norwegian Sea, is cooled 0.06° C. while being hauled up; a sample from the same depth in the Mediterranean is cooled 0.17° C. This difference is due to the fact that the amount of cooling depends on the temperature of the water, which at 1000 metres in the Norwegian Sea is about $-1°$ C. and in the Mediterranean $+13°$ C.

We are here confronted with a problem of considerable interest. When a body of water sinks from the surface down to great depths, its temperature rises a little because of the compression. The "bottom-water" of the Atlantic Ocean averages nearly $2\frac{1}{2}°$ C.; supposing that it has sunk from the surface to a depth of 3000 metres, it has been heated about 0.27° C. in the course of its descent, by reason of the increasing pressure. If it should appear at the surface again, the reduction of pressure will have lowered the temperature by the same amount,—0.27° C. There are various other conditions which produce changes in the temperature, as, for instance, mixing with other bodies of water, in the upper layers absorption of solar heat, near the bottom possibly a very slight influence from the internal heat of the earth. It is, of course, difficult in such a combination of factors to single out the effects of one of them individually.

During the "Michael Sars" Expedition in the North Atlantic we made a certain number of observations in the deeper layers with a Richter reversing thermometer, which seemed to prove in several cases that the temperature increased slightly towards the bottom. The following extract from the "Michael Sars" tables shows the number of the station, the depth, the temperature (measured *in situ*), and the temperature that the water would acquire—on account of the reduction of pressure—if it were raised to the surface. The latter temperature has by the author of the present chapter been called the *potential temperature*, a term used in meteorology. Potential temperature.

Station. Depth to the bottom.	Depth of observation in metres.	Temperature *in situ*.	Potential Temperature.
10 A 4700 m.	3000 4500	2.43° C. 2.55°	2.16° C. 2.08°
49 C about 5400 m.	3950 4950	2.42° 2.46°	2.03° 1.92°
63 5035 m.	4000 4850	2.35° 2.37°	1.95° 1.85°

From these and many similar observations it is seen that the temperature in the deepest strata of the North Atlantic is about $2\frac{1}{2}$° C. (as a rule a little lower). The temperature of the deepest strata below 2000 fathoms appears to remain almost constant through long periods of time, the variations probably not amounting to more than a few hundredths of a degree. Very delicate instruments are necessary to detect them, and as yet we have insufficient observations to enable us to study the details.

It is apparent from the tables that the temperature would fall several tenths of a degree if the "deep-water" were raised to the surface without being heated by mixing on the way. This we have been able to prove in a direct way by means of the insulating water-bottle, which we used at Station 91 at a depth of 4750 metres, the temperature inside the water-bottle after hauling up being only 2.00° C., whereas the water at that depth was in reality several tenths of a degree warmer. When *in situ* the water has the temperature indicated by the reversing thermometer, but when brought to the surface it has the potential temperature nearly indicated by the thermometer inside the insulating water-bottle. Granted that no other change has taken place, the bottom-water must have had a temperature of about 2° C. at the time when it began sinking down from the surface; as it sinks the temperature gradually rises, and at Station 10 A, for instance, it was found to be 0.12° C. higher at 4500 metres than at 3000 metres. Some such increase of temperature towards the bottom has long been suspected as an effect of the internal heat of the earth; as early as about 1840 Aimé looked for it, but his methods were not sufficiently accurate. More recently several indications of a rise of temperature towards the bottom have been observed. The pressure and the internal heat having the same effect, it is difficult—at our present stage—to determine how much is due to the internal heat of the earth. In any case the bottom-water temperatures would be considerably lower but for the effect of pressure on the sinking waters.

It may be stated as a general rule that the temperature of

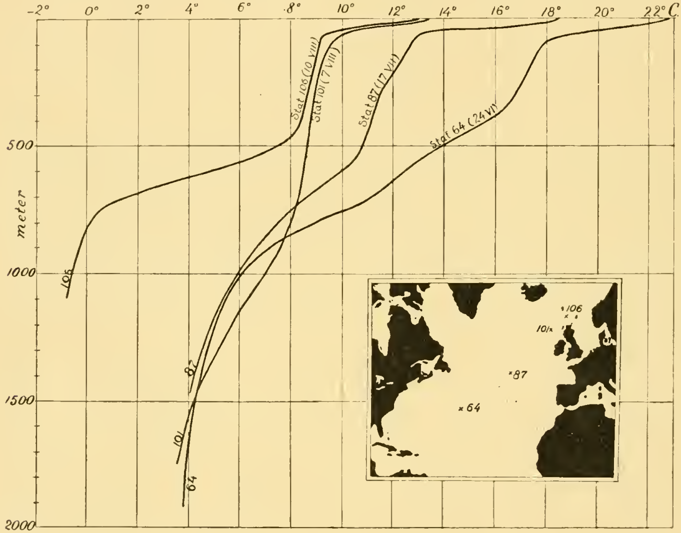


FIG. 157.—THE DISTRIBUTION OF TEMPERATURE AT FOUR DIFFERENT STATIONS IN THE SUMMER OF 1910.
The positions of the Stations are shown in the small inset map.

Decrease of temperature with increase of depth.

ocean water is in summer highest at the surface, and decreases gradually towards the bottom. Fig. 157 shows the distribution of temperature as observed at four stations during the "Michael Sars" Atlantic Expedition, the position of the stations being indicated on the little inset map. Station 64 is situated in the Sargasso Sea westward of the Azores, Station 87 in mid-ocean between France and Newfoundland, Station 101 between Scotland and Rockall, and Station 106 in the Faroe-Shetland Channel north of the Wyville Thomson Ridge. Station 106 belongs to the region of the Norwegian Sea, whereas the other three belong to the Atlantic proper; Stations 87, 101, and 106 all lie within the precincts of the "Gulf Stream." At all four stations the temperature is highest at the surface: 22°-23° C. in the Sargasso Sea (24th June), over 18° C. at Station 87 (17th July), 13°-14° C. westward of Scotland (7th August), and 13° C. at the station west of Shetland (10th August). It is worthy of note that a temperature of about 13° C. was observed at the surface near Scotland, while the same temperature occurred at a depth greater than 500 metres in the Sargasso Sea.

From the surface downwards the temperature falls very rapidly for the first 50 or 100 metres; at 100 metres it is from 4° to 6° C. colder than at the surface. Beyond 100 metres the temperature decreases at first much more slowly, then rapidly again, and then very slowly until the great depths are reached, where the temperature changes very little. The layers in which the temperature changes very rapidly are called "discontinuity-layers" (by the Americans "thermocline," and by the Germans "Sprungschicht"). They are particularly marked at Station 106, where there is such a layer immediately below the surface, and another extending from 450 to 750 metres. Between the two (from 50 to 450 metres) there is a fairly uniform stratum, and another one under the deeper layer, from 750 metres to the bottom. At the other three stations the upper discontinuity-layer is also very strongly marked, but the lower one is not so sharply distinguished from the adjoining water-strata.

Discontinuity-layers.

It will be noticed that the temperatures in the deep strata (below 800 or 900 metres) were, at the same depths, nearly identical at the three stations in the Atlantic proper, the differences not exceeding 1° C., although these stations are situated far apart; but at Station 106 in the Norwegian Sea the temperature was 7°-8° C. colder. This is due to the form of the bottom, the Wyville Thomson Ridge separating the deep layers of the Atlantic from the deep layers of the Norwegian Sea, so that at a depth of 1000 metres the temperature is 6°-7° C. in the Atlantic Ocean, and below 0° C. in the Norwegian Sea. That implies two widely different deep-sea regions: a warm one south of the ridge, and a cold one to the north of it, with great differences in the deep-sea fauna of the two regions. The influence of the Wyville Thomson Ridge is very clearly seen in a section across the ridge (see Fig. 106, p. 124), from Station 101 to Station 106; in the upper strata, down to 500 metres, there is little difference, but the deeper strata are like

Wyville Thomson Ridge.

two different worlds, the Atlantic world south of the ridge, the Arctic world north of it.

Decrease of surface-temperature from equator to poles.

The surface-temperature is naturally high in the equatorial regions, decreasing toward the poles, where it falls below 0° C. Krümmel has calculated the mean surface-temperatures for each 10-degree zone throughout the great ocean basins, his figures for the North Atlantic being:—

Zone	0°-10°	10°-20°	20°-30°	30°-40°	40°-50°	50°-60°	60°-70° N. lat.
Temp.	26.83	25.60	23.90	20.30	12.94	8.94	4.26 °C.

It is interesting to compare this horizontal distribution of temperature with the vertical distribution in tropical waters. The following temperatures, for instance, were recorded by the German Antarctic Expedition in July 1911, at a station in lat. $7\frac{1}{2}°$ N. in the middle of the Atlantic:—

Depth	0	100	200	400	800	1000 metres.
Temp.	26.86	18.57	10.71	7.70	5.13	4.81 °C.

At a depth of 100 metres the temperature is seen to be the same as the average surface-temperature in about 40° N.; the mean surface-temperature at 50° N. is the same as that found at 200 metres in the tropics, and the mean surface-temperature at 60° N. corresponds to the temperature at a depth of 700–800 metres in the tropics. In other words, we have a horizontal distribution of temperature from the equator towards the poles similar to what we have vertically from the surface towards the bottom in the tropics. Near the equator one need only send a thermometer down to 800 metres in order to find the same temperature that one would have to travel 60° northwards to find at the surface, but the other physical conditions are widely different. In the deep water at the equator there is an enormous pressure and unchanging darkness, but at the surface far north and south there is a pressure of only one atmosphere and good light, at least in summer. Thus the physical conditions in the deep layers of the tropical waters are really very different from those at the surface towards the poles, and in consequence the conditions of life also differ; organisms living in the surface-layers of high latitudes are found in far deeper water in low latitudes, in so much as they are capable of adapting themselves to the excessive pressure and the infinitesimal quantity of light. Some organisms seem to be mainly dependent on the degree of light, the temperature being of less importance to them. We shall return to the questions of light and pressure, and the geographical distribution of animals, later on.

Absorption of heat at the surface of the sea.

The high temperature at the surface evidenced by the curves in Fig. 157, is principally due to the absorption of heat-rays from the sun. In places the water is heated by contact with warm air, but this source of heat is of less importance, the temperature of the surface-water being, as a rule, higher than the temperature of the air. The sun's rays penetrate into the water and are absorbed; the dark heat-rays are absorbed in the uppermost layers, while the light rays, which also convey a little heat, make their way down to a depth of several hundred metres before disappearing altogether. The action of the sun's rays is strongest in the tropics, declining towards the north and south, and this in a general way explains the distribution of the surface-temperature.

Storage of heat in closed basins.

A fine example of the heating action of the sun's rays is afforded by the Norwegian oyster-basins. Along the west coast of Norway there are in many places salt-water basins, separated from the outer fjord by a sill, which is covered only at high water. At the surface the water of the "poll"—as such a basin is called in Norway—is comparatively fresh, and consequently light; from a depth of about one metre to the bottom it is very salt and heavy. The sun's rays in summer penetrate into the water and heat it, mostly at the surface, but also to some extent down to a depth of a few metres. The surface-water is cooled during the night, but at a depth of one or two metres beneath the surface the heat will not be given off so readily, because the heavy water there does not reach the surface. When this has gone on for some time, the temperature at a depth of a few metres may be remarkably high, sometimes fully 35° C., while the temperature at the surface might be about 20° C. In these "polls" the surface-layer of relatively fresh water prevents the layers below from coming into contact with the cooling air, and such polls may indeed be compared to hot-houses, the fresh surface-layer corresponding to the fixed transparent roof, under which heat is stored.[1] In these oyster-basins absolutely tropical conditions are developed in summer. It is significant that Gran once found in one of them a small crustacean, which according to G. O. Sars belongs to the Guinea Coast. Fig. 158 shows the temperatures and salinities in an oyster-basin in the early part of the summer before

[1] Compare Murray and Pullar, *Bathymetrical Survey of the Fresh-Water Lochs of Scotland*, vol. i. pp. 580, 581, and 587, Edinburgh, 1910.

the maximum temperature has been reached, but already on the 10th June (1903) the water of this poll is seen to be 5° C. warmer at a depth of 2 metres than at the surface.

Conduction of heat.

To understand how such a high temperature can be preserved for a length of time at a depth of 2 metres, one must bear in mind the fact that the conduction of heat plays an altogether subordinate part in the thermal conditions of the sea. Kelvin and Wegemann have made some calculations on the transmission of heat in water by conduction; Wegemann commences with a sea 5000 metres deep, with a temperature of 0° C. throughout; the surface is supposed to be in contact with a

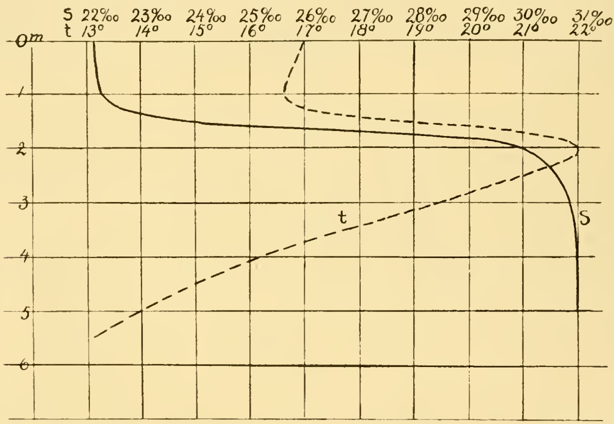


FIG. 158.—THE VERTICAL DISTRIBUTION OF TEMPERATURE (*t*) AND SALINITY (*s*) IN THE KVERNE-POLL, 10TH JUNE 1903.

source of heat at a temperature of 30° C. No forces intervening other than conduction, no heating effect would be perceived at a depth of 100 metres after 100 years, and after 1000 years the temperature at 100 metres would only have reached 7.3° C., and at 200 metres 0.6° C. It is thus seen that transmission of heat by conduction is practically negligible in the sea. The heat conveyed by the sun to the uppermost water-layers cannot therefore be propagated into deep water by conduction, but only through movements of the water—waves, currents, convection "currents," etc. Where there is no such motion, and where the sun's rays cannot penetrate, heat cannot be transmitted by conduction, and hence we find temperatures as low as 2° C. or less in deep water even under the equator.

In winter, heat will be radiated from the sea-surface to the colder air, and the temperature will be lowered. In Figs. 159 and 160 two maps of the North Atlantic, one for February and one for August, are reproduced from *Atlantischer Ozean, ein Atlas*, published by the Deutsche Seewarte in Hamburg. In the February map the isotherm of 25° C. runs from the Antilles towards the east and a little to the south, in the direction of Africa, whereas in August this line lies, in the western part of the ocean, as much as twenty degrees of latitude

Radiation of heat from the surface of the sea.

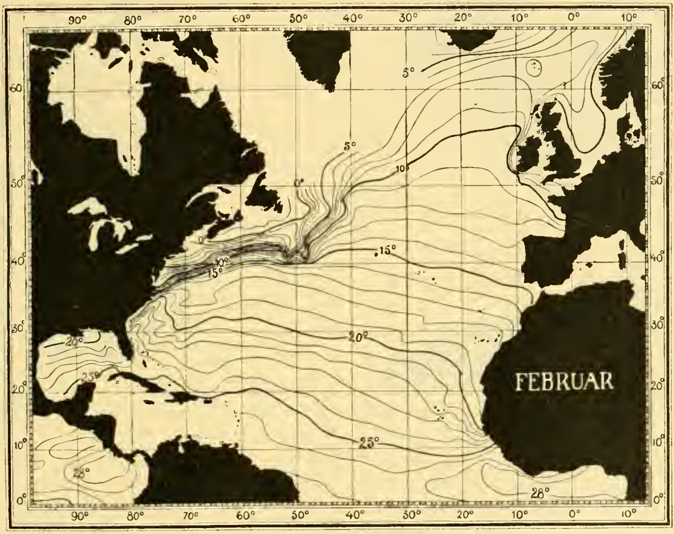


Fig. 159.—Surface Temperature of the North Atlantic in February.

farther north. In the same way the other isotherms have more northerly positions in summer than in winter. The difference between the surface-temperature in February and in August is about 5° C., in some places less, in others considerably more. Near land the annual variations are much greater, as in the coast-water within the Norwegian skjærgaard ("skerry-guard," literally: "fence of islands"), where the surface-temperature in summer is 15°-20° C., and in winter only a few degrees above zero. Beneath the surface the variations gradually decrease, and at a depth of a few hundred metres no marked seasonal variations can be traced.

At a certain depth a displacement of the seasons is often found. Repeated observations have been made by the "Michael Sars" at a station outside the entrance to the Sognefjord in different seasons and in different years. In 1903, measurements were made at this station in the months of

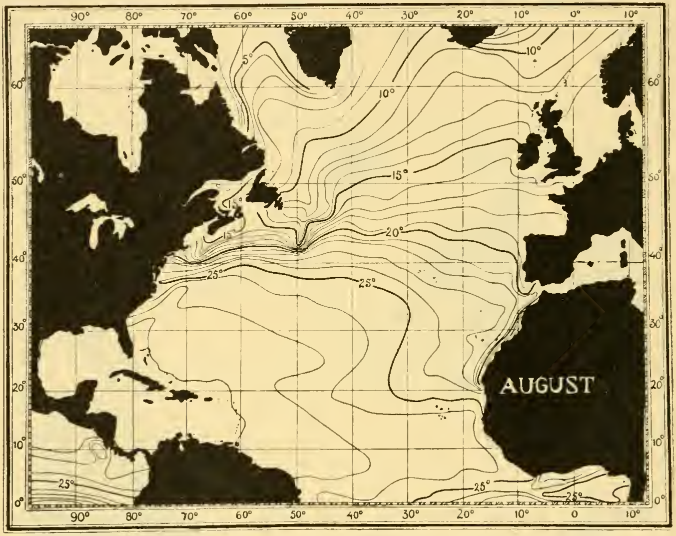


FIG. 160.—SURFACE TEMPERATURE OF THE NORTH ATLANTIC IN AUGUST.

February, May, August, and November, and the following temperatures were found :—

	February.	May.	August.	November.
Surface	4.8° C.	7.3° C.	13.8° C.	8.7° C.
100 metres . . .	6.8°	6.4°	6.9°	9.3°
200 ,, . . .	7.9°	7.0°	6.7°	7.9°
300 ,, . . .	6.3°	6.5°	6.4°	...

Reversal of seasons at a depth of 200 metres.

At the surface it was coldest in February and warmest in August—the difference being 9° C. At 100 metres it was coldest in May and warmest in November, with a difference of 2.9° C. At 200 metres it was coldest in August, warmest in February and November, the difference being 1.2° C., so that at this depth the seasons were reversed: it was "winter" in the water in the middle of the summer, and "summer" in the middle of the winter. Murray's observations in Upper Loch Fyne in 1888 gave similar results. At 300 metres at the "Michael Sars" Station there were hardly any variations at all, the temperature being very much the same as the mean annual temperature of the air, as Nordgaard has shown to be the case with regard to the bottom-water of the Norwegian fjords.

Vertical circulation of ocean waters.

When sea-water is cooled its density increases, and it often happens in winter that the surface-water becomes heavier than the water below. The surface-layer then sinks, and the underlying water comes to the surface. By this vertical circulation the conditions are equalised, so that exactly the same salinities and temperatures are found as far down as the vertical circulation extends; wind and current aid in the process. This takes place especially from January to March; in April the weather again becomes warmer and the temperature begins to rise at the surface. A very good example of this phenomenon is afforded by the "Michael Sars" observations taken to the westward of Plymouth in April 1910; at the very surface the temperature had risen slightly, but otherwise practically the same salinities and temperatures prevailed at every station down to a depth of 150 metres or more. Later on in spring the surface temperature gradually rises, and a marked discontinuity-layer is formed. In many places near the coast, where the salinity is low at the surface and high beneath the surface, a brisk vertical circulation cannot be set up; the comparatively fresh water on top is so light that, even when considerably cooled, it does not change places with the salt and heavy water below. But farther out to sea the vertical circulation may extend down to a depth of 200–300 metres or more.

Effect of heat given off by the sea.

It is thus not only the surface-water that may give off heat to the air, but a great body of water extending to several hundred metres in depth, and hence the great influence of the sea on winter climates. The capacity for heat of water is very great compared with that of the air. Supposing that we have 1 cubic metre of water giving off enough heat to the air to lower the temperature of the water one degree, this heat would be sufficient to raise the temperature of more than 3000 cubic metres of air by one degree. An example will show the importance of this. Suppose a body of water, 700,000 square kilometres in extent and 200 metres deep, to give off enough heat to the air in winter to lower the water-temperature one degree, then the heat given off would be sufficient to raise the temperature of a stratum of air covering the whole of Europe to a height of 4000 metres on an average ten degrees. This explains how the Gulf Stream renders the climate of northern Europe so much milder in winter than would be expected from its northerly latitude. We shall see later on that the oceanographical researches of the last few years give reason to hope that it will even be possible to predict the winter temperature of northern Europe from the temperature of the sea some time in advance.

Gulf Stream.

The salts of the sea.

There are many different salts in the sea. Salinity means the total amount of salts in a given quantity of sea-water, and is usually stated in parts per thousand (*per mille*), indicating how many grams of salt are contained in one kilogram of sea-water. The salinity of the sea varies considerably both horizontally and vertically, and its distribution is determined by examining samples of water from different parts and different depths; these samples are secured by means of various water-bottles. From the surface a sample may be drawn with an ordinary bucket. For shallow waters down to 30 or 40 metres a common glass bottle is often employed; the line is bound to the neck of the bottle and a weight is suspended underneath. The stopper is fastened to the line a little way above the bottle, and is inserted when the bottle is lowered. When this simple water-bottle has arrived at the depth from which the sample is to be taken, the line is given a sharp pull, so that the stopper is drawn out and the bottle fills. In hauling up, a little water from the upper layers may, of course, enter the bottle, but this simple method does well enough for shallow water near land, where the variations are so great as to render extreme accuracy unnecessary.

Salinity determined from water-samples.

Obtaining samples from surface and shallow water.

Obtaining samples from deep water.

Many varieties of water-bottles for investigations in deep water have been constructed. A few of those most in use, and most effective in working, may be described, and the different principles involved explained.

Buchanan's stopcock water-bottle.

We will begin with an apparatus designed by J. Y. Buchanan for the "Challenger" Expedition, a so-called stopcock water-bottle (Fig. 161). It consists of a brass tube (A), which can be closed at both ends by means of metal stopcocks (B, B); the latter are, through two levers (D, D), connected with a rigid rod (O, O). When the side-rod is in the upper position, as seen in the left-hand and central figures, the cocks are open. A tilting plate

(E) is hinged on to the rod. In the left-hand figure the plate is tilted upwards, and it remains in that position while the

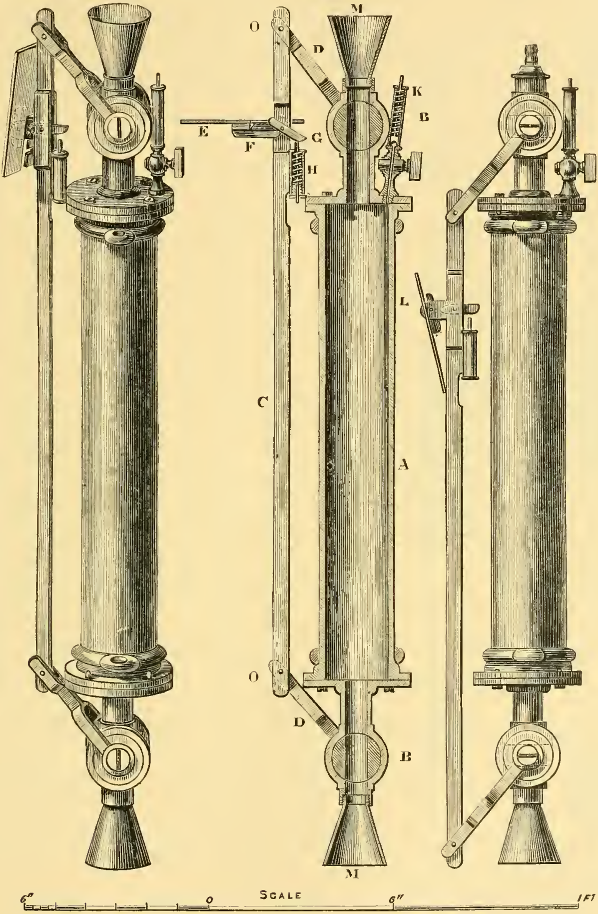


FIG. 161.—BUCHANAN'S STOPCOCK WATER-BOTTLE.

apparatus is being lowered. But as soon as it is pulled upwards the water presses against the plate, tilting it into the position shown in the middle figure; the rod is then forced downwards, and along with it the levers, closing both stopcocks simultaneously. The plate then falls into the position seen in the right-hand figure. This simple arrangement allows of enclosing a water-sample at any depth required. This water-bottle has done very good service; it was much used on board the "Challenger," and has also—with a few small improvements—been employed a good deal in later times.

In a stopcock water-bottle of this construction the temperature of the water-sample may alter during the hauling-up process, and it is impossible to get a record of the temperature *in situ* with the water-sample, without having a special apparatus for the thermometer. Buchanan himself, and later on Nansen, modified this water-bottle by adding an arrangement for a thermometer, which would be reversed the moment the cocks were closed. In the meanwhile Otto Pettersson had adopted F. L. Ekman's old idea of making a water-bottle which should be insulating, so that the water-sample would retain its temperature unchanged, even when drawn up from a great depth. Pettersson availed himself of the circumstance that the water itself is an excellent insulator, its power of conduction being small and its capacity for heat very great. This water-bottle consisted of a bottom-piece, a cylinder, and a lid; these three parts could be separated by lifting up the cylinder and the lid along two brass rods forming the sides of the encompassing frame. The cylinder is a composite one; inside a strong cylinder of ebonite there are various other cylinders of celluloid and brass, one inside the other like a set of Chinese boxes. Between these concentric tubes are narrow cylindrical spaces which fill with water when the apparatus is lowered into the sea, and in this way a system of excellent water-insulators is formed. The outer cylinder may alter in temperature considerably in the course of hauling-up, the inner ones less and less, until in the central chamber the temperature will not change at all for some time, although the water-bottle be strongly heated from without. On the bottom and on the lid Pettersson attached a number of parallel plates, which likewise enclose insulating water-layers.

Pettersson's insulating water-bottle.

Nansen has introduced several improvements, and the latest model—the so-called Pettersson-Nansen water-bottle—is an excellent apparatus, which is now very widely used (see Fig. 162). On the left it is seen open, as it is let down into the water; the lid is suspended in the upper part of the frame, and supports the cylinders as well as a weight hanging below the

Pettersson-Nansen water-bottle.

apparatus. When a messenger is sent down the line and strikes the water-bottle, the lid is released, and the weight draws both lid and cylinders down, clasping the apparatus together and closing it hermetically. The right-hand figure shows the water-bottle closed and ready for hauling up. The Nansen thermometer is seen in the left-hand figure, and is — as mentioned above — a thin delicate instrument, fitted inside a strong protective glass-tube in order to withstand the enormous pressure of the deep sea. The Pettersson-Nansen water-bottle is so well insulated that the temperature of the water-sample is not influenced from without, even when being hauled up from a depth of 1000 metres. But the temperature is lowered slightly, in consequence of the reduction of pressure during the process of hauling up, as has already been mentioned. This circumstance asserts itself quite appreciably in the case of the insulating water-bottle when used at great depths. The water-bottle is, however, fitted with a frame for carrying a reversing thermometer, so that a double determination may be made. During the "Michael Sars" Expedition we very often employed the insulating water-bottle, and took temperatures both with the Nansen thermometer and with the Richter reversing thermometer simultaneously. As an example, an observation made at Station 101 in 1400 metres may be mentioned: after correction the Nansen thermometer read 4.45° C., the Richter thermometer 4.59° C., that is 0.14° C. lower in the first case than the second. The water in the water-bottle should, according to the calculation by Lord Kelvin's formula, have been cooled 0.12° C.; granting that the determinations

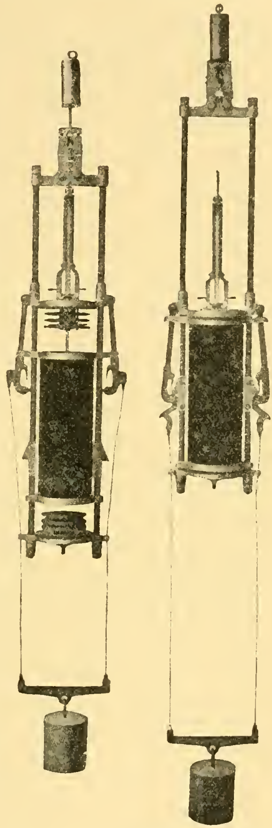


Fig. 162. — Pettersson-Nansen Water-Bottle.

Shown open in the left-hand figure, and closed in the right-hand figure.

are absolutely correct, the cooling of the solid parts of the apparatus accounts for the difference of two-hundredths of a degree, which is a very probable value. This is an instance chosen at random from a vast number of observations, and proves how accurately deep-sea temperatures can now be determined.

Ekman reversing water-bottle.

V. W. Ekman has constructed an apparatus to serve as a reversing mechanism and a water-bottle at the same time. The apparatus is made of brass, and consists of a frame carrying inside a cylinder pivoted on an axle at the middle of the frame (see Fig. 163). At either end of the cylinder there is a lid, to which are attached two pairs of levers fastened to the frame near the axle of the cylinder. The cylinder can be placed in such a position that both lids are open, and it is kept in this position by means of a small pin, seen at the top of the frame on the right. Thus adjusted the water-bottle is let down into the sea. A messenger is sent down after it and knocks out the pin; the cylinder is poised in such a way that it turns over in the frame. The levers gradually draw the lids closer, and when the cylinder is wholly reversed it is held fast by a catch and encloses the water-sample hermetically. To the side of the cylinder is attached a metal sheath for holding a reversing thermometer, which is consequently reversed along with the water-bottle. This apparatus may be fastened anywhere on the line, and a number of them may be used at the same time, in which case the messenger-release is arranged in the following manner: In the figure a messenger is seen hooked on to a small bar underneath the water-

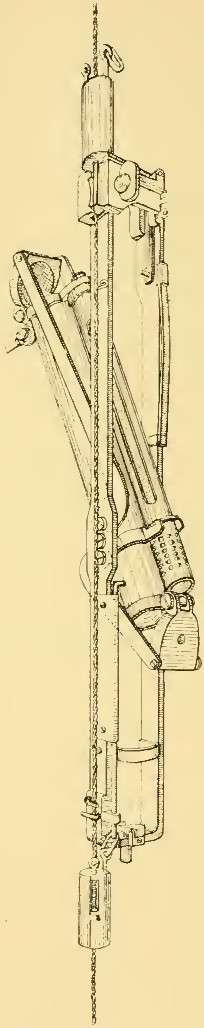


Fig. 163.—Ekman's Reversing Water-Bottle in process of being reversed, and shortly after being released.

bottle; when the water-bottle is reversed the bar is withdrawn, and the messenger is let go. The next water-bottle is knocked over, releasing in its turn the following messenger, and so on. It is indispensable with this, as with all other water-bottles, that when closed it should be absolutely water-tight, otherwise water might get in from the higher layers and vitiate the sample.[1]

The water-sample, when brought on board, may be dealt with at once, and its salinity, etc., determined, but it is generally the best plan to store the samples for examination in a shore laboratory. In this case the samples must be preserved absolutely air-tight, so that they shall not suffer any change in the interval. As a rule, the water may be kept in good glass bottles with lever stoppers, like those used in soda-water bottles. Cork stoppers will not do, unless capped with paraffin or wax, as it is difficult to avoid some degree of evaporation which would invalidate the results.

Preservation of water-samples for examination on shore.

The chemical composition of sea-water has been very carefully determined. Wellnigh all known elements are found in solution in the sea, but most of them in such small quantities as to be detected only by the most delicate methods. A kilogram of sea-water contains about 35 grams of solid substances altogether; the quantity varies slightly in different places, but on an average there are about 35 weight-units of solids in 1000 weight-units of sea-water (35 per thousand). According to the results of Dittmar's analyses of the "Challenger" water-samples there are on an average in 1000 grams of sea-water :—

Chemical composition of sea-water.

	Grams.	Percentage on total solids.
Sodium chloride ($NaCl$) . . .	27.213	77.76
Magnesium chloride ($MgCl_2$) . .	3.807	10.88
Magnesium sulphate ($MgSO_4$) . .	1.658	4.74
Calcium sulphate ($CaSO_4$) . . .	1.260	3.60
Potassium sulphate (K_2SO_4) . .	0.863	2.46
Calcium carbonate ($CaCO_3$) . .	0.123	0.34
Magnesium bromide ($MgBr_2$) . .	0.076	0.22
Total	35.000	100.00

[1] The highest perfection must be exacted with regard to this point. It formerly frequently occurred that the instruments leaked a little; as the knowledge of the sea has grown, many

The numerous other substances in solution are present in such extremely small quantities that they may be disregarded. Although the total salinity may vary widely, the composition of the dissolved solids proves to be practically the same everywhere. Hence if in a sea-water the percentage of any one component, say chlorine, be known, the total salinity can be ascertained by calculation.

Determination of salinity.

The direct determination of salinity by evaporating a known volume of water to dryness does not give accurate results, unless the amount of chlorine is carefully determined before and after the evaporation, because in the last stages of evaporation and in drying the residual salt uncertain amounts of chlorine are disengaged in the form of hydrochloric acid. Such a determination is very circumstantial, and it is therefore necessary to resort to indirect methods, which may be physical or chemical.

Physical methods.

An old-established physical method consists in determining the density by means of the hydrometer. This is a glass cylinder which floats in the water and has a graduated stem, on the scale of which densities are read off. The temperature of the water must be determined at the same time. Densities so found are recalculated by means of tables to a standard temperature, generally 17.5° C. Now, owing to the uniform composition of sea-salts, a definite density at 17.5° corresponds rigidly to a definite salinity. Hence by referring to tables the salinity of a sea-water can be found from its density at standard temperature.

The hydrometric method is easily applied on board ship, and may be made to give densities correct to four places of decimals. Densities can be determined to a yet higher degree of accuracy by means of the pycnometer, but this method is practicable only in a laboratory on land, and is not often employed.

Two other physical methods have been tried by way of

errors have been detected in earlier determinations referable to the leaky condition of the water-bottles.

When the forms of apparatus described above are to be used, the vessel must be stopped and hove to as long as the work goes on. Recently several investigators have studied the problem of constructing a 1 apparatus to be used while the ship is under way. Water-bottles have been made which can be let out when the ship is going at full speed, with the line running freely so as to allow them to sink. On checking the line the apparatus is closed by a mechanism like that used by Buchanan in his water-bottle. The water-bottle being insulating, a temperature-reading is secured together with the water-sample. In such an experiment a metre-wheel showing how much line has run out is no use; one must have a special depth-gauge, usually one to measure the compression suffered by a certain volume of air from the weight of the water. These new instruments are not in common use as yet, being still in the experimental stage, but the time is not far off when we shall have automatic water-bottles working with absolute precision. That will mark an important step forward, as much time will then be saved in an expedition.

experiment, but are not in general use. The one consists in measuring the refractivity of the water, *i.e.* the deflection undergone by a ray of monochromatic light when passing from air to water; this quantity, again, stands in definite relation to the salinity of the sample. The other method is based on the electrolytic conductivity of sea-water, and has the advantage that no sample need be brought up, a pair of electrodes being simply sent down to any required depth and the readings being taken on board. This method has been applied by Martin Knudsen with good results in shallow water.

Chemical methods.

The most convenient, and on the whole the most satisfactory, method of determining salinity is a chemical one, and is based on the fixed relation between the chlorine contained in a sea-water and its total salinity.

Chlorine titration.

The amount of chlorine can be determined by a rapid and easy method. When a solution of silver nitrate is added to sea-water, the chlorine is thrown down as a white precipitate of silver chloride. If a few drops of yellow chromate of potassium are added it is easy to see when all the chlorine is precipitated, for the silver nitrate will then act on the chromate so that the yellow colour is changed into red. When the chlorine content of a water-sample is to be determined, a certain quantity (*e.g.* 15 c.c.) is measured off and poured into a glass; a few drops of the yellow chromate solution are added as an indicator, and then nitrate of silver from a burette, that is, a graduated glass tube with a stopcock (for discharge) at the lower end (see Fig. 164). When the red colour appears, the burette is read off to find out how much silver solution has been added, and it is easy from this value to calculate the amount of chlorine. From Knudsen's Hydrographical Tables the salinity or the specific gravity, corresponding to this chlorine-value found by titration, may be determined. All this can now be done quickly and accurately; in fact, the salinity of a water-sample is determined in less than five minutes to within about $\frac{1}{100}$ *per mille*, *i.e.* 1 centigram of salt per kilogram of sea-water. The modern method of chlorine titration is a great improvement on former methods, and it has been much used in recent oceanographical work, thousands of such determinations being now made yearly.

Density of sea-water.

The density of sea-water depends both on the salinity and on the temperature; the water is comparatively light when the salinity is low and the temperature high, and increases in density with a rise of salinity and a fall of temperature.

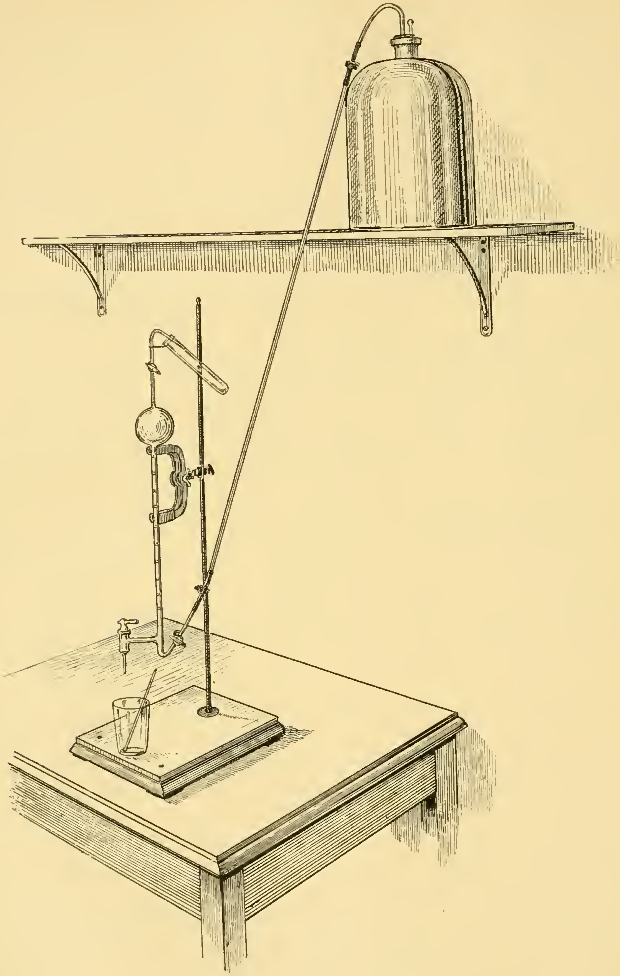


FIG. 164.—TITRATION APPARATUS.

On a shelf there is a large bottle for the silver solution, which can flow through a glass tube into the burette ; the latter is provided with cocks for regulating the inflow and the outflow of the solution.

Fresh water has its greatest density at 4° C., which is taken as unity. Salt water becomes heavier the lower the temperature, the density of sea-water with a salinity of 35 per thousand and at a temperature of 0° C. being 1.02813. By means of Knudsen's Tables the density is quickly found when both salinity and temperature are known. The value of most interest to us is the density at the potential temperature (see above, p. 221) corresponding to the temperature *in situ*. It has been found that this density always increases from the surface downwards to the bottom, even when the compression is left out of account. If this were not so, in order to attain equilibrium the heavier overlying water and the lighter underlying water would have to change places, and this is what actually takes place in winter, when the density at the surface exceeds that of the waters below. The layers will always arrange themselves in such a way that the lighter water is on the top and the heavier water underneath.

Freezing-point.

Salt water freezes at a lower temperature than fresh water; thus sea-water with a salinity of 35 per thousand freezes at $-1.9°$ C., so that temperatures below zero are found in the sea, $-1\frac{1}{2}°$ C., for instance, being a common temperature in the polar currents. When the salinity exceeds 24.7 per thousand the water becomes heavier on being cooled, until the freezing-point (below zero) is reached. This implies an essential difference between salt water and fresh water. In the deep water of lakes temperatures below 4° C. are never found, while in the bottom-water of the ocean considerably lower temperatures prevail, as, for instance, $-1°$ C. or still lower recorded in the Norwegian Sea, and about $+2°$ C. recorded in the Atlantic. Thus it is, as a general rule, colder in the great depths of the ocean than it is at the bottom of deep lakes.

Distribution of salinity.

We shall now indicate in a general way the distribution of salinity. It must be remembered that the salinity is raised by evaporation, and lowered by dilution with fresh water either from rainfall or from rivers. Where the evaporation outweighs the supply of fresh water the salinity increases, as is the case, for instance, in the Mediterranean and in the Red Sea, where the air is dry and hot, and in the ocean north and south of the equator, where the warm trade-winds blow, producing a strong evaporation. In such places a high salinity will be found.

Mediterranean.

There is a steady inflow of Atlantic surface-water with a salinity of about 36 per thousand into the Mediterranean Sea, where the water removed by evaporation is far greater than the supply of fresh water, so that the salinity rises to 38 per thousand, accompanied by an increase in density, which is accentuated by the cooling down in winter, and the surface-water becomes so heavy that it sinks and forms the bottom-water of the Mediterranean.

Coastal districts.

On the other hand, there are coastal districts where the many large rivers constantly carry more water into the sea than what is evaporated from it. In such places the salinity is decreased, as, for instance, off the coasts of Scandinavia. A great part of the rain falling in Northern and Central Europe, as far south as the Alps, is carried by rivers into the Baltic and the North Sea, where it is mixed with the salt water, producing the so-called "coast-water" of comparatively low salinity. The density of the coast-water is so low that it

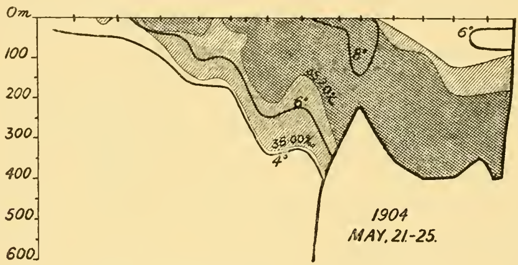


Fig. 165.—The Sognefjord Section, May 1904.

Salinities above 35.0 per thousand shown by single hatching; salinities above 35.20 per thousand shown by cross hatching.

always floats on the top, and often glides along a substratum of more saline water. Such coast-water forms the Baltic current, running out of the Baltic Sea through the Kattegat and Skagerrak, continuing on its way along the coast of Norway, above the salter and heavier Atlantic water carried north by the "Gulf Stream."

Fig. 165 represents a section from the mouth of the Sognefjord (near Feje) westwards to a little north of the Faroe Islands. The Atlantic water is marked by hatching, and we see the coast-water lying on the top, close to the land on the right. This section has been examined through a succession of years in the month of May, and we have measured the coast-water section in square kilometres. The top curve (I.) in Fig. 166 shows how this section has varied from year to year. Now it proves to be the case, as was to be expected, that these variations to a certain degree correspond to the variations in the rainfall. The other curves show the divergences (per cent) from the normal annual rainfall, (II.) for Christiania, (III.) for Bergen, (IV.) for Germany; (V.) shows the divergences in Norway during the months of October, November, and December. On the whole, the rainfall corresponds well with the transverse section of the coast-water some time afterwards. The rainfall was comparatively small in 1902, and the coast-water had a small transverse section in May 1903; the rainfall was large in 1903, and there was much coast-water in May 1904, and so on. The effect of the rainfall on the land is not immediately felt in the coast-current off western Norway; there is a delay which seems to make it possible to predict some time beforehand if there is going to be much or little coast-water. This is an example of the predictions likely to be undertaken in the future, when the sea and the air have been more closely studied.

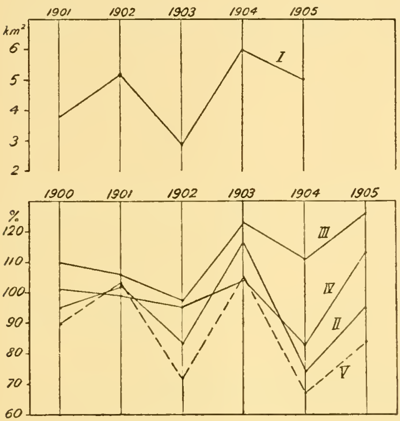


FIG. 166.—CURVES SHOWING THE VARIATIONS IN I. the transverse section of the coast-water off Feje (May); II., III., IV., the annual rainfall for Christiania, Bergen, and Germany respectively; V., the rainfall in Norway during October, November, and December.

We shall now, after these introductory remarks, examine the vertical distribution of salinity in some different places, as found in the cruise of the "Michael Sars." Fig. 167 represents the physical conditions a little to the north of the Sargasso Sea, at Station 65, on 25th June 1910. In this, as well as in the following figures, the continuous line indicates the salinity, the broken line the temperature, and the dotted line the density.[1] We see that the salinity is greatest at the surface, 36.43 per thousand; this is the result of the strong evaporation. It decreases downwards, at first rapidly, then more slowly, more rapidly again, and finally very slowly; in the deep layers below 1250 metres the salinity is less than 35 per thousand, and throughout the great body of the deep water 34.9 per thousand.

Sargasso Sea region.

[1] The density is given in abbreviated form, *e.g.* 25.56 instead of 1.02556, and is indicated by the Greek letter σ (σ_t being the density at the temperature *in situ* disregarding the compression).

The density increases from the surface to the bottom, but with varying rapidity; through the first 100 metres it increases rapidly, and also in the discontinuity - layer between 600 and 1100 metres.

Between Scotland and Rockall.

Fig. 168 shows the conditions on the 7th August 1910, at Station 101, between Scotland and Rockall, in that branch of the Gulf Stream which flows towards northern Europe. The salinity at the surface is here 1 per thousand lower than at Station 65 near the Sargasso Sea,

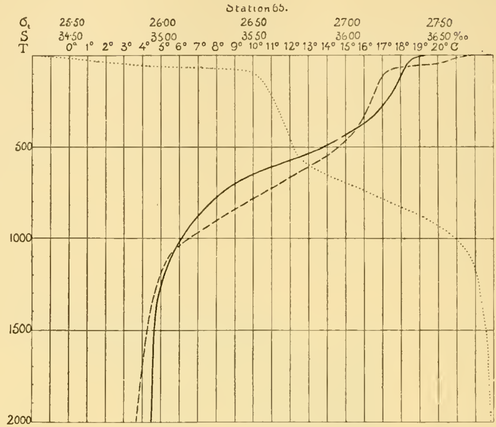


Fig. 167.—Temperature (broken line), Salinity (continuous line), and Density (dotted line) at Station 65, a little north of the Sargasso Sea (25th June 1910). Depth in metres.

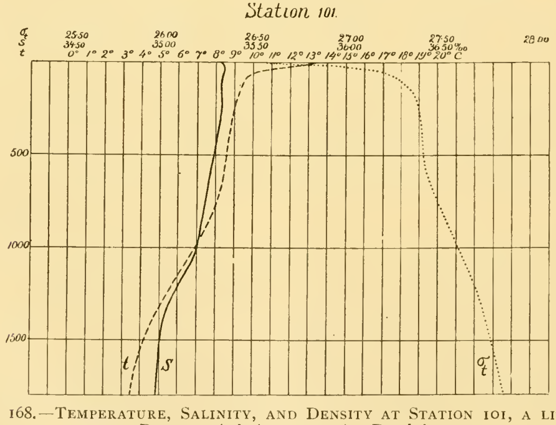


Fig. 168.—Temperature, Salinity, and Density at Station 101, a little east of Rockall (7th August 1910). Depth in metres.

due to admixture of fresh water; but from about 900 metres down to the bottom the salinity, temperature, and density are all very much alike in these two places, nearly 2000 nautical miles distant from each other. There is thus a marked difference as far as the upper layers are concerned, both salinity and temperature decreasing northwards, while in the deep layers below 500 fathoms the conditions are the same throughout the middle and north-eastern part of the North Atlantic. Northwards from Station 65 to Station 101 the decrease of temperature in the upper layers is more marked than that of the salinity, so that the density of the surface-layer increases from 1.0254 at Station 65 to 1.0266 at Station 101. As a general rule, the upper water-layers, on being cooled, become gradually heavier from the tropics toward the poles.

Fig. 169 shows the conditions at Station 106, 10th August 1910, in the Faroe-Shetland Channel to the north of the Faroe Channel.

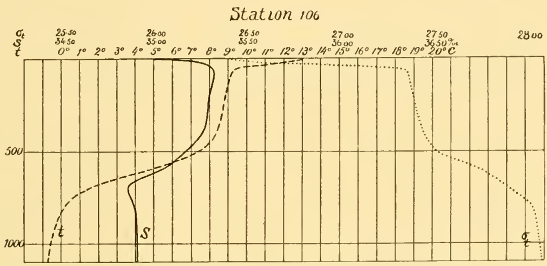


FIG. 169.—TEMPERATURE, SALINITY, AND DENSITY AT STATION 106, IN THE FAROE-SHETLAND CHANNEL (10th August 1910). Depth in metres.

Wyville Thomson Ridge, about 300 miles north-east of Station 101. At Station 106 some fresher water was found at the surface, but otherwise the salinity, temperature, and density were the same at both stations as far down as 500 metres; the water had grown slightly colder and heavier in these 300 miles, but the difference was very small. Below 500 metres, however, there is a great contrast, the temperature of the deep water being, as already indicated, much lower north of the Wyville Thomson Ridge than south of it, and the density is therefore greater on the north side. The deep water of the Norwegian Sea is thus colder and heavier than that of the Atlantic, but, strange to say, there is no difference in the salinity of the deepest layers of the two regions.

At all three stations the surface-layers are occupied by a warm, comparatively saline, northerly current. On proceeding northwards, there is a fall of temperature and of salinity and an increase of density, but the differences are not so great as to forbid the inclusion of the three stations in one region with regard to the upper water-layers ; it is a region with a southern character.

Off Newfoundland.

The conditions are widely different when we come to a northerly region, like that where the East Greenland Polar Current and the Labrador Current bring down great water-masses from the Arctic seas. On our passage to and from St. John's we sailed across the Labrador Current and took a number of observations at different places in it. Fig. 170 shows the conditions at Station 76, due east of St. John's, towards the eastern margin of the cold current. Here the temperature at the surface was about 6° C., falling rapidly to −0.35° C. at 55 metres (30 fathoms), rising again, at first rapidly, to 3° C. at a

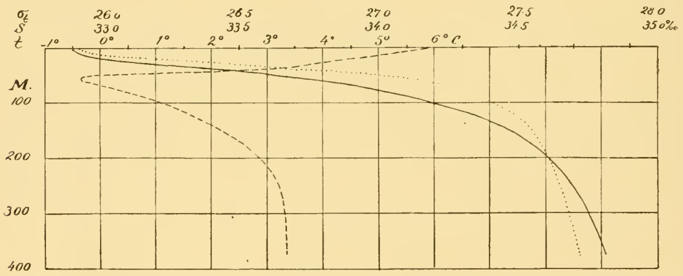


Fig. 170.—Temperature, Salinity, and Density at Station 76, in the eastern part of the Labrador Current, off Newfoundland (9th July 1910). Depth in metres.

little more than 200 metres, and then slowly to 3.4° C. towards the bottom in about 400 metres. If the depth had been greater, we should have found that the temperature fell again as we penetrated into the deep water. This is an example of the usual conditions in Arctic and Antarctic regions, where in summer the temperature decreases gradually from the surface to a minimum at 50 to 70 metres, then rises to a secondary maximum at 300 to 400 metres, falling again towards the bottom, and it is in a case like this that the ordinary maximum and minimum thermometer is inadequate (see p. 216). At Station 76 the water was warmer through the influence of the Gulf Stream ; it was much colder, for instance, at Station 75 farther west, where we found −1.43° C. at 55 metres, and at Station 74, just off St. John's, where the temperature was −1.52° at 91 metres. As a rule, it may be said that in a polar current in depths between 50 and 100 metres the temperature is below zero, and where there are banks at these depths they are covered with ice-cold water ; hence the great difference between such banks and those which lie within the region of the warm currents. Fig. 95, p. 110, represents a section across the Newfoundland Banks from the Gulf Stream (Station 69) northwards to a point just outside St. John's (Station 74). On the northern part of the bank it is very cold, for there we are in the middle of the Labrador Current; on the southern slope it is much warmer, because of the vicinity of the Gulf Stream. There are accordingly great differences in temperature and salinity in different parts of the Newfoundland Banks, especially in the deeper parts.

From Fig. 170 we see that the salinity was below 33 per thousand at the surface, that it increased rapidly downwards (to 34.6 per thousand at 200 metres), and afterwards more slowly, but it nowhere attained the salinity of the "Atlantic water," viz. more than 35.0 per thousand. This is characteristic of the Arctic and Antarctic regions, especially in summer. The water brought by the currents from the North Polar basin is a kind of coast-water. The great rivers of Siberia and of the north of America empty volumes of fresh water into the Polar Sea, where it mixes with the salt water, diminishing the surface salinity, which is further reduced by the melting of the drifting ice in summer. The low salinity at the surface renders the density comparatively small, but it increases rapidly downwards, so that the water at 100 metres is heavier than at any of the three stations within the warm water region just mentioned. We have not in any of these examples taken into consideration the fact that the density is slightly increased with increase of depth by the pressure due to the weight of the overlying water.

The pressure in the sea.

The pressure in the sea increases by about 1 atmosphere for every 10 metres of depth. Thus there is a pressure of about 100 atmospheres 1000 metres below the surface, and of 500 atmospheres at a depth of about 5000 metres. When differences in pressure occur in adjacent areas at the same level below the surface, various currents arise, just as air-currents are produced by differences of barometric pressure. The circumstance that the water is not equally heavy everywhere is one of the main causes of the ocean currents, and, the water being easily moved, small differences of pressure will be sufficient to produce a sensible motion. By the great pressure the water itself, and all the materials carried into deep water, are compressed. Water is, however, only to a slight extent compressible, so the effect of pressure is not so great as is popularly supposed. Tait and Buchanan have shown conclusively that compressibility decreases slightly but sensibly with increase of pressure. V. W. Ekman has recently made a very careful investigation on the compression of sea-water, and has published *Tables for Sea-Water under Pressure.* From his tables we may easily compute the actual density with compression, when depth, salinity, and temperature are known.

Let us take, as an example, the conditions at Station 63, near the Sargasso Sea, 22nd June 1910, as shown in the following table, giving for the depths specified: (1) the temperature, (2) the salinity, (3) the density disregarding the compression (calculated by means of Knudsen's Tables), and (4) the actual density with compression (calculated from Ekman's Tables):—

Depth.		Temp. °C.	Salinity per thousand.	Density.	
Metres.	Fathoms.			Without compression S.	Actual density S_1.
0	0	22.30	36.44	1.02525	1.02525
183	100	16.71	36.27	1.02658	1.02741
366	200	15.22	36.00	1.02671	1.02835
549	300	12.35	35.54	1.02696	1.02943
732	400	8.41	35.11	1.02732	1.03067
915	500	5.97	35.16	1.02770	1.03190
1830	1000	3.54	34.94	1.02781	1.03631
3000	1640	2.90	34.92	1.02786	1.04171
4000	2187	2.35	34.88	1.02787	1.04621

It is seen that the density is practically identical, for instance, at 3000 metres and at 4000 metres when leaving compression out of account, whereas a considerable difference was actually produced by the compression. At 4000 metres the effect of the pressure of 400 atmospheres was so great that the density increased from 1.02787 to 1.04621, equal to an increase of weight of $1\frac{3}{4}$ per cent. As a matter of fact the water at 4000 metres has become only $1\frac{3}{4}$ per cent heavier by reason of the compression; a fairly delicate weighing would have been necessary to detect this increase. The case may also be stated thus: 1 litre of water at 4000 metres weighs 1046 grams; if

Pressure and density.

this litre were brought up to the surface, it would expand so that its volume would be increased by 18 cubic centimetres; subtracting the 18 c.c. and weighing the remaining litre we find a weight of 1028 grams. Thus even at a depth of 4000 metres the difference caused by pressure is not great.

Sinking of a solid body.

Now, what is the effect of this increase of density on a solid body lowered into the sea? Let us suppose a piece of solid iron, weighing 1000 grams in the air, to be sent down to 4000 metres at Station 63. When it is lowered just beneath the surface it becomes lighter by 131 grams, thus weighing 869 grams. When it has reached a depth of 4000 metres the buoyancy is 134 grams, so that the piece of iron there weighs 866 grams—a difference in weight of 3 grams for a piece of iron weighing 1000 grams in air. This is merely 0.3 per cent of the weight, and consequently quite insignificant. In other words, metals and other solid substances are practically just as heavy in deep water as they are at the surface, and will sink as rapidly there as in shallow water. This may be proved by direct observation, for if a messenger is sent down to close a water-bottle at a depth of 2000 metres it will be found to take four times as long as when sent down to 500 metres.

Sinking of an air-filled capsule.

But suppose that, instead of a massive piece of iron, we take a perfectly tight capsule of thin iron filled with air, and lower it down to 4000 metres; in the course of the descent the pressure increases, forcing the walls of the capsule together. The volume of air within the capsule may be so large that it only just sinks at the surface, its total specific gravity being then very little greater than that of the water; but when it has reached a depth of 10 metres the air is compressed to half its original volume, granted that the capsule is collapsible, and the weight of the iron then acting more freely, the capsule will sink faster and faster; when it reaches a depth of 4000 metres it is exposed to a pressure of 400 atmospheres, and the compressed air having hardly any buoyancy left, the capsule will sink almost as fast as if it had been made of solid iron throughout. Collapsible solid bodies containing air will accordingly sink faster in deep water than at the surface. A piece of wood floats at the surface because it contains a large amount of air, but there is nothing to prevent it from sinking when it is sent down into deep water; therefore wood and cork are not suitable for floats at great depths. It is the same with the dead bodies of marine animals, etc., for when the air is compressed they will easily sink.

The penetration of light into the sea.

When the sun's rays fall on the surface of the sea, some of them are reflected, and the rest penetrate into the water, though in a somewhat altered direction. The direction is not much altered when the sun is high in the heavens, as at noon in the tropics. When the sun is just above the horizon its rays are most strongly deflected, the few rays penetrating into the water forming an angle of about 42° with the surface. As the sun rises and the light becomes more intense, the deflection from the course in the air gradually decreases, so that the rays do not penetrate so deep as might be expected, even if the angle with the surface increases. When the sun is 60° above the horizon, the refraction in the water is about 8°, the angle between the surface and the penetrating rays then being about 68°, and when the sun is at its zenith, the rays are not bent at all, but proceed perpendicularly into the water.

Absorption of light rays.

The rays making their way into the water are, however, gradually absorbed, some quickly, others more slowly, according to the wave-length of the ray and the limpidity of the water. The sun's light, of course, consists of many different kinds of rays: the dark heat-rays, imperceptible to the eye, lie beyond the red end of the spectrum, and are therefore called ultra-red rays; then comes the visible spectrum with the colours in the well-known order—red, orange, yellow, green, blue, indigo, and violet; beyond the violet end are the ultra-violet rays, remarkable for their chemical action, but having no effect on our senses. These different rays are refracted and absorbed in different degrees. The red rays are refracted somewhat less than the blue and violet rays, and are much more quickly absorbed. The dark heat-rays are absorbed in the very uppermost water-layers. The light rays also convey some heat, and they penetrate deeper before disappearing—the deeper the nearer the blue end of the spectrum is approached. Light at a certain depth in the sea has not the same composition as on the surface of the earth, there being fewer of the red rays and more of the blue, which proportion becomes gradually more pronounced with increasing depth.

Intensity of light at different depths.

Attempts have been made to determine the intensity of the light at different depths, especially in the Mediterranean, by means of the action of the rays on photographic plates. Ordinary plates are most influenced by the rays at the blue end of the spectrum, and by the ultra-violet rays, and only slightly by the red. Fol and Sarasin, working off the Riviera, traced an effect on the plate as far down as between 465 and 480

Fol and Sarasin.

metres; Petersen found that in the neighbourhood of Capri a plate was influenced by the rays at a depth of 550 metres. Luksch made some investigations in the eastern part of the Mediterranean, exposing his plate for fifteen minutes, and found that the limit of the light-rays must be drawn at 600 metres. In these experiments the influence of the collected rays on an ordinary photographic plate was studied. Petersen. Luksch.

In order to make some investigations on this subject in the

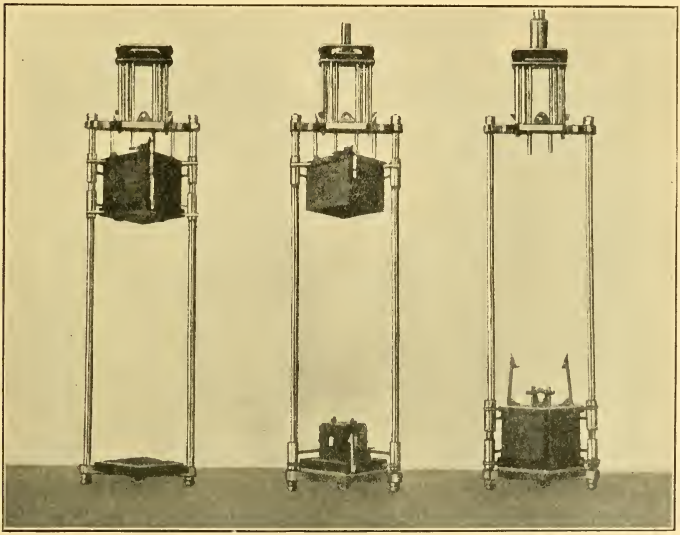


Fig. 171.—Helland-Hansen's Photometer.
On the left, as it is sent down; in the middle, open for exposure; on the right, closed and ready for hauling up.

"Michael Sars" Atlantic Expedition, the author constructed a new kind of photometer, which is represented in Fig. 171. In the centre figure—at the lower part—is seen a brass cube; the four sides and the top have square "windows," and on each of them a small square frame with a similar window (2×2 cm.) can be screwed fast; the screws and openings are seen in the figure. The cube rests on a larger brass plate, or rather on an india-rubber mat covering the brass plate. The plate and cube are fastened inside a frame, along which they can be moved up and down. At the top of the central figure is seen a larger Helland-Hansen's photometer.

metal cube without any base; it is intended to cover tightly the lower cube to which the photographic plates are fastened. On the left the apparatus is seen closed, with the cubes suspended at the top of the frame, the smaller one inside the larger. In this position the apparatus is lowered into the water. A small messenger is sent down the line and releases the inner cube, which drops to the bottom of the frame (see the middle figure). The plates are thus exposed. After a certain time a larger messenger is sent down, releasing the large cube, which falls like a shutter over the plates, as seen in the figure on the right. The apparatus is then ready for hauling up, and the cubes are taken out of the frame into the dark-room for development and change of plates.

In all previous photometric apparatus for use in the sea the plates were hermetically closed behind a strong glass pane, in order to shield them against the great pressure, but in the photometer here described a totally different principle was applied. The gelatine-film was covered with a glass plate and inserted into a small envelope of thin caoutchouc, with a square opening in front through which the light is admitted. The envelope with the plate was then placed on one of the sides of the inner cube, and the corresponding brass frame was screwed on tightly. The water could penetrate both outside and inside the cube, so that there was the same pressure on both sides of the film and the glass cover. The rubber envelope would be pressed tightly on to the glass plate, so that no water could enter and spoil the film. By this arrangement the apparatus might be exposed to any pressure without any special protection, and it was used at various depths down to 1700 metres without a single plate being cracked or spoilt by water.

Highly sensitive pan-chromatic plates (4 × 4 cm.) were employed in the experiments—the windows being, as mentioned above, 2 × 2 cm. In several experiments a gelatine colour filter was inserted between the photographic plate and the glass cover. Wratten and Wainwright's three-colour filters (red, green, and blue) admit respectively only a certain portion of the spectrum. This made it possible to study the rays present within the separate fields of the spectrum, as well as the total intensity of the rays. These investigations were carried out in the southern stretch of the cruise, and though time and weather did not allow of many experiments, those that were made gave interesting results.

Some of the plates exposed are represented in Fig. 172. In the upper row are seen some results without a light-filter at Station 51. The plate on the left (No. 10), exposed for 40 minutes at 500 metres, was strongly influenced by the rays. The next plate (in the middle of the upper row), exposed for 80 minutes at 1000 metres, was also blackened by the light-rays. The third plate was exposed for 120 minutes at 1700 metres, and showed no effect whatever. These experiments were made at noon on the 6th June with a clear sky, and show that a good deal of light penetrates to a depth of 1000 metres—considerably deeper than was previously supposed. The limit of light

Results at different depths with and without colour-filters.

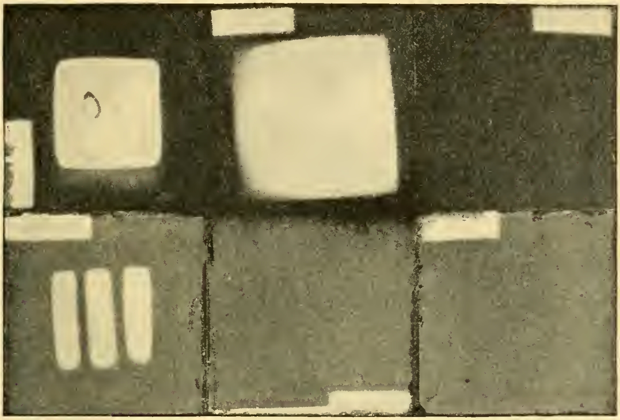


FIG. 172.—PHOTOGRAPHIC PLATES EXPOSED AT DIFFERENT DEPTHS.
The upper row from Station 51, the lower row from Station 55.

sufficient to influence the plate in the course of two hours lies at a less depth than 1700 metres.

The lower row in Fig. 172 shows some plates from Station 55, all exposed for forty minutes at a depth of 500 metres. The plate on the left was used without filter, and shows the same strong effect as the corresponding plate from Station 51, in the upper row. The next plate (in the middle of the lower row) was exposed with the blue filter; an influence of the blue rays is visible on the original plate (a faint Roman V), but not so clearly in the reproduction given here. The right-hand plate in the figure was exposed with a green filter, and shows no effect. A plate with the blue filter needs an exposure six times, and one with the green filter eighteen times, as long as a plate with no filter. It is therefore difficult to compare the plates quantitatively, but it may at least be maintained that there must be many blue rays, though hardly any red ones, at a depth of 500 metres. Series of experiments with and without filters were also made at a depth of 100 metres; in forty minutes all the plates were over-exposed, those with a red filter only a little, those with a blue one very much, so that there are many rays of all kinds at 100 metres, though fewest of the red. When plates without colour-filters were exposed on the top and on the sides of the cube simultaneously, the plate on the top proved to be more strongly influenced than the others. This fact is not without interest, as it shows that the rays in the clear tropical waters have a distinct direction at 500 metres, not having yet become altogether diffuse; shadows should, then, be thrown even at that depth.

Regnard's photometer.

Regnard constructed an apparatus for determining the length of the day at different depths, in which a clockwork arrangement inside a cylinder causes a photographic film to pass before an aperture. At the end of March 1889 the Prince of Monaco made some experiments with Regnard's apparatus in the harbour at Funchal, Madeira; the water was not so clear as in the open sea, so the times recorded may be rather short. At 20 metres the day lasted eleven hours; at 30 metres it began at 8.30 A.M. and ended at 1.30 P.M., the sky becoming overcast; at 40 metres, with the sun shining brightly, the film exhibited only a slight influence of light for a quarter of an hour about 2 P.M. These and a few other experiments show that the day becomes gradually shorter, and the intensity of light decreases, as the depth increases.

Prince of Monaco's experiments.

Fol's diving-dress experiments.

The Swiss naturalist, Hermann Fol, has several times gone down in diving dress off Nice to examine the bottom. At a depth of 10 metres the solar light disappeared quite suddenly in the afternoon a long time before sunset. At 30 metres the light was so bad that it was difficult to gather the animals on the bottom; he could see a stone only at a distance of 7 or 8 metres, whereas shining objects in favourable positions could be discerned at a distance of 25 metres. He also noticed that dark red animals (like *Muricæa placomus*) looked quite black, while the green and green-blue algæ appeared lighter in colour. This is explained by the fact that the red light disappears much sooner than the blue. A coloured object will always look black when untouched by rays of its own colour. As the white sunlight contains all colours, objects display in it their proper tint, but when the red rays, for instance, are cut off, a piece of red paper will look black.

Transparency of sea-water.

The usual method of studying the transparency of the water is to lower a large white disc, noting the depth at which it disappears from view. The degree of transparency is found to vary greatly, for in the clear dark-blue water in the middle of the ocean near the tropics the white disc can sometimes be seen as far down as 50 metres below the surface, or even more, while in those places where rivers bring down large quantities of detritus from the land the disc may occasionally be invisible a couple of metres beneath the surface. The enormous quantities of small plankton organisms inhabiting the upper layers may also render the water relatively opaque. The penetration of light thus varies according to circumstances, but few direct observations of the light-intensity have as yet been made. It would be of the greatest interest to know the amount of light at different depths in different seas, and thereby gain a better understanding of the conditions of life, for instance, as regards the development of the plankton, as the small plankton algæ need light for the processes of assimilation.

Gases in the sea.

Sea-water normally contains oxygen, nitrogen (with argon), and carbonic acid. These gases are absorbed at the surface from the atmosphere, and are carried by currents even into the deepest parts of the ocean in varying amounts. A study of these variations is of considerable interest, and may be briefly dealt with here, although no gas-analyses were made during the "Michael Sars" Atlantic Expedition. There are several good methods of analysis. For the three gases named, the method introduced by Bunsen, and further developed by Pettersson and Fox, may be employed, the water-sample being boiled at a low pressure, and the escaping gas collected and analysed. The oxygen may be determined by a very simple titration, according to Winkler's method, or Krogh's method of examining the tension of the several gases in solution may be applied.

Oxygen.

Oxygen is not so readily soluble in salt water as in fresh; the higher the salinity the less the absorption of oxygen by the water. It is also a well-known fact that cold water dissolves more air than warm. This is clearly seen in the following excerpt from Fox's tables, showing the cubic centimetres of oxygen in 1 litre of water at different temperatures and salinities, when the water is saturated with this gas:—

Temperature.	Salinity.		
	0 per thousand.	20 per thousand.	35 per thousand.
	O. in c.c. per litre.	O. in c.c. per litre.	O. in c.c. per litre.
0° C.	10.29	9.01	8.03
10° C.	8.02	7.10	6.40
20° C.	6.57	5.88	5.35
30° C.	5.57	4.96	4.50

At 30° C. a litre of water which is saturated with oxygen contains little more than half as much as at 0° C. There is therefore normally more oxygen in the cold water-masses of the Arctic and Antarctic regions than in the warm water-masses of the tropics. The salinity is not such an important factor in the solubility of oxygen as the temperature.

Marine animals need oxygen for respiration, and therefore consume some of that contained in the water. By the act of respiration carbonic acid is produced and dissolved in the water. The same thing goes on through the respiration of plants. These are some of the principal oxygen-consuming processes. But plants assimilate besides breathing; that is to say, they make use of the carbonic acid by dissociating it into oxygen and carbon; they employ the carbon for building up cells, while the oxygen is again dissolved in the water. This is the chief oxygen-producing process, but it is carried on only through the influence of light-rays. It is doubtful what rays are the most important for marine plant life, and in what quantity they are necessary. Experiments have shown that many higher aquatic plants assimilate much better in yellow light than in blue or violet light; this is the case with most adherent green algæ, and hence they are found in the upper water-layers near the surface, where there is enough yellow light. The red algæ, on the other hand, assimilate better in blue light than in yellow, and therefore live in deeper water than the former. We know nothing of the assimilation by the plankton-algæ of the various light-rays; we only know that they need light, and that they are found in the upper water-layers, but not in deep water. The production of oxygen in the sea is thus limited to the upper layers, while the consumption of oxygen takes place wherever there are living organisms (excepting certain bacteria). Now, supposing the processes of assimilation and of respiration are balanced, the quantity of oxygen in the water is not altered however many organisms are present. But if there is an excess of animal life the amount of oxygen decreases (as it always does in the dark); if there is an excess of plant life the amount of oxygen increases, provided there is light enough. Knudsen and Ostenfeld made some experiments to prove this. They filled some bottles with a capacity of 1 litre with sea-water, and into one they put some living crustacea (copepods). After three hours there was 3.88 cubic centimetres less oxygen in this bottle than in the others, while the quantity of carbonic acid had increased. They filled two litre-bottles with sea-water, and introduced equal quantities of vegetable plankton (diatoms), covering one of them with tin-foil so as to shut out the light. After

Knudsen and Ostenfeld's experiments.

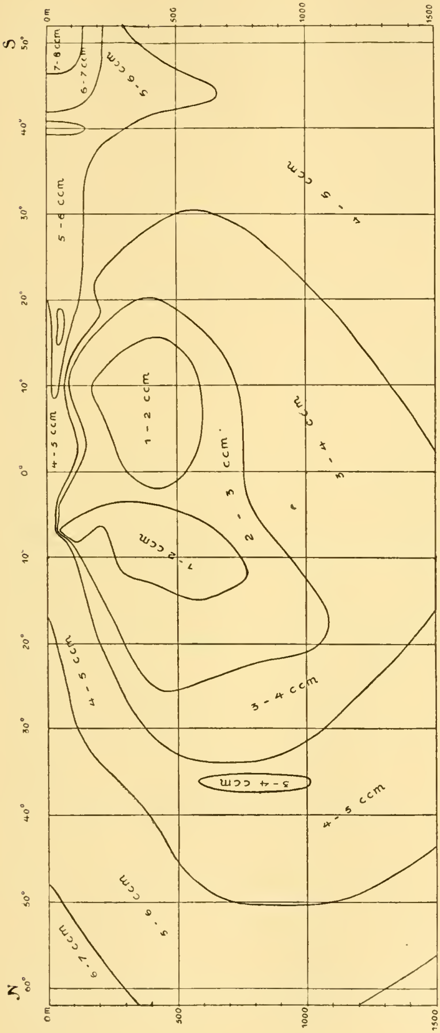


Fig. 173.—The Distribution of Oxygen in the Atlantic Ocean between 60° N. and 50° S. The figures give the amount in cubic centimetres per litre of water. Depth in metres.

three hours it was found that the diatoms had consumed 2.34 cubic centimetres of the oxygen in the dark bottle (the amount of carbonic acid being slightly increased), whereas in the uncovered bottle the quantity of oxygen had increased by 11.00 c.c. (the amount of carbonic acid being decreased).

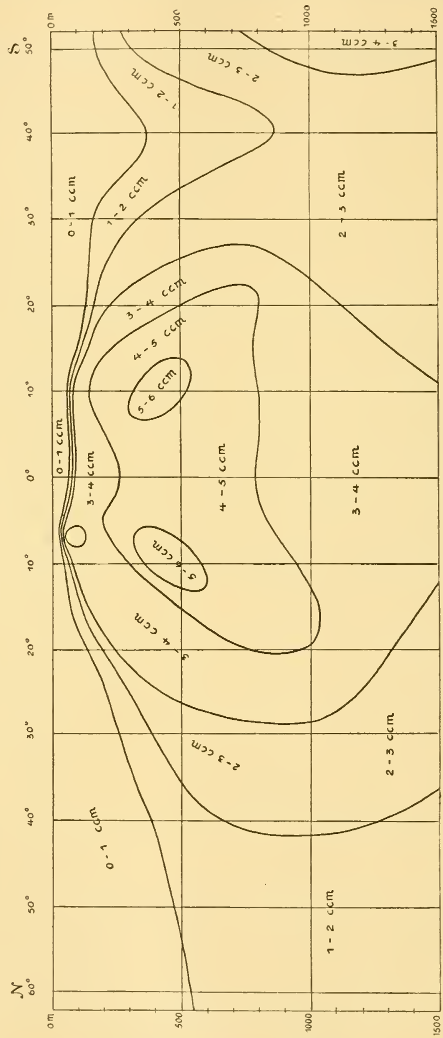


Fig. 174.—Oxygen in the Atlantic Ocean.
The figures indicate the deficiency from saturation in cubic centimetres per litre. Depth in metres.

Brennecke's figures for oxygen in the Atlantic.

Brennecke has compared the results of a number of oxygen-determinations from the Atlantic Ocean, and in Figs. 173 and 174 his two sections showing the vertical distribution of oxygen in the Atlantic (from the surface to a depth of 1500 metres) between lat. 60° N. and 50° S. are reproduced. The first section shows the quantity in cubic centimetres per litre. A little north and south of the equator the value is only 1–2 c.c. per litre in the water between 200 metres and 600 or 700 metres; on the equator, where the cold water from below comes comparatively near the surface, it is a little more; the highest value, over 6 c.c. per litre, is found in high northern and southern latitudes. The second section shows the deficiency from saturation in cubic centimetres per litre at the temperature and salinity *in situ*. In the upper 50–100 metres the water is nearly saturated all over the Atlantic, while in greater depths the oxygen is deficient, especially in tropical waters; at a depth of about 500 metres in lat. 10° N. and S. the deficit amounts to five or six cubic centimetres per litre. This is explained by the abundant supply of oxygen in the surface-layers, through absorption from the atmosphere, and through assimilation by the rich plant life, while the oxygen is being constantly consumed at greater depths, where plant life is scarce and animal life in excess. As a rule, where there is a great deficit of oxygen the water is characterised as "stale," a long time having elapsed since it was aerated at the surface or purified through the action of plants.

The disappearance of the oxygen is not, however, due only to the respiration of animals, but may also be caused by various hydro-chemical processes. In the Black Sea oxygen is found only in the upper 150–200 metres (about 100 fathoms) of water; below this it has disappeared totally, whereas sulphuretted hydrogen is present in increasing quantities down towards the bottom. The Black Sea is separated from the Mediterranean by the Bosphorus ridge, so that the water in its deep basin lies stagnant, unrenewed by the influx of other water. Similar conditions prevail in several Norwegian "threshold fjords," or on a smaller scale in the oyster-"polls." In such places the bottom is thickly covered with organic matter; a slimy black mud is formed, swarming with bacteria that produce sulphuretted hydrogen, which spreads through the water, combining with the oxygen to form various sulphates. This causes the oxygen to decrease and finally to disappear altogether, when the sulphuretted hydrogen begins to appear free in solution. It gradually spreads upwards, until the water is devoid of oxygen and contains free sulphuretted hydrogen, at a depth of only 100 fathoms in the Black Sea, and in the oyster-basins in autumn often at merely a couple of metres below the surface. In summer the "bottom-water" of the oyster-"polls" lies stagnant, but in the course of the autumn and winter it is generally renewed by the supply of comparatively heavy water from without; then the sulphuretted hydrogen disappears and

Black Sea.

Norwegian threshold-fjords and oyster-"polls."

the oxygen returns, producing thus an annual change in the gaseous conditions of the deeper parts of the oyster-"polls." In autumn the state of things may become critical for the oysters, which are suspended in baskets at a depth of $1\frac{1}{2}$–2 metres; it happens occasionally that the animals all die at this time by suffocation through want of oxygen or by sulphur poisoning.

The water may, on the other hand, become over-saturated with oxygen, as occurs sometimes in the Kattegat, or in spring in some parts of the oyster-"polls," where plant life is particularly luxuriant.

Carbonic acid. *Carbonic acid* occurs combined as carbonates and bicarbonates, and only in very small quantities as a free gas. The quantity varies considerably, among other things because of the activity of plants and animals, as above mentioned. Usually there is about 50 c.c. of carbonic acid in 1 litre of sea-water, but of this only a few tenths of a cubic centimetre is free gas in solution.

Carbonic acid has probably been present from the formation of the primitive ocean, together with the salts of the sea, but the quantity varies from place to place and from time to time, depending on the number of plants and animals, on the composition of the bottom, and more especially on atmospheric conditions. At times considerable quantities of carbonic acid gain access to the water through submarine volcanic activity, but this has probably less influence on the variations than the atmospheric conditions. August Krogh has made some very valuable investigations on this point, and has arrived at the conclusion that the sea is a sort of regulator for the amount of carbonic acid in the atmosphere. When there is much carbonic acid in the air, much will be absorbed by the sea; this is the case near land, and especially where there is a dense population and extensive industrial activity, or near active volcanoes. The tension of carbonic acid is everywhere small, but it is on the average greater over the land than over the sea. Now, if the tension in the air over a certain portion of the sea is smaller than it is in the sea, the latter will give off carbonic acid to the air. The sea thus has a regulating influence on the variations in the carbonic acid of the atmosphere. Many important questions arise with regard to these relations, but we cannot enter into further detail here; investigations on the subject are few.

Krogh's investigations.

Nitrogen. *Nitrogen* is so inert a gas that it is of little importance in oceanography. It is absorbed from the atmosphere in considerable quantities, 1 litre of water at a temperature of 10° C. and with a salinity of 35 per thousand, for instance, containing when saturated 12 c.c. of nitrogen. It is possible that marine bacteria partly dissociate nitric compounds so as to liberate nitrogen, and partly bind free nitrogen in various salts. These variations are always small, and not easily demonstrable. As a rule, though not without exception, the surface-water is saturated with nitrogen from the air, and when the water leaves the surface it carries down with it practically the same amount of nitrogen.

Currents in the sea.

A vessel running a certain course at a speed measured by the log often proves to have arrived at another point than that which would be expected from the reckonings. This will be the case when there is a strong wind, but even in a calm a displacement is frequently experienced, which is then caused by a current, and when the calculated position is compared with that actually arrived at, the difference will indicate the effect of the current on the ship. In sailing across the Gulf Stream off the east coast of North America, for instance, the ship is carried north or north-east of its latitude according to the compass and the log. The deviation is then an expression of the direction and velocity of the current, and much information with regard to the set of the currents has been obtained in this way. But the method is not trustworthy when there is a wind acting on the ship. The drift of various objects floating on the sea, wreckage for example, has also been studied. When wreckage belonging to the "Jeanette," which foundered in the Arctic Sea, was found in the North Atlantic, Nansen concluded that a current must run from the polar basin between Greenland and Spitzbergen into the Atlantic Ocean, and on this supposition he planned the "Fram" Expedition. In the Atlantic Ocean wrecks are often encountered drifting about with wind and current. These are reported, and from such reports one can follow the movements of wrecks for a long time. Fig. 175 shows some such wreck-courses; many of the wrecks have drifted from North America towards Europe, thus showing the effect of the Gulf Stream; others have been carried eastward in the direction of the Azores, then south, and finally west back towards America again. But in these cases the wind always plays an important part, so that it is difficult to form a correct idea of the movements of the water. In the far north and far south we can follow the drift of the icebergs; one, for instance, breaking

Drift of wreckage.

Floating icebergs.

loose far north on the west coast of Greenland would float towards the south along the coasts of Labrador and Newfoundland, and even farther south, thus proving the existence of the Labrador Current. An iceberg lies deep in the water, a fraction only of its bulk rising into the air, so that the wind will have little influence on its motion, which will practically express the aggregate effect of the currents through which the foot of the iceberg stretches.

Drift of vessels in the ice.

It has occurred more than once that vessels have been locked up in the ice east of Greenland, and have been carried

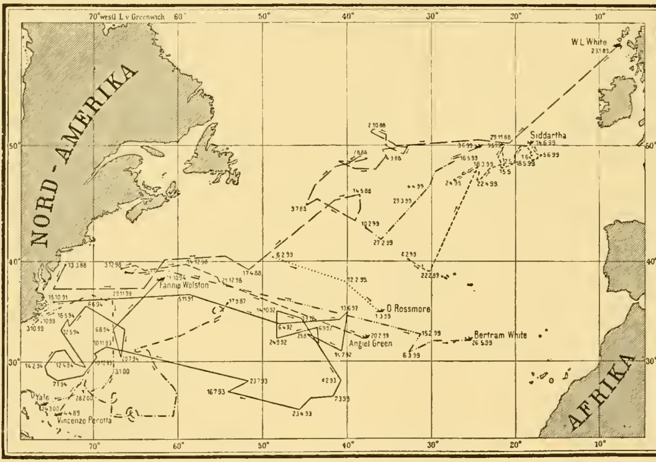


FIG. 175.—DRIFT OF WRECKAGE IN THE NORTH ATLANTIC. (After Krümmel.)

along with the drifting ice far towards the south. In the year 1777 a number of whalers were caught in the ice north of Jan Mayen, and all their efforts to free themselves were in vain, many of the ships being crushed, while most of the men perished; when the last ship was lost it had drifted 1100 nautical miles in 107 days, or an average of 10 miles per day. On the second German Arctic Expedition one of the ships, the "Hansa," was locked up in the ice in lat. 74° 6′ N. and long. $16\frac{1}{2}$° W. on the 6th September 1869, and was carried southwards until it was crushed on the 19th October. The crew took refuge on an ice-floe, and drifted on till the 7th May 1870, when they were able to land in Greenland in lat. 61° 12′ N.

They had been carried 1080 nautical miles in 246 days, that is, 4.4 miles per day on an average.

Information about the currents is also obtained from objects found drifting along with them. At Lofoten golf-balls have been found which must have come across from Scotland. In the Norwegian Sea drift-wood from Siberia is occasionally met with; once we came across the trunk of a Siberian tree thickly covered with littoral diatoms, which had thus travelled right through the polar sea, so that the log had come from the northern coast of Asia with the same current that carried the "Fram" through the northern waters.

Drift-bottles.

In order to study the currents, drift-bottles have often been employed, in which are enclosed slips of paper with directions to the finder to send the note to the address given, with information about when and where it was found. Fig. 176 shows the results of some of the bottle-experiments made in the North Sea by Fulton, who has in this way been able to give a more complete account of the currents of the North Sea than was previously possible. In this case the method gave quite trustworthy results, because there were shores all round where it was comparatively easy to recover the bottles within a short time. As regards the great oceans, the method often gives rather doubtful results. In the first place, one cannot know the route followed by the bottle from the time it was thrown overboard till the time it was found, and then it may lie for years on the shore before it is found, so that no one can tell how long it has been on its journey.

Fulton's experiments.

These methods give a certain amount of information about the motion of the superficial layers, but none about the deeper currents. We can also study the set of the water-masses by means of their physical or chemical qualities, especially temperature and salinity and gaseous contents. It is, for instance, known that the Gulf Stream carries much salt water (with a salinity above 35 per thousand) from the Atlantic into the Norwegian Sea, and the course of this salt water can be traced farther north; it forms a band along the coast of Norway, and branches off in several places. The position of this salt water indicates the course of the current itself, not at the surface only, but also in the deeper layers.

From a study of the distribution of salinity and temperature the average direction of the drift of the water-masses may be deduced, and an idea of the velocity obtained by calculation. Mohn, and more recently especially Bjerknes, have greatly

Mohn.

Bjerknes.

aided oceanographical work by giving the mathematical basis

Fig. 176.—Results of Dr. Fulton's Drift-Bottle Experiments in the North Sea.

for these investigations. This method, however, is indirect, and is in many cases insufficient for obtaining an exact knowledge of the motions of the sea, for which purpose direct current-measurements are necessary.

Measuring the currents at different depths in the sea is much more difficult than might appear at first sight, and re-

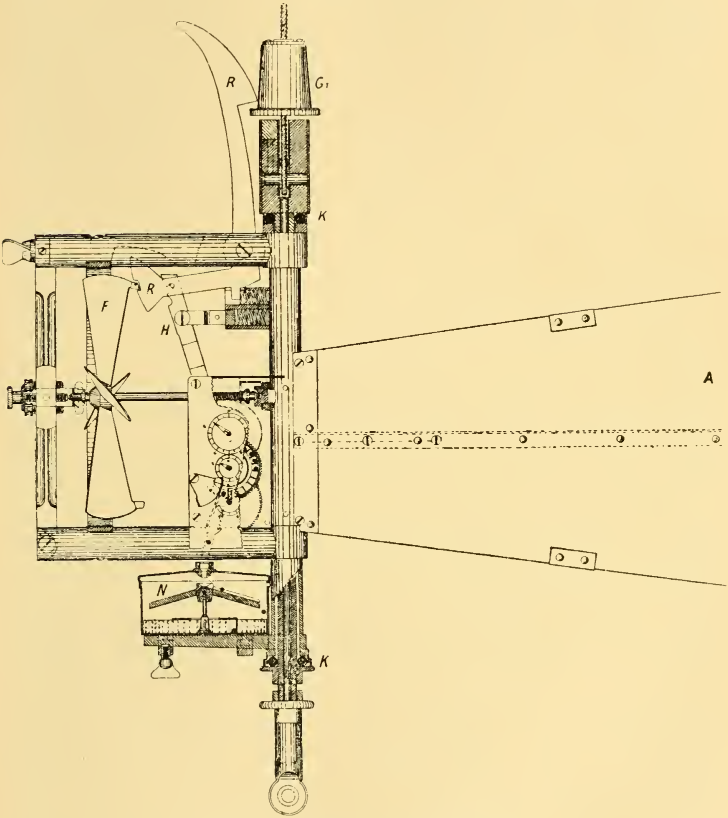


FIG. 177.—EKMAN'S CURRENT-METER.

quires good apparatus. Many excellent current-meters have been constructed, the one made use of during the cruises of the "Michael Sars" being that invented by V. W. Ekman, represented in Fig. 177. The apparatus consists of a double wing (A), that points in the direction of the current. In front

Ekman's current-meter.

is a propeller which is moved by the current, the velocity determining the number of revolutions in a certain period. The propeller works some small cog-wheels connected with hands showing on a dial the number of revolutions. The mechanism for indicating the direction of the current is very ingenious. Some small shot are inserted into a tube leading to one of the cog-wheels, which is provided with notches each holding one little ball. The balls are carried round by the wheel, and after half a revolution are discharged through another tube into the centre of a metal box, in which is poised a magnetic needle with a groove along the top of one branch. As the shot fall, they roll along the needle and drop off its point into the box. Their path may be traced in the figure. The bottom of the box is divided into thirty-six small partitions, and the balls fall into one or other of these according to the position of the needle. The position of a ball in the box thus indicates the angle between the axis of the apparatus and the magnetic meridian, that is, the direction of the current. When the apparatus is lowered into the water, the propeller is set and fixed, and is subsequently released by a small messenger so as to spin with the current; when desired, a larger messenger is sent down to arrest the propeller before hauling up. With this current-meter a great number of observations have now been made, many of which have given very important results.

In order to obtain good results it is necessary that the apparatus should hang practically still, without being carried along by the ship or the water, or—if this be unavoidable—that the drift should be perfectly well known. The boat from which the work is done must be very firmly anchored. In the Norwegian investigations we have, as a rule, worked from a small boat with anchors fore and aft, and it was possible in this way to hold the boat, even when more than 500 metres over the bottom, the most exact bearings showing that the boat did not drift sufficiently to influence the current-meter; one anchor alone is usually not sufficient, for the boat may swing, thus affecting the apparatus. When measuring the currents in the Straits of Gibraltar, we tried double staying with the life-boat, using a strong hemp line about one inch in circumference, but the current was so strong that the line broke again and again, and we had to give it up. When the current (or the wind) is very strong, good results may be obtained by means of a single anchor forward, so we dropped one of the large anchors of the "Michael Sars," and the steamer lay so still that we could work with the current-meters from deck, but the strain on the wire was enormous. Double staying is much too difficult at great depths, although a single line may sometimes do. At Station 58, south of the Azores, we had the trawl out in about 900 metres of water, when it caught on something and stuck fast on the bottom, holding the ship practically still (the compass was carefully observed the whole time); we improved the occasion by making a series of current-observations, and the results, which will be discussed farther on, prove the drift or the swing to have been insignificant, so that the observations are fairly reliable.

In the deep ocean, where current-measurements would be of special interest, it is impossible to anchor the ship on the bottom, but the drift of the vessel may, when exactly known, be allowed for, and measurements may be made at any depth. We tried this two or three times. At Station 19, in the Mediterranean, all the nets and young-fish trawls were towed at the same time. The speed of the vessel then just balanced the surface current; the motion appeared to be quite steady, and some observations were made at different depths to determine the deeper currents in comparison with the surface current. Again, at Station 49 C, west of the Canaries, we employed the large bag-net (3 metres in diameter) with the wire as a drift-anchor. The net was lowered to a depth of 1000 metres and held there for many hours; the drift of the vessel was fairly steady, and the compass showed the swing to be trifling. The depth of water was about 5000 metres, and measurements were made at different depths down to 1830 metres (1000 fathoms) with two Ekman current-meters, the results being indicated in Fig. 178. It may be interesting to see how an attempt at determining the currents above so great a depth turned out.

Current-measurements to the west of the Canaries.

The cardinal points of the compass are shown by dotted crosses, and arrows are used to indicate the velocity and direction according to the current-meters sent to different depths, a broken line for 915 metres (500 fathoms) and 1830 metres (1000 fathoms), and a thin line for 10 metres. Now, we know nothing directly about the currents in deep water in the open ocean between 500 and 1000 fathoms, but we must suppose the movements to be comparatively insignificant when the depth to the bottom is very great, say more than 2000 fathoms. Supposing there were no current at these depths, the apparatus would act as a log, showing the velocity and direction of the drift of the vessel. Granting this to have been the case, the

10-metre arrow will represent the resultant of the two components: the actual current at 10 metres and the actual motion

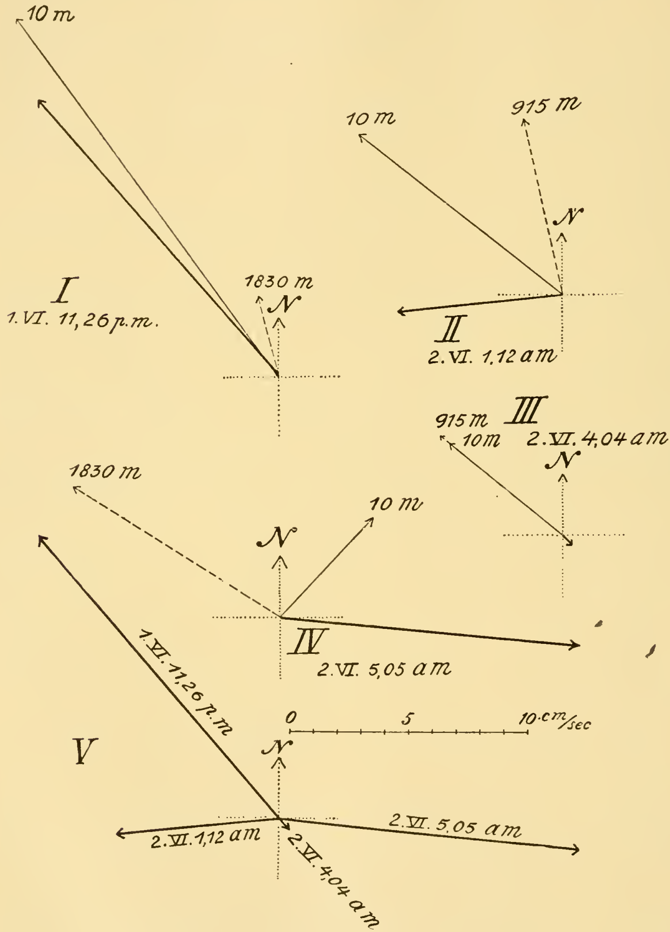


FIG. 178.—CURRENT-MEASUREMENTS AT STATION 49 C (1st-2nd June 1910).

of the ship, as indicated by the deep-water measurements. The actual current at 10 metres is then easily determined; it is here indicated by the thick arrows. Two measurements were made at 1830 metres (Nos. I. and IV. in the figure), and two at 915 metres (Nos. II. and III.), and at the same time observations were made at 10 metres with another apparatus. The time by the watch is noted in the figure. The arrows in V. show the currents thus found at 10 metres after allowing for the assumed drift of the vessel, and it is seen that the variations both in velocity and in direction are large. This method is, however, uncertain so long as the currents in deep water are unknown; if these are considerable, the thick arrows in Fig. 178, V., do not give the actual currents at 10 metres, but only the relation between these currents and those in deep water. Still one thing is at least clear from the figure: the thick arrows alter their direction regularly, and the change is counter-clockwise. A continuous alteration of set is one of the characteristics of tidal currents, and the conclusion is in all probability admissible that our measurements at Station 49 C prove the existence of tidal currents in the Atlantic Ocean, even where it is very deep.

Tides and tidal currents.

Tidal motion in the sea is due to the attraction exercised by the sun and moon on the water-masses, which varies from place to place. It would take us too far to enter into the theories of the tides here, and besides, we have not yet a clear solution of the problem, because, among other reasons, we have no observations from the open sea, but only those from the coasts. The rise and fall of the surface, known as tides, are accompanied by currents, and the study of these currents in the open sea would be of great importance for the comprehension of tidal phenomena. In the "Michael Sars" Expedition, as mentioned above, we made a number of current-measurements, the principal object being to find out if it were possible to make trustworthy observations of the velocity and direction of tidal currents in the ocean. This has not been done before in deep water. Buchanan in 1883 made some interesting measurements on the Dacia Bank, off the west coast of Morocco, and found marked tidal currents during the couple of hours the observations lasted. Afterwards R. N. Wolfenden discovered tidal currents on the Gettysburg Bank. Beyond these and a few other observations, we have no observations from the open ocean far from land and none at all in deep water.

Buchanan.

Wolfenden.

Tidal waves.

We usually figure to ourselves the attraction of the moon and the sun producing a tidal wave which can develop freely in the Southern Ocean, where a zone of water encircles the earth. This wave has a very great length, with high-water at the crest and low-water in the trough. Its form remains, fettered by the moon, while the earth revolves beneath it. Passing the opening between Africa and South America, it gives rise to a lateral wave moving from south to north through the Atlantic. This tide-wave reaches the coasts of northern

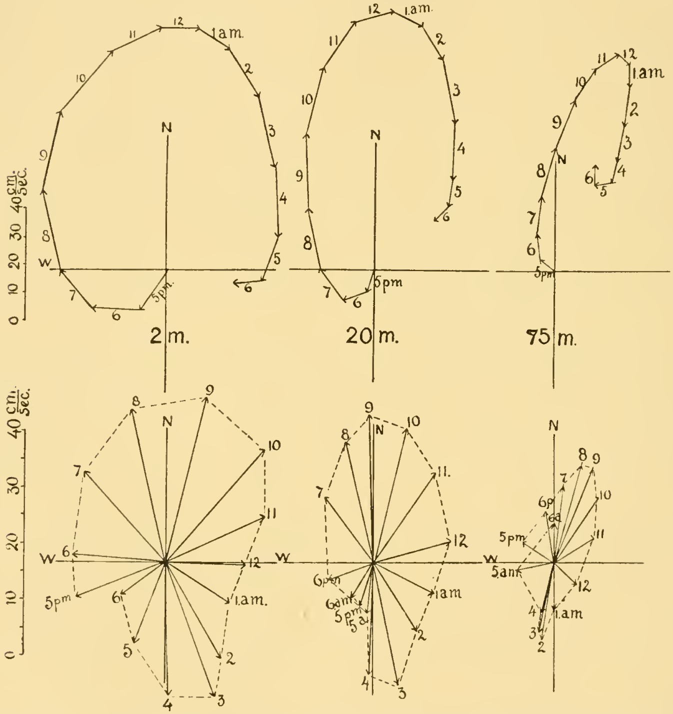


FIG. 179.—THE CURRENTS ON THE LING BANK IN THE NORTH SEA (7th-8th August 1906).

Europe, producing tidal effects there. But besides this wave coming from the Southern Ocean there is formed an Atlantic tide-wave following the movement of the sun and moon from east to west. As already remarked, these things are somewhat enigmatical, but as there is a connection between tidal waves and tidal currents, we may hope that careful current-observations will contribute to the unravelling of these problems.

In August 1906, a series of current-measurements was made by the "Michael Sars" on the Ling Bank in the North Sea. Fig. 179 shows the currents at depths of 2, 20, and 75 metres (the depth of water being 80 metres). In the lower row the direction and velocity of the current are indicated by arrows for every hour from 5 P.M. on the 7th August to 6 A.M. on the 8th August. It is seen how the water moved at the different depths, varying in direction and velocity; in the course of twelve or thirteen hours the direction of the current had passed through all the points of the compass. In the top row all the arrows are joined, thus forming a line which shows roughly the motion of the water during the period of thirteen hours. The course proved to be somewhat elliptic, the water returning very nearly, but not quite, to its point of departure. This is a typical case, for tidal currents are, as a rule, characterised by this turning, the water arriving at its starting-point again after a period of about twelve and a half hours. The displacement in the course of this time, as exhibited by the current-lines, is attributable to a general motion of the water, towards the east at 2 metres, north-east at 20 metres, and north-north-east at 75 metres. But this

Current-measurements in the North Sea.

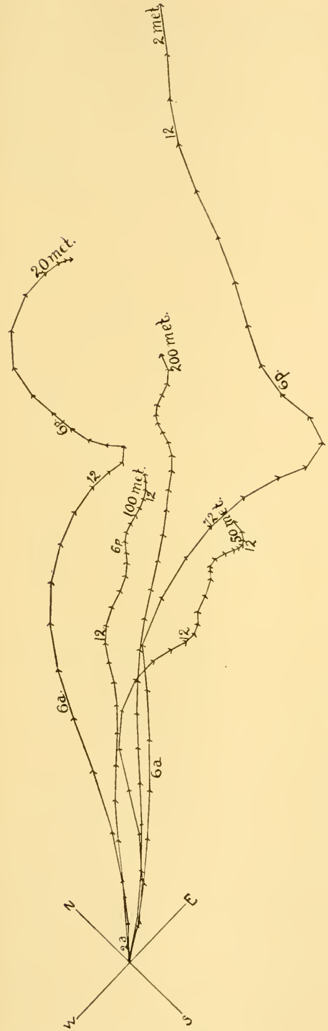


FIG. 180.—THE CURRENTS AT DIFFERENT DEPTHS ON STOREGGEN (12th-13th July 1906).

general motion is quite insignificant compared with the tidal current.

Current-measurements on Storeggen.

In Fig. 180 we see some current-lines of a totally different form, the results of a number of measurements made on Storeggen, westward of Aalesund, on the 12th and 13th July 1906. A line is drawn for each of the following depths below the surface: 2, 20, 50, 100, and 200 metres (the depth of water being 260 metres). It is seen that the current on the whole flowed in a north-easterly direction at all depths, but the

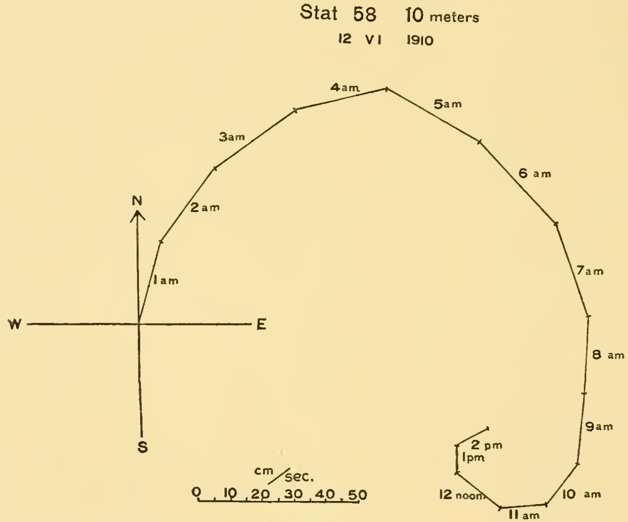


FIG. 181.—RESULT OF CURRENT-MEASUREMENTS AT 10 METRES AT STATION 58, SOUTH OF THE AZORES (12th June 1910).

direction was not constant, as implied by the bends in the lines. The variations of direction were due to the tides, but here the tidal current was weak compared with the general motion of the water-masses. In this place the coast-current of the upper 75 or 100 metres, and that portion of the Gulf Stream which traversed the layers below, both ran towards the north-east; had there been no tide-motion on the bank, the lines would probably have been straight, not sinuous.

The measurements at these two stations give an idea of the movements of the water-masses in the sea, and show that current-lines may have very different courses, largely determined by the relation between the tidal current and the general drift of the water.

We have already mentioned that the observations made at

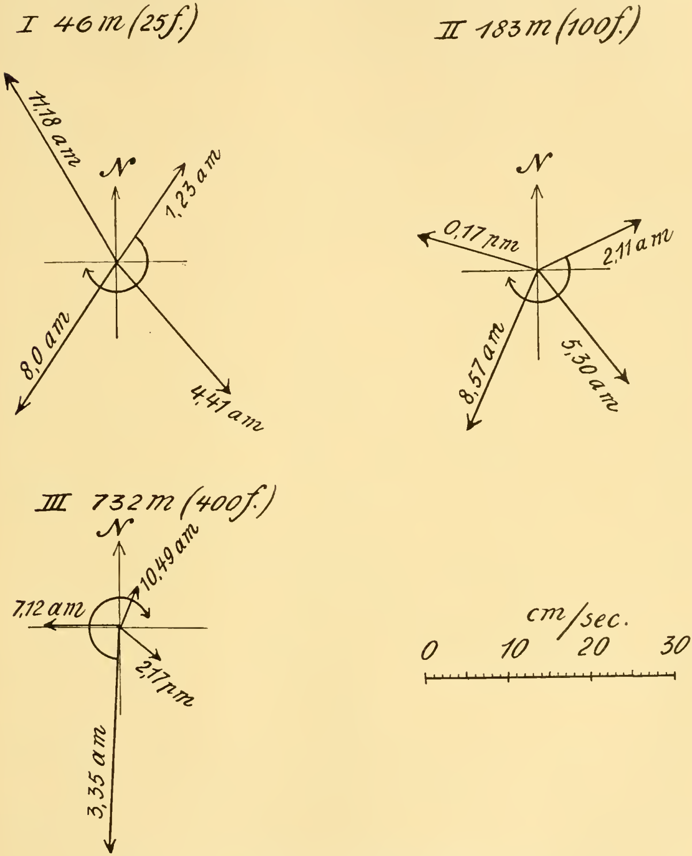


Fig. 182.—The Currents at different Depths at Station 58, south of the Azores (12th June 1910).

Station 49 C lead us to infer that tidal currents exist even in the deep sea. Again, at Station 58, south of the Azores, we made a number of current-measurements from the ship at anchor throughout one complete tide-period. With one of the

Current-measurements to the south of the Azores.

current-meters we took regular observations at 10 metres, 70 in all, from 1 A.M. till 2.45 P.M. on the 12th June. Fig. 181 shows the variations at this depth, which recall the current-lines on the Ling Bank. The tidal current predominated, attaining a maximum velocity of 38 cm. per second (0.7 knot per hour); there was also a general drift of the water towards the south-east, with a mean velocity of 8-9 cm. per second (0.2 knot per hour). Simultaneously another apparatus was employed to determine the current at different depths down to 732 metres (400 fathoms), the depth of water exceeding 900 metres. Some of the results are represented in Fig. 182, which shows the current at different depths: I. at 46 metres (25 fathoms); II. at 183 metres (100 fathoms); and III. at 732 metres (400 fathoms). At all depths the velocity and direction varied constantly, the changes in direction being clockwise, and it is notable that the direction shifted about 180° in the course of half a tide-period. In this case there is no doubt that tidal currents prevailed throughout the whole body of water from the surface to the bottom; they were unmistakable even at 732 metres; at this depth a velocity of more than 27 cm. per second (more than $\frac{1}{2}$ knot per hour) was once measured, showing that the tide can make its influence felt down to considerable depths. This is particularly the case where a plateau or ridge obstructs the passage of the tidal wave; in such places the current near the bottom is probably increased. This would explain the remarkable fact that on many submarine slopes and ridges no fine mud is deposited, because the strong current sweeps the bottom clean.

Another interesting result of these measurements is represented in Fig. 183, where the arrows show the currents at several depths simultaneously: I. at 3.35 A.M., and II. at 7.12 A.M. on the same date. We see that the currents set in different directions at the different depths. In the upper layers the direction shifted more and more to the right with increasing depth, but from 100 fathoms (183 metres) down to the bottom the direction was reversed. Thus the current at 500 metres ran in the opposite direction to that of the upper layers, which again approached that of the currents at the greatest depths. At a certain moment the currents are, then, arranged in the fashion of spiral staircases, the whole system turning in clockwise direction from top to bottom.

These observations in the Atlantic give rise to many interesting ideas about the currents in the sea, and show that there is still much to be done in this line. But the fluctuations of the ocean-currents are determined by more influences than tides, for many other forms of motion supervene, rendering the whole picture highly complicated. A careful analysis of the measurements made on Storeggen in 1906, led to the conclusion that there were certain regular variations which took the form of

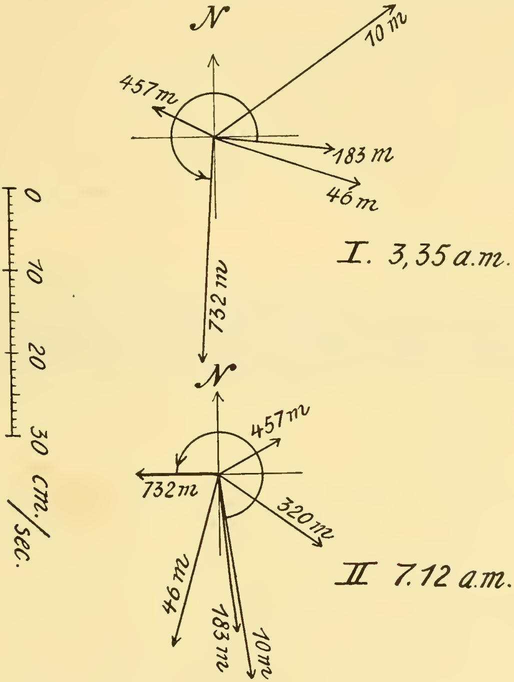


FIG. 183.—THE CURRENTS AS DETERMINED BY SIMULTANEOUS MEASUREMENTS (3.35 A.M. AND 7.12 A.M.) AT DIFFERENT DEPTHS AT STATION 58.

pulsations in the current. When the effect of the tide was subtracted it appeared that the ordinary current at 10 metres ran for some time with considerable velocity (up to $\frac{1}{2}$ metre per second); then the velocity decreased during seven or eight hours until it approached zero, increasing again during the next seven to eight hours, and so on. The fluctuations had thus a period of about fifteen hours, but we are as yet ignorant of the particular cause, though it may be a usual phenomenon in the

Pulsations in currents.

T

sea. Supposing the coexistence of two different periodical variations, one with a period of about twelve and a half hours, the other with one of about fifteen hours, an infinite number of variations would ensue, to which might be added the more casual influence of the wind and other factors, causing among other things incessant dislocations of the boundaries between the different water-layers or currents.

Wind-produced currents.

The wind may produce a current, particularly in the surface layers, thus altering the direction and velocity of the existing current. We know very little, however, about the relation between wind and current, through lack of detailed observations, although the question is naturally of the first importance from an oceanographical point of view, as well as from its bearings on the conditions of everyday life. This is one of the principal tasks for the oceanographer of the future; such observations are difficult to make, no doubt, but with modern methods much can be done.

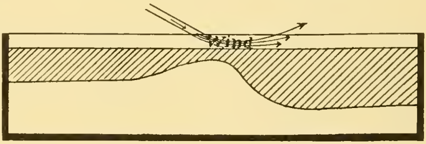


Fig. 184.—Sandström's Experiment for producing a Submarine Wave by a gust of wind.

A wind blowing over the sea will carry the surface water along with it. In the open ocean the current thus produced is generally somewhat deflected from the direction of the wind itself. During the drift of the "Fram" over the North Polar Sea, Nansen found that the ship, as a rule, was carried to the right of the wind's course. V. W. Ekman has studied the question theoretically, arriving at the conclusion that such a deflection is a result of the earth's rotation. Later, Forch, by extracting the records from a number of ships' journals, found the same deflection to the right in the Mediterranean and in the North Atlantic, while, as might be expected, there is a deviation to the left in the southern hemisphere. Now, as the surface-water is carried along by the wind, the deeper layer will approach the surface at the place of origin of the wind-current. In Fig. 184, which represents one of Sandström's experiments, we see how the wind may raise the boundary between the upper and lower water-layers. When the wind ceases this rise again subsides, producing a boundary-wave which will proceed farther. A wave like this may attain a considerable height, without being perceptible at the surface; its dimensions will depend on the distribution of density. A boundary-wave in the Norwegian

Boundary-waves.

Sea 100 metres in height would manifest itself as a surface-wave about 5 cm. high, that is, practically imperceptible, as the wave is very long and proceeds slowly. Several of the "Michael Sars" investigations indicate such boundary-waves, but here also precise observations are lacking. They are, however, known in one particular form, viz. as the boundary-wave producing "dead water." When a comparatively fresh and light water-layer, 2 or 3 metres thick, rests on a salt and heavy layer, a passing ship may give rise to a boundary-wave between the two layers. This wave may stop the ship, so that it lies in dead water hardly able to move at all. Ekman, who has investigated these phenomena, has demonstrated the dead-water wave by the following experiment (see Fig. 185). He put salt water, coloured dark, into a long basin, and on the top he poured a thinner layer of fresh water; when he slowly towed a small model of a ship through the upper layer, a

"Dead water."

Fig. 185.—Ekman's Experiment to show the wave producing Dead-water.

boundary-wave arose, as seen in the figure, which, when strongly developed, checked the speed considerably.

Naturally when a wave like this passes a certain spot on the sea, the undulating boundary between the two water-layers will at one moment be vertically nearer to that spot, at another moment farther down. Similar vertical oscillations may arise in other ways, as we shall now briefly indicate before describing some observations made during the cruises of the "Michael Sars," which prove that such undulations do exist in the sea.

Effect of the earth's rotation

We may first mention one of the effects of the rotation of the earth. By reason of the earth's rotation a body moving freely in the northern hemisphere in any direction will be deflected to the right, and with great velocities this deflection is quite considerable. There are many examples of it: a swinging pendulum constantly turns; the wind does not blow straight towards a cyclonic area, but in a spiral direction, bending to the right in the northern, and to the left in the southern, hemisphere; the effect of the earth's rotation is also seen in the direction of the trade-winds, monsoons, etc. The rivers of Siberia flowing northwards to the Polar Sea, eat into their eastern beaches as an effect of the rotation of the earth. It is the same influence which directs the course of the great ocean-currents. In the North Atlantic the warm currents from the south bend in general to the right, that is to the east, and the cold currents from the north likewise bend to the right, that is to the west; thus the Gulf Stream flows across to Europe, and the polar currents to Greenland and Labrador. Let us now suppose that we take observations at a couple of stations right across a current. This may be represented roughly by a vertical section, as in Fig. 186; we must here imagine that the motion takes place in the direction from the eye through the paper, that the motion is swiftest at the top, and that we are in the northern hemisphere. The rotation imparts to the water-mass a tendency to move to the right; there will be a pressure in that direction (indicated by the arrows), forcing the layers down at Station B, raising them nearer to the surface at Station A. This gives the boundary-layers a slanting position, as shown by the broken lines, the incline being slight if the surface-current is slow (I.), and strong if the current is rapid (II.). Consequently the light water will go deep at B, the station situated to the right in the current, while at Station A, on the left, the heavy water from below will come nearer to the surface. Wherever there is a strong current in the upper water-layers the following rule will apply in the northern hemisphere: on the right-hand side the water is comparatively light, on the left-hand side comparatively heavy; the conditions are reversed in the southern hemisphere. There are many examples illustrating this. Off the west coast of Norway the current runs north, and the water to the right, near the coast, is light, while that to the left, in the middle of the Norwegian Sea, is heavy. In the Gulf Stream off the east coast of North America the water is light (warm) on the right side of the current, and cold (heavy) on the left. The southern hemisphere

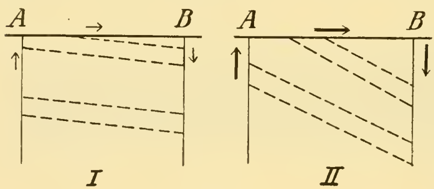


Fig. 186.

By reason of the deflecting influence of the earth's rotation (represented by the horizontal arrows) the water-layers acquire a slanting position, determined by the difference of velocity and density in the different layers.

affords many other examples; the distribution of temperature in the remarkable Agulhas Current, for instance, is explained in this way.

The Norwegian coast-current presents a good example of the effect of the earth's rotation on the inclination of the water-

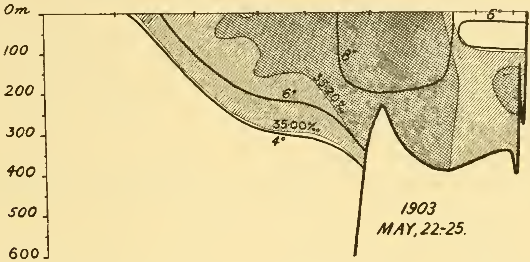


FIG. 187.—THE SOGNEFJORD SECTION IN MAY 1903.
(Fig. 165 shows the same section in May 1904.)

layers. Fig. 187 shows the conditions in May 1903 along a section through the Norwegian Sea from the mouth of the Sognefjord to the west; on the right, close to the land, the coast-water attains a depth of about 100 metres. By heating in the course of spring and summer this water becomes lighter

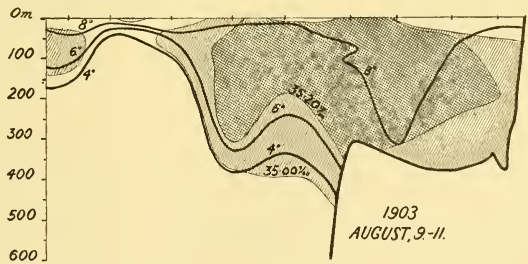


FIG. 188.—THE SOGNEFJORD SECTION IN AUGUST 1903.

and acquires a greater tendency to spread over the surface. This tendency counteracts the deflecting force of the earth's rotation, and finally causes the surface-layers to extend towards the west, becoming less thick in proportion. Fig. 188 shows the conditions along the same section in August 1903, when we repeated the investigations. The coast-water now lay much farther from the land than in May, reaching only to a depth of

60 metres near the coast, the water naturally having become lighter and its tendency to spread westwards having overcome the effect of rotation acting eastwards. When the coast-water is cooled down in autumn it becomes heavier again, is not then so much lighter than the Atlantic water, and has consequently not such a great tendency to spread westwards over the surface as in summer; it is then forced towards the land (to the right) again by the rotation of the earth. Thus there are in the course of the year periodic lateral movements of the coast-water, which are of importance, for instance, in their effect on the distribution of the young fish.

The water-layers, then, slant differently according to the strength of the surface-current and the vertical distribution of density. Supposing the surface-current to run sometimes fast and sometimes slow, the layers will respectively be lowered or raised. Again, regarding Fig. 186, the layers that in I. are comparatively deep at Station A, by an increase of the surface-current (as in II.) will rise considerably higher. Thus vertical oscillations are set up as a consequence of the fluctuations of the current; at a certain fixed point the movement will be like that of a submarine wave. Such vertical oscillations may be imagined to arise in other ways. It is, for instance, highly probable that there exist in the sea standing waves with one or more nodes, similar to the undulations of a violin string. Forel, Chrystal, and others have found these standing waves in lakes, the Japanese have shown them to be present in their seas, and we have several indications of their existence in the Norwegian Sea.

Vertical oscillations.

We cannot dwell any longer upon this question, but will now examine some observations made during the "Michael Sars" Expedition, which show marked vertical oscillations of one kind or another. We made a number of careful measurements in the course of twenty-four hours at Station 115, in the eastern part of the Faroe-Shetland Channel, near the slope west of Shetland, in 570 metres of water. Here we anchored a buoy, near which the steamer kept as long as the observations lasted. We made continuous observations of temperature and salinity at the same depths, and were thus able to see whether or not the conditions at a certain depth varied. At the same time similar measurements were made by the Scottish research steamer, the "Gold-Seeker," on the Faroe side of the channel. By these simultaneous investigations we hoped to determine

Observations in the Faroe Channel.

whether the variations were due to a progressive wave, or to fluctuations in the current, or to standing waves. The results have not yet been worked out, so we can only discuss some of the "Michael Sars" observations. Unfortunately it was impossible to make direct current-measurements, as the weather was too rough.

During the twenty-four hours we made 86 observations at the buoy, care being taken that the line was absolutely vertical. Surface-observations apart, most of the measurements were made at a depth of 300 metres (19 observations). The temperatures found at this depth are noted in Fig. 189 along the vertical scale, while the hours are put down along the horizontal scale. There were considerable variations: on the 13th August at 5.8 P.M the temperature was 5.60° C., and on the 14th August at 12.25 A.M.

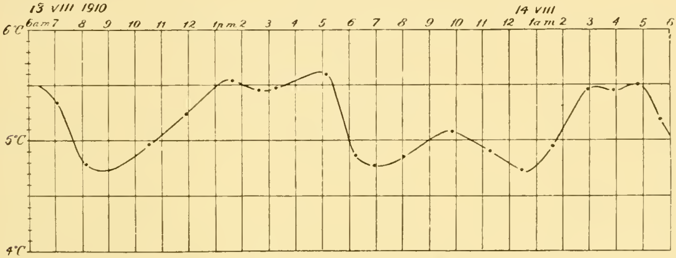


Fig. 189.—Temperature Variations at 300 metres at Station 115 (13th-14th August 1910).

it was 4.73° C.—a difference of 0.87° C. When the mean temperatures of the different water-layers are calculated and represented in curves, it is easy to see how much the temperature altered for each metre of depth. At about 300 metres the temperature decreased with increase of depth to such an extent that a difference in temperature of 0.87° C. corresponded to a difference in depth of about 35 metres. In the other layers there were similar variations, indicating vertical oscillations of between 15 and 35 metres. These observations go far to prove the presence of such undulations of the water-layers, which is indicated also by the form of the curve in the figure, among other things. But these variations are not comprised in one single period, as if they were due to an ordinary progressive wave, or an ordinary standing wave alone. The shape of the curve points to complicated fluctuations of the velocity as the cause of the variations, but it is possible, nay probable, that we are here confronted with an inter-play of several different factors. It is, by the way, worthy of notice that there is an interval of twelve or thirteen hours between the two principal maxima of temperature; this agrees with the tide-period, and we *know* that the velocity of the current varies with the tide.

In previous investigations in the Norwegian Sea we have several times encountered variations which are most naturally explained by supposing that there are great undulatory movements of the water-layers, and the investigations just described strongly corroborate this supposition. The problem is one of the greatest importance, and its solution will, in more ways than one, lead to a fuller comprehension of the science of the sea, in the first place with regard to the dynamics of the water-masses, and in the second place with regard to certain biological questions. The discontinuity-layer is often a boundary between two different worlds of living organisms, and it is a point of interest for the study of these to know if this boundary is moving up and down, for this would probably imply that the organisms themselves (possibly even shoals of fish) were also being moved up and down. On the continental slope, just below the edge, there live multitudes of marine animals, the warm water having one characteristic fauna, and the deeper cold water another. Now, if the fairly definite boundary between the two water-masses swings up and down, one must expect that there is a comparatively broad transitional region, where the particularly hardy individuals of either of these characteristic domains would live together. Where the change of temperature is slow and regular the effect upon the organisms would be of little importance; not so, however, where there is a marked discontinuity-layer, as for instance in the Norwegian Sea. The proof that there are such oscillations would also be of very great importance for our methods of studying the sea. Let us look, for example, at Fig. 190, showing a section from Shetland to the Faroe Islands, taken during the "Michael Sars" Expedition on the 10th and 11th of August. The positions of the stations are shown in Fig. 104, p. 122. Isotherms are drawn at intervals of two degrees Centigrade; single hatching indicates salinities between 35.00 and 35.25 per thousand, and cross-hatching salinities above 35.25 per thousand; in the deep layers the salinity was below 35 per thousand. The lines both for temperature and salinity are strikingly wave-like in the intermediate water-layers. The saltest water has come from the Atlantic in the south, and the cold deep water from the Norwegian Sea; the boundary between these layers lies deeper at Station 106 than at the neighbouring stations, the difference of level amounting to 200 metres. In order to get as true a picture of the conditions as possible the stations were placed at short intervals of only 20 nautical miles; there may be great differences within 20 miles, as from Station 105 to Station 106, and fewer stations at longer intervals might have given a totally false representation. Knowing the distribution of salinity and temperature, we may now draw conclusions as

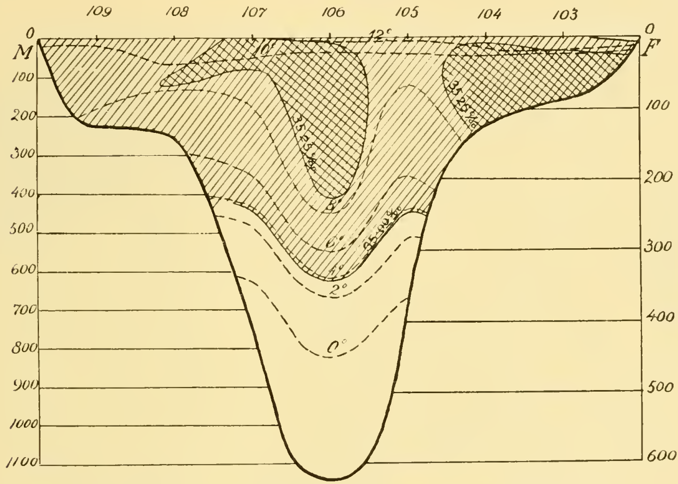


FIG. 190.—THE SOUTHERN SECTION IN THE FAROE-SHETLAND CHANNEL (10th-11th August 1910).

to the nature of the currents, their direction, breadth, and depth. Our section has a rather irregular look, suggesting complicated conditions; it seems, for instance, as if the Gulf Stream were divided into two branches, one close to Shetland, and one in the middle of the channel. In the present case the variations from one station to another are probably in part caused by the vertical oscillations mentioned, but they are evidently in part due also to another important phenomenon, viz. vortex movements.

Vortex movements.

One of the objects of our joint-research with the Scottish investigators in the Faroe-Shetland Channel was to throw light on possible vortex movements. Four parallel sections were made, the two in the middle by the "Michael Sars," the southerly one being represented in Fig. 190, and the northerly one in Fig. 191. In the map of the stations (Fig. 104, p. 122) the position of the sections is seen, the distance between them being 20 to 25 nautical miles. Although the sections were so close together they differed greatly. In the northern section the lines are fairly regular; high salinities of more than 35.25 per thousand are found only in the neighbourhood of Shetland, not in

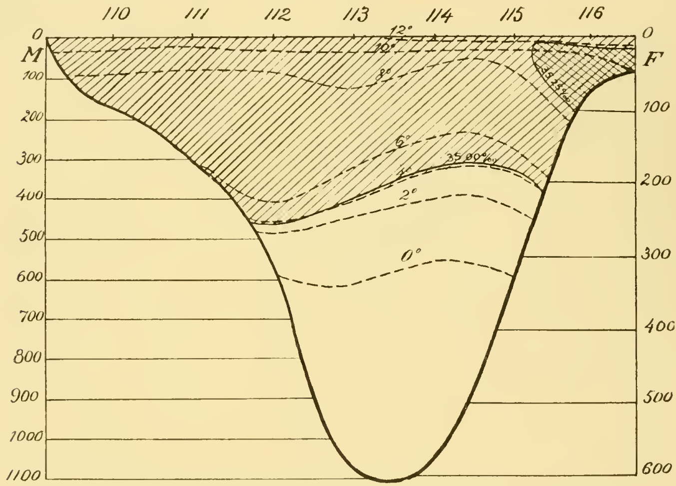


FIG. 191.—THE NORTHERN SECTION IN THE FAROE-SHETLAND CHANNEL (11th-14th August 1910).

the middle of the channel. Vertical oscillations may have had great influence on the appearance of the section. The two sections might not have presented such great differences if the observations had been taken at other times, but in any case they point to other irregularities, in the first place to vortices with vertical axes, similar to those known in rivers, only very much larger. These vortices have rendered the motion of the water highly complicated. The "Atlantic water" has moved towards the north, having a breadth of 50 or 60 miles in the neighbourhood of Shetland; between Stations 105 and 106 the water of the upper layers has probably moved southwards, between Stations 106 and 107 to the north, and so on. Previous investigations have shown that there are great vortices in several places in the Norwegian Sea. Fig. 192 shows the distribution of salinity at a depth of 100 metres in the southern part of the Norwegian Sea and the northern part of the Atlantic in May 1904. The arrows mark the probable direction of the movements. There are several vortices of different dimensions, one being drawn in

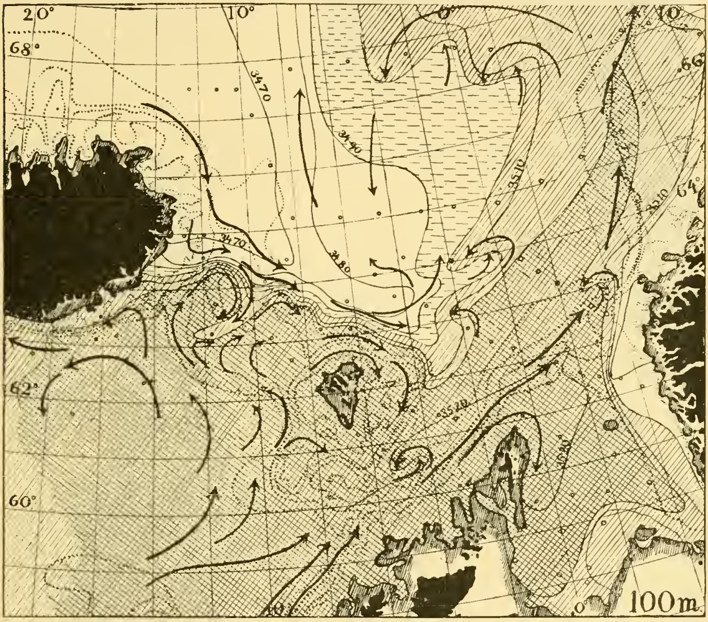


FIG. 192.—THE DISTRIBUTION OF SALINITY IN THE NORTHERN PART OF THE ATLANTIC OCEAN AND THE SOUTHERN PART OF THE NORWEGIAN SEA AT A DEPTH OF 100 METRES (May 1904).

the Faroe-Shetland Channel; similar conditions prevailed in this place in August 1910.

Currents and vortices in the Norwegian Sea.

Nansen and the writer have discussed[1] at some length the oceanographical conditions of the Norwegian Sea on the basis of earlier investigations. Fig. 193 shows the currents and vortices in the Norwegian Sea. We arrived at the conclusion that there must be many forms of motion of great and far-reaching importance, though hitherto hardly known at all,

[1] *The Norwegian Sea*, Bergen, 1909.

among them vertical oscillations of the water-layers and vortex movements. Many things go to prove that these are phenomena of general occurrence. We must picture to ourselves great

FIG. 193.—THE CURRENTS OF THE NORWEGIAN SEA.

submarine waves moving through the water-masses, alterations of depth in the layers according to changes in the velocity of the currents, standing waves, and great vortices. We must further conceive of constant fluctuations in the velocity, partly also in the direction, of the great ocean currents, not only by reason of the tides and as the effect of the wind, but also because the currents are subject to a sort of pulsation, the nature and origin of which are as yet unknown. There is an interplay of many different forces, producing an extremely variegated picture; the sea in motion is a far more complex thing than has hitherto been supposed. Physical oceanography is confronted with a host of new problems, the solution of which will be a matter of the highest interest. It was to attack a few of these general problems that the physical and chemical investigations of the "Michael Sars" Atlantic Expedition were undertaken.

Current-measurements in the Straits of Gibraltar.

We shall now consider the investigations made during the "Michael Sars" Atlantic Expedition into the physical conditions in the Straits of Gibraltar. At the current-measurement station (Station 18) on the 29th and 30th April we obtained a series of observations from different depths throughout one complete tide-period. Some of the results are represented in the accompanying three figures. Fig. 194 shows the direction and velocity of the movement at different depths on the 30th April: (1) at 10 metres (about 5 fathoms), (2) at 46 metres (25 fathoms), (3) at 91 metres (50 fathoms), (4) at 183 metres (100 fathoms), and (5) at 274 metres (150 fathoms). The arrows are drawn in the true directions; the velocities are seen by the scale. The current 10 metres below the surface (1) had a westerly set on the 30th April between 2 and 4 A.M., afterwards—until 4 P.M. at least—running without interruption eastwards (between south-east and north-east), that is into the Mediterranean. The velocities were at times very considerable, being greatest about 9 A.M., when we measured velocities up to 118 cm. per second, corresponding to 2.3 knots per hour; velocities of about 1 metre per second, or 2 knots per hour, were found during the whole time from 7 to 11 A.M. Later in the day the current slowed down; at noon it was only 40 cm. per second (0.8 knot per hour), increasing a little later; at 4.30 P.M. it was 70 cm. per second (1.4 knot per hour); then the observations were broken off, but it was ascertained that the velocity was decidedly on the increase. The current thus ran into the Mediterranean with no very fixed set, the uncertainty of direction being partly due to the formation of vortices on the sides of the strait. Early in the morning the current set from the Mediterranean into the Atlantic, as mentioned above; the velocity at 2 A.M. was 47 cm. per second (0.9 knot per hour), but it was then

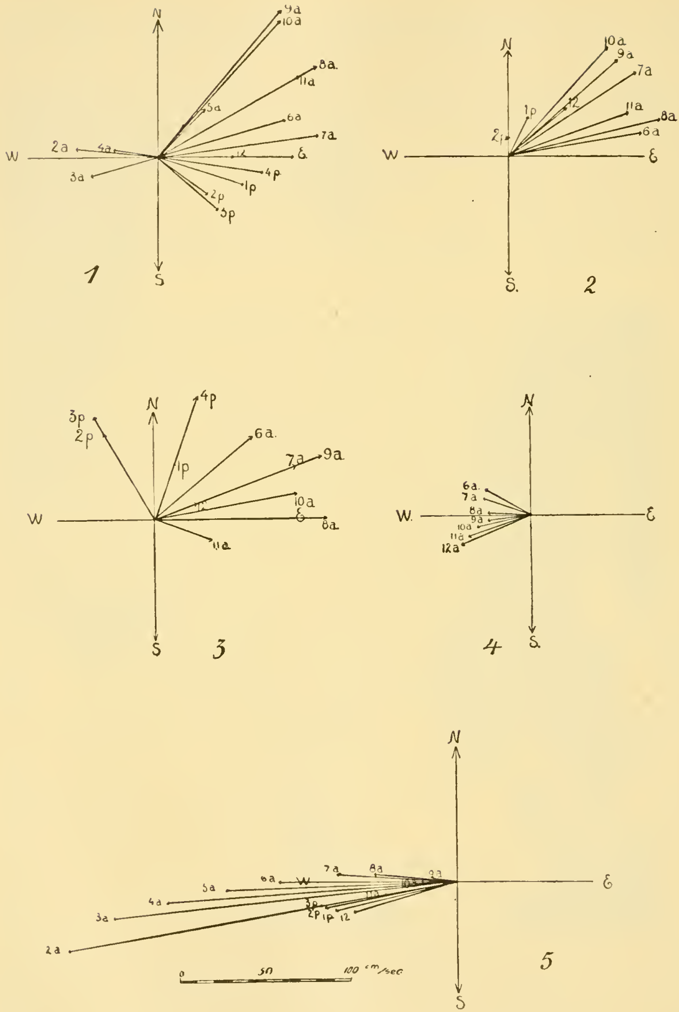


FIG. 194.—THE CURRENTS IN THE STRAITS OF GIBRALTAR ON THE 30TH APRIL 1910 AT DIFFERENT DEPTHS.

1 at 10 metres, **2** at 46 metres, **3** at 91 metres, **4** at 183 metres, and **5** at 274 metres.

decreasing. These periodic changes, between a strong current running east and a much weaker one running west, are caused by the tides, which are strong enough to reverse the current. The tide-period being nearly twelve and a half hours, one might expect the turning of the current about 2 in the afternoon; at this time it was, however, still setting east, though with comparatively small velocity. It was thus only once in the day that the current at 10 metres ran out of the Mediterranean; in other words, there was a difference between the two tide-periods in the same day. It is probably connected with the so-called "daily difference" of the tide, well known in many places, which manifests itself by each alternate high-water being conspicuously greater than the intervening one. We must, however, bear in mind that these results, of course, only apply to the particular day on which the observations were made, and we must therefore beware of drawing general conclusions until observations during a longer period and at different times of the year are available.

On the preceding afternoon (29th April) we obtained from the life-boat some measurements of the velocity of the current at a depth of 5 metres. At 5.15 P.M. the velocity was 113 cm. per second (2.2 knots per hour), and was then on the increase, being more than 150 cm. per second (nearly 3 knots per hour) at 6 P.M., and the current then set eastwards. This corresponds to the increasing velocity eastwards at a depth of 10 metres half a day and a whole day afterwards. Some observations in the deeper strata were also made from the life-boat about 6 P.M. on the 29th April, the velocity at 25 metres being 124 cm. per second (2.4 knots per hour), and at 50 metres 138 cm. per second (2.7 knots per hour); at both depths the current set in a north-north-easterly direction. Unluckily the observations were then interrupted for many hours by the breaking of the anchor-cables, otherwise we should have had continuous observations during two whole tide-periods.

On the 30th April we obtained some series of measurements from the steamer down to the bottom in about 200 fathoms of water. The current often ran so fast that the wire with the apparatus was brought into a slanting position, and the first messenger was not sent down for some minutes to allow time for adjustment. This rendered the determination of depth somewhat uncertain; the depths quoted refer to the length of wire out, and may sometimes exceed the actual depth, but it was useless to apply corrections, as we did not know the lie of the line in the water. Fig. 194, 2, shows the current at 46 metres (25 fathoms) below the surface between 6 A.M. and 2.20 P.M. In the forenoon the current ran east in the same manner as at a depth of 10 metres; about 8 A.M. the velocity was more than 90 cm. per second (1.8 knot per hour); about 11 A.M. it was slackening considerably, and at 2.20 P.M. it was merely 9 cm. per second (0.2 knot per hour); the current then set to the north. The variations in velocity correspond to those found at 10 metres.

Similar results (Fig. 194, 3) were obtained at 91 metres (50 fathoms), where the current ran into the Mediterranean in the forenoon with velocities attaining 105 cm. per second (2 knots per hour); but between 2 and 3 P.M. it turned to the north-west, that is, mainly towards the Atlantic and contrary to the current at 10 metres.

Fig. 194, 4, shows the results obtained by sending down the current-meter with 183 metres (100 fathoms) of wire. The observations were made between 6.40 A.M. and 11.26 A.M., and all this time the current ran out from the Mediterranean in the direction opposite to that of the higher layers, the greatest measured velocity being rather more than 40 cm. per second (0.8 knot per hour). The transition from the current running into the Mediterranean to that running out must have been somewhere above 100 fathoms.

The observations with the apparatus out with 274 metres (150 fathoms) of wire are particularly interesting (see Fig. 194, 5). They were made from 2.15 A.M. to 3.30 P.M., and the current all that time ran west, from the Mediterranean into the Atlantic. At 2.15 A.M. the enormous velocity of 227 cm. per second (4.4 knots per hour) was observed; at this time the current at 10 metres had also a westerly set. Then the velocity decreased; at 8.49 A.M.—half a tide-period later—a velocity of only 17.5 cm. per second (rather more than 0.3 knot per hour) was measured; at this time the current in the opposite direction at 10 metres ran its fastest. Later on, the deep current increased in velocity, running at 3.27 P.M.—after another half-tide period—83 cm. per second (1.6 knot per hour). There was a similar difference between two successive tides at 274 metres and at 10 metres. These observations gave this important result: that when the surface current ran fastest to the east the under current setting west was at its slowest, and *vice versa*.

At 12.22 P.M. one of the current-meters was sent down with 366 metres (200 fathoms) of wire, but after working for ten and a half minutes it was hauled up in a wrecked condition. The wings were battered and bent, and the compass was gone; it was clear that the apparatus had been bumping against the stones on the bottom. The propeller had made 280 revolutions, implying a velocity of 11 cm. per second (0.2 knot per hour), so that the water had moved along the bottom at that rate at least, probably faster, as the propeller must have revolved too slowly after being injured. This separate measurement gives the interesting result that there may be an appreciable current even along the bottom.

Now, in what relation do these currents stand to high and low water? The tide-tables show that at Cadiz and Algeciras high water and low water on 30th April 1910 occurred at the following hours:

	High Water.	Low Water.
Cadiz . .	4.51 A.M., 5.16 P.M.	11.04 A.M.
Algeciras . .	5.15 A.M., 5.40 P.M.	11.28 A.M.

In the straits high water may with sufficient accuracy be referred to about 5 A.M., low water to a little after 11, and the next high water to about 5.30 P.M. It follows that the water ran fastest into the Mediterranean about four hours after high water, *i.e.* at falling tide, and that it ran fastest out from the Mediterranean three or four hours after low water, that is, with a rising tide.

In Figs. 195 and 196 the current-conditions between the surface and the bottom are shown, in the first for the 30th April at 9 A.M., when the current into the Mediterranean was running at its maximum, and in the second the mean for the movements at 2 A.M. and at 3 P.M., when the current out of the Mediterranean attained its greatest velocity. The velocities at the different depths have been calculated with regard to the longitudinal direction of the strait, the varying directions of the current having been taken into account; the actual velocities are shown in Fig. 194. The two diagrams give a good picture of the relation between the upper and the lower current in the middle of the straits, the former about four hours after high water, the latter three or four hours after low water. It is seen that the boundary between the two currents lay at a depth of about 160 metres when the inflow into the Mediterranean was greatest, and that it approached the surface when the inflow was least,

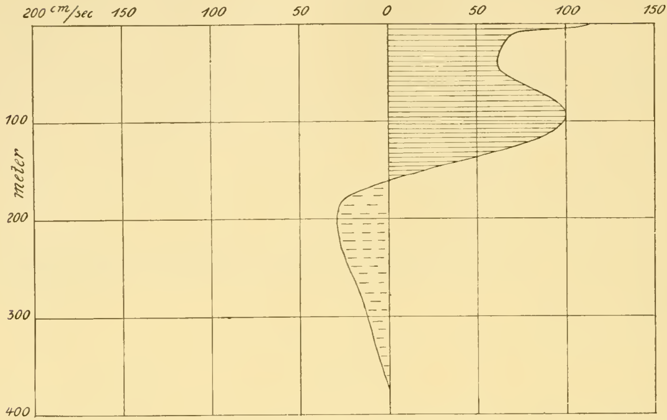


FIG. 195.—THE MOTIONS IN THE DIFFERENT LAYERS IN THE STRAITS OF GIBRALTAR (CALCULATED FOR THE LONGITUDINAL AXIS OF THE STRAITS) WHEN THE CURRENT WAS SETTING INTO THE MEDITERRANEAN AT ITS STRONGEST (30th April 1910).

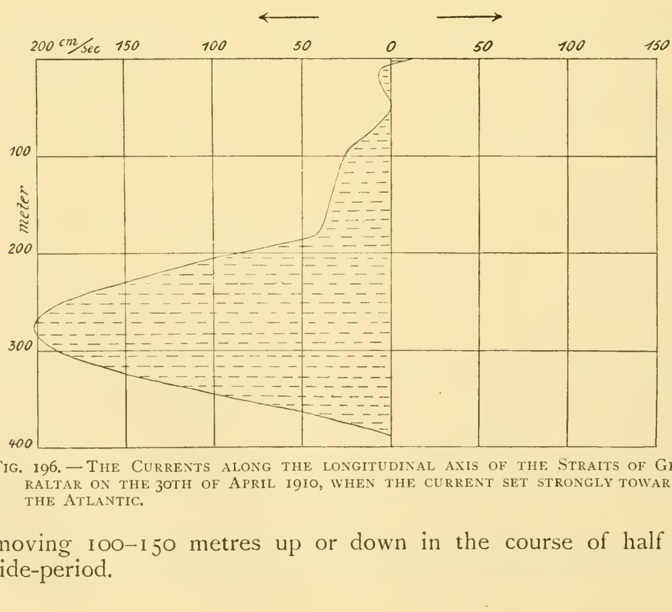


FIG. 196.—THE CURRENTS ALONG THE LONGITUDINAL AXIS OF THE STRAITS OF GIBRALTAR ON THE 30TH OF APRIL 1910, WHEN THE CURRENT SET STRONGLY TOWARDS THE ATLANTIC.

moving 100–150 metres up or down in the course of half a tide-period.

Together with the current-measurements four series of water-samples and temperatures were taken; the results are given in the following table:—

Temperatures and salinities in the Straits of Gibraltar.

Depth. Metres.	Station 18 A. 29 IV. 11½ A.M.-12½ P.M.		Station 18 B. 29 IV. 2-2½ P.M.		Station 18 C. 29 IV. 11-12 P.M.		Station 18 D. 30 IV. 9½-10½ A.M.	
	Temp.	Salinity.	Temp.	Salinity.	Temp.	Salinity.	Temp.	Salinity.
0	17.0	36.12	16.6	36.14	16.6	36.02	17.4	36.17
25	15.16	36.19	14.89	...	15.6	...	16.18	...
50	13.29	37.80	13.35	...	15.09	36.20	15.39	...
100	12.92	38.30	12.92	38.33	14.38	36.28	14.09	...
200	12.91	38.39	...	...	13.11	37.97	12.94	38.36
300	12.87	38.39	...	...	12.89	38.39	...	...

Here also we see considerable variations from time to time at the different depths, variations corresponding to a difference

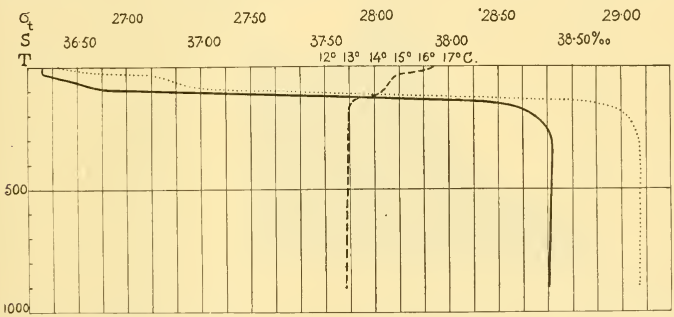


FIG. 197.—TEMPERATURE (BROKEN LINE), SALINITY (CONTINUOUS LINE), AND DENSITY (DOTTED LINE) AT STATION 19, IN THE MEDITERRANEAN (2nd May 1910).

of level between the layers of 100–150 metres. On the 29th April, about 2 P.M., the current running in must have been feeble and that running out must have been strong, judging from the later current-measurements, and the salt Mediterranean under current extended up towards the surface, whereas on the 30th April, between 9.30 and 10.30 A.M., the upper current was very strong and the under current from the Mediterranean very feeble in comparison, and the salt water from the Mediterranean lay about 100 metres deeper. The vertical distribution of salinity and temperature is seen to accord with the currents.

Two days after these observations in the Straits of

Observations in the Mediterranean.

Gibraltar, the "Michael Sars" entered the Mediterranean, and took observations at Station 19, the hydrographical conditions being shown in Fig. 197. The surface temperature varied from 16° to 17° C., and the salinity was nearly 36.4 per thousand. The temperature decreased and the salinity increased downwards, until we struck the Mediterranean deep water at a depth of about 160 metres; from this point downwards we found exactly the same temperatures and salinities as in the undercurrent in the straits. This was on the 2nd May, between 10 A.M. and 1 P.M.; the observations in the uppermost 300 metres were made between 10.30 and 11.30 A.M. Judging from the previous measurements the inflow in the straits should then be about its strongest. Between 5 and 6 P.M. some of the observations were repeated, and the boundary between the surface-layers and the deep water then lay somewhat higher; it might be a matter of 10 or 15 metres. The under current setting out of the straits was then very strong and the surface current comparatively feeble. So there were fluctuations in the position of the boundary in the Mediterranean eastward of the straits corresponding to the fluctuations in the straits, only considerably smaller, because the current-velocities naturally would be much smaller where the basin was broad.

FIG. 198.—"MICHAEL SARS" STATIONS IN THE SPANISH BAY BETWEEN SPAIN AND MOROCCO IN MAY 1910.
The lines indicate the positions of the two sections represented in the two following figures.

Observations in Spanish Bay.

A few days later a number of observations were taken in the Spanish Bay westward of the straits. The positions of the stations are indicated in Fig. 198, and the salinities and temperatures are shown in the two sections: Fig. 199, in an east and west direction, and Fig. 200, in a north and south direction. In the east to west section the salt Mediterranean water with a salinity exceeding 38 per thousand is seen stretching out through the Straits of Gibraltar, its salinity, however, soon decreasing to little more than 36 per thousand. A great mixing process must be going on here, as might be expected with the mighty submarine current rolling its saline waters into the strata occupying

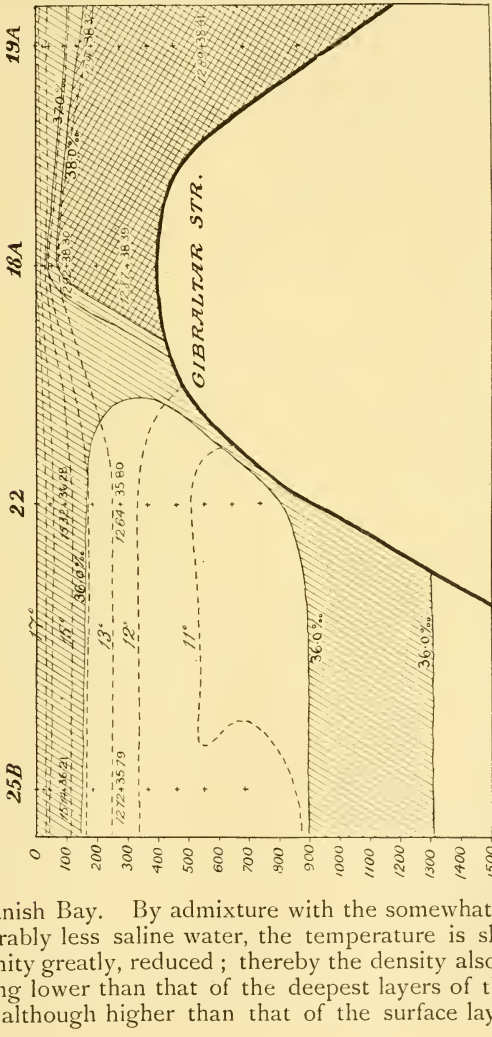


Fig. 199.—Section from the Mediterranean through the Straits of Gibraltar to the Atlantic Ocean (May 1910).

the Spanish Bay. By admixture with the somewhat colder and considerably less saline water, the temperature is slightly, and the salinity greatly, reduced ; thereby the density also decreases, becoming lower than that of the deepest layers of the Atlantic region, although higher than that of the surface layers. This

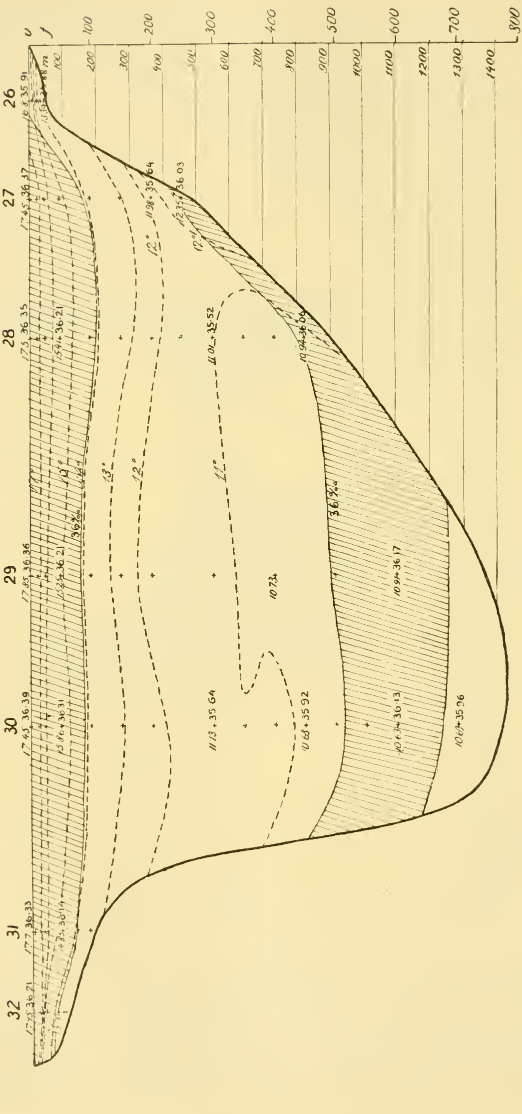


FIG. 200.—SECTION THROUGH THE SPANISH BAY IN A NORTH AND SOUTH DIRECTION (MAY 1910).

mixed water enters like a wedge between the other water-masses at a depth of about 1000 metres, as clearly shown in the two sections. In this part of the Atlantic Ocean the salinity and temperature first decrease for some hundred metres below the surface; then both increase a little through the influence of the outflow from the Mediterranean, below which they again decrease. The admixture of water from the Mediterranean can be widely traced over the eastern part of the North Atlantic, as already pointed out by Buchanan and Buchan. It is also evident from our observations at a number of stations, for instance at Station 17, off the coast of Portugal, as shown in Fig. 201. In the map showing the physical conditions at the depth of 500 fathoms (given in Fig. 202), we can trace it by the comparatively high salinities and temperatures reaching north towards Ireland and west towards the Azores. This admixture is far more in evidence along the coasts of Europe than along those of Africa; this signifies a drift towards the north, which might be expected as an effect of the earth's rotation and the consequent deflection to the right. It appears, however, that some of this mixed water is carried far to the south-west by the great currents running between Madeira and the Azores.

Outflow of Mediterranean water into the North Atlantic.

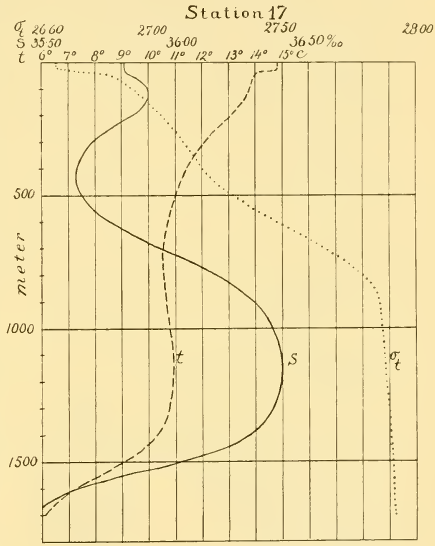


Fig. 201.—Salinity, Temperature, and Density at Station 17, west of Portugal (23rd April 1910).

This wedge of mixed water from the Mediterranean is not met with near the surface nor in the greater depths. Thus it is not seen in the map (Fig. 203) showing the physical conditions at a depth of 200 fathoms (366 metres). At this level the saltest water (with a salinity above 36 per thousand) is found in the south-western part of the North Atlantic (excluding the fresher

American coast-water). Farther north the salinity decreases, being a little more than 35.5 per thousand off the south-western coasts of Europe, and between 35.0 and 35.5 per thousand farther

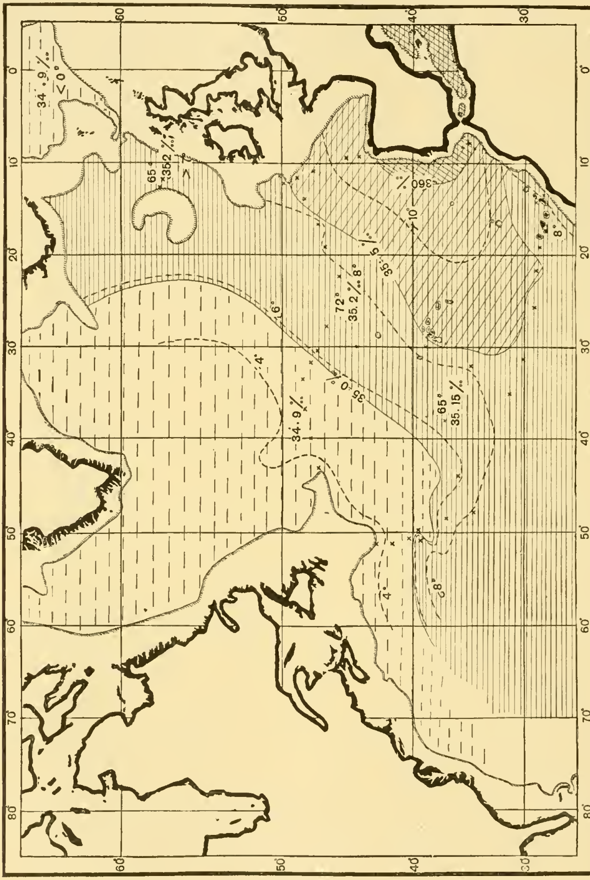


FIG. 202.—SALINITIES AND TEMPERATURES IN THE NORTH ATLANTIC AT A DEPTH OF 500 FATHOMS IN THE SUMMER OF 1910.

north off the British Isles towards the Faroe Islands and Iceland. In the northern part of the ocean the saltest and warmest water is found on the European side, the Gulf Stream making its influence felt there, whereas the less salt and much colder water-masses south of Greenland are derived from the polar currents.

Alternating currents off Newfoundland Bank.

In this map (200 fathoms) the lines south and east of the Newfoundland Banks have a peculiar form. The warm and

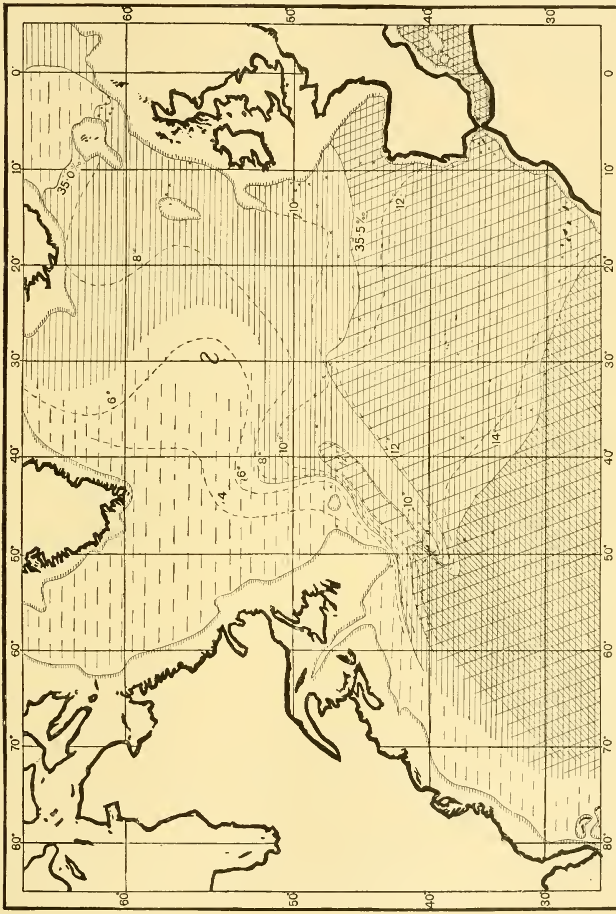


FIG 203.—SALINITIES AND TEMPERATURES IN THE NORTH ATLANTIC AT A DEPTH OF 200 FATHOMS IN THE SUMMER OF 1910.

salt water-masses appear to be cleft in two by a colder wedge from the north-east. This indicates a current towards the south-west, forcing its way between the other water-masses flowing in the opposite direction. Now, it is quite possible that the lines in the map are wrongly drawn, because had there been many more stations the lines might have formed a number of vortices, like those mentioned above, p. 282. However that may be, it is a fact that we fell in with a current running south-west, in the midst of the water-masses following the direction of the Gulf Stream towards the north-east, and this singular circumstance may be dealt with in greater detail.

The section shown in Fig. 204 stretches from the Sargasso Sea along the track of the "Michael Sars" northwards to the

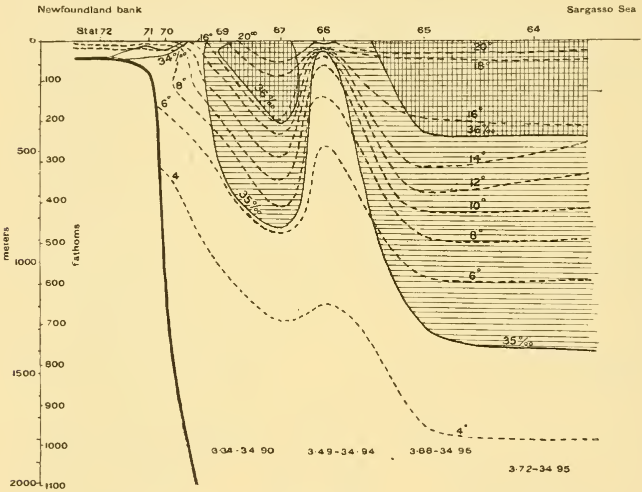


FIG. 204.—SECTION FROM THE SARGASSO SEA TO THE NEWFOUNDLAND BANK.

Newfoundland Bank. At Stations 64 and 65 the conditions were uniform, resembling those found during the cruise from the Canaries westwards (see Fig. 63, p. 84). All this part of the Atlantic in and about the Sargasso Sea belongs to an oceanographically homogeneous region, but at Station 66 we suddenly met with very different conditions, for it was much colder in all the layers above the deep water, and the salinities were much lower. On proceeding farther north we again found, at Station 67, the same warm and salt water-masses as farther south at Stations 64 and 65. There was a decided difference also as regards the pelagic flora and fauna, which had a more northern facies at Station 66 than at Stations

65 and 67. Now, when we consider the position of the water-layers and the effect of the earth's rotation, as treated above (p. 276), we come to the following conclusion: the current in the upper water-layers sets towards the north-east between Stations 65 and 66, another current runs towards the south-west between Stations 66 and 67, then a current runs to the north-east again towards Station 70.

As we were working at Station 67 on the afternoon of the 27th June, a gale arose, increasing in the course of the night to a hurricane from the south-west, veering later on to the west. There was a rough sea with choppy waves, as is usual with the wind blowing against the current. We kept the ship's head to the wind all night, and it was as much as we could do under heavy steam pressure to stem the storm without drifting off. Next morning the wind fell somewhat; it was fresh from the west when we occupied Station 68. When the captain got an observation, it proved that we had been carried southwards about fifty nautical miles from Station 67 to Station 68. This agrees excellently with our conclusions from the distribution of temperature and salinity, and it is established beyond doubt that in this place there was a strong current running towards the south-west. The west wind caused the ship to drift more to the south than the course of the current. Peake and Murray[1] and Schott tell us that a current running south-west has been met with before in the same region; thus, the cable-steamer "Podbielski," in May 1902, drifted 53

[1] "The climate of the British Isles being influenced to such a large extent by the warm water of the Gulf Stream, the movements of this great body of water, the course of its main current, and the manner in which this spreads itself over a very large portion of the North Atlantic, should be a subject of special interest to the inhabitants of these islands. Among those who have not carefully studied the observations that have been made on this subject, a general impression obtains that after leaving the American coast the Gulf Stream consists of a body of warm water moving steadily across the North Atlantic in the direction of the Irish coast. An increasing number of observations tend more and more to show that this is not the case; the movement of this great mass of water is more probably somewhat in the form of bands of current which curve and recurve on one another, forming swirls of large area whose strength and direction change almost daily. A glance at the current charts shows how the Gulf Stream in its passage across the Atlantic spreads itself out at the surface like a fan, and forms what is known as the Gulf Stream drift.

"It will also be noticed that on the line of observation given herewith, an easterly current was met with considerably farther to the westward than would have been expected from the Admiralty current charts; this, however, merely exemplifies the variations which occur in the course of even the main body of the stream at the surface, the course as shown on the Admiralty current charts being its average direction.

"In the appended list of observations the total 'sets' are given, and these are again corrected for the pressure of the wind and the force of the sea, leaving a 'set' due to current only. The correction for wind and sea is necessarily only an approximation, but the result approaches more nearly to the current effect than would have been the case had no correction been attempted. The direction of the current as observed between the Azores and North America is shown on the accompanying map by arrows" (Peake and Murray, "On the Results of a Deep-Sea Sounding Expedition in the North Atlantic during the Summer of 1899," extra publication of the Roy. Geog. Soc. London, 1901, pp. 13-14).

miles to the south-west in the course of twenty-four hours in lat. 40° N. and long. 55° W. It would be interesting to know whether these conditions are constant in this region, as it might then be of importance for navigation, or whether there may be certain irregularities, perhaps one or more progressing vortices.

As a matter of fact, the general current was here split into two branches. Whether it proceeds as two separate currents or not is difficult to judge from our investigations, as we had too few stations in the neighbourhood, and there are no previous observations. Our section from Newfoundland to the Bay of Biscay (Fig. 99, p. 115) has a suggestion of a similar division at Station 85, but it is too slight to base any conclusions upon. It is, however, known that farther south there occur "bands" of water with comparatively low temperatures in the surface-layers of the Gulf Stream. But we are on many points deficient in our knowledge of this most important ocean current, among other things also with regard to the yearly variations to which it is subject.

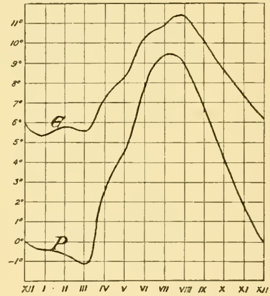


Fig. 205.—Air-temperature at the Faroe Islands

G, when the wind blew from the "Gulf Stream" region; and P, when the wind blew from the East Iceland Arctic-current region.

Influence of the Gulf Stream on the climate of Europe.

It is a well-known fact that the climatic conditions of northern Europe are influenced by that branch of the Gulf Stream which flows northwards along the shores of the British Isles into the Norwegian Sea. In places with such a maritime climate as that of the Faroe Islands this influence is especially felt. Martin Knudsen has examined some meteorological observations from the Faroe Islands, and has found (see Fig. 205) a conspicuous difference between the temperature of the air when the wind blew from the Gulf Stream region in the south and west, and when it blew from the north, over the Arctic East Iceland current. The difference was greatest in winter (as much as $6\frac{1}{2}$° C.) and least in summer (smallest difference $1\frac{1}{2}$° C.). Pettersson at an early period entered on the study of questions regarding oceanic influence on the climate of Scandinavia, and his work on this subject has been more conducive than anything else to the establishment of the international investigations of North European waters.

Figs. 206 and 207 show some of his results. At that time (in the nineties) no systematic investigations of the Norwegian Sea through any length of time had been carried on, so he could only study the surface-temperatures noted at three Norwegian lighthouses.

In Fig. 206 we see the variations in the surface-temperature off the west coast of Norway (indicated by the thick line) and in the air-temperature at Örebro in Sweden (indicated by the thin line), both for January during the years 1874 to 1892. The vertical scale indicates the deviation from the mean temperature, which for the coast-water is 5.3° C. and for the air 3.4° C. On the whole the curves agree well, a high temperature in the

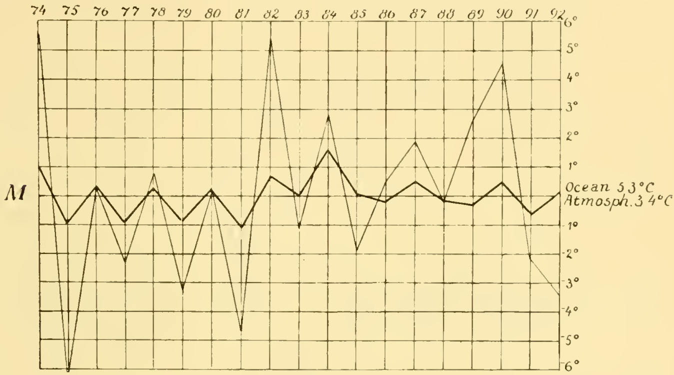


Fig. 206.

The thick line shows the variations in January of the surface temperature off the west coast of Norway from year to year; the thin line the variations of the air-temperature at Örebro (Sweden).

surface-water corresponding to a high temperature in the air. Pettersson further pointed out that a certain deviation from the normal temperature of the air, as a rule, lasts for a length of time; a cold period, for instance, often lasts for weeks, or even months. Now, there are many relations on the land which are influenced by the deviations of the air-temperature from the normal, among other things, the duration of the snow-covering, the time of blossoming of many plants, the time for beginning field-labour in spring. Pettersson found the variations in some of these particulars to agree with the variations in the temperature of the air and of the surface-water off the west coast of Norway some time before. Fig. 207 shows an example of this agreement; the lower curve gives the variations in the temperature of the sea-surface off the Norwegian lighthouses for the month of February, while the upper curve shows the variations of the date at which the coltsfoot (*Tussilago farfara*) began to blossom in central Sweden (Upsala). This plant begins to blossom, on the average, about the 9th April, the exact date varying in different years from the 18th March to the 28th April. The two curves agree in many points; when the water off the lighthouses was relatively warm in February the flowering commenced early, and when it was cold the blossoming was late.

Pettersson had at his disposal only observations from the water in the immediate vicinity of these coast stations, but since

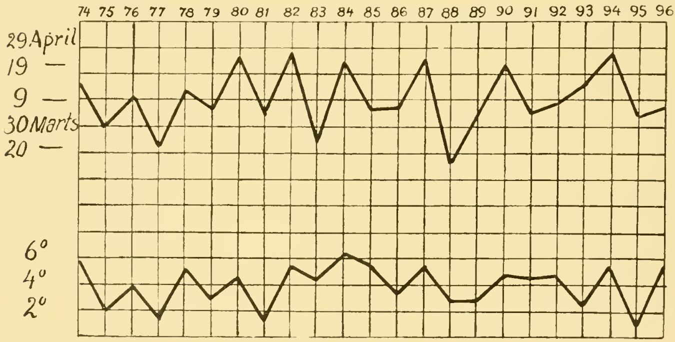


FIG. 207.

The upper curve shows the time of blossoming of *Tussilago farfara* at Upsala during a series of years. The lower curve shows the surface-temperature of the sea off the west coast of Norway, in the month of February of the same years.

regular investigations were started in the Norwegian Sea in 1900, we have excellent series of observations during a succession of years, not only in the coast-water, but also in that branch of the Gulf Stream which flows into the Norwegian Sea. Nansen and the writer have found, by going through all the observations made in the years 1900 to 1905, that there are great variations in the temperature-conditions of this Atlantic current, and that these variations are apparently followed by corresponding variations in many other conditions; for example, the temperature of the air, the year's harvest, the growth of the trees, and various circumstances touching the appearance of great shoals of fish. One or two instances may be referred to here.

During the Norwegian investigations a section was run from the mouth of the Sognefjord westwards, in the middle of May, every year from 1901 to 1905. One of these series is figured on p. 240. Nansen and the writer have calculated the mean temperatures in the Atlantic water of this section, both for the surface and for the deeper water. The variations in the surface-temperature are represented in curve I., Fig. 208, curve II. showing the variations in the growth of the pine in eastern Norway during the following year. The low surface-temperature in May 1902 corresponded to the small growth of the pine in the succeeding year, 1903, and the high temperatures in the surface of the Gulf Stream in May 1905 corresponded to a great addition to the height of the pine trees in the year 1906. This is explicable by the fact that the annual growth of the pine is not determined by the meteorological conditions of the same year, but by those of the year before, when the bud was formed, the growth mainly depending on the formation of the bud. Continued investigations will prove whether the agreement strongly suggested by the figure is really a general rule, in which case it may be possible, on the basis of investigations in the Norwegian Sea, to predict with a high degree of probability how much the Norwegian pine will grow in the following year.

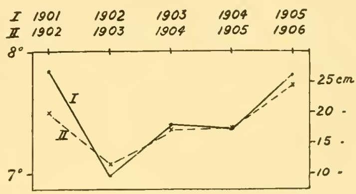


FIG. 208.

I., mean temperature of the surface of the "Gulf Stream" in the Norwegian Sea (Sognefjord section, May); II., mean growth of the pine in eastern Norway.

By calculating the mean temperature of the Atlantic water-masses below the surface in the Sognefjord section, and multiplying the ascertained value by the area of the transverse section of these water-masses, an expression is obtained for the amount of heat in the northern branch of the "Gulf Stream." This has been done from the observations made during the May cruises, and the results are exhibited in curves I. and II. in Fig. 209; the two curves are obtained by two different methods of calculation which need not be discussed here. The lower curve shows the variations in the mean temperature of the air in Norway during the winter months from the 1st November to the 30th April. The coincidence is striking; when, for instance, the amount of heat in the Gulf Stream was great in the month of May, the air-temperature in Norway was high in the following winter. This holds good throughout six years, but, of course, that is too short a period from which to draw definite conclusions. Anyhow, these preliminary results point to possibilities of no little importance, and we may in the future be able to predict, months beforehand, whether the coming winter will be warmer or colder than the normal. Many similar relations could be pointed out between the conditions in the sea and facts of interest bearing upon our daily life, but the above examples give an indication of the problems to be faced in modern oceanography.

The Atlantic current flowing northwards over the Norwegian Sea, which in our waters is also called the Gulf Stream, is thus subject to considerable variations in temperature and total amount of heat. This current is, however, a mixture of water from the Atlantic proper with water from the northern currents penetrating intothe Norwegian Sea, north of the Faroe Islands. and the character of the "Gulf Stream" will depend on the conditions of mixture, and on the individual temperature of each of these currents, factors of which we know little. It is highly probable that the Gulf Stream of the Atlantic also shows annual variations, and, though they may not be of much importance in their effect on the small branch in the Norwegian Sea, they may prove to be of great climatological significance for the countries on both sides of the Atlantic Ocean; a thorough study of this current in the immediate future is therefore looked forward to with great expectations. That there are large annual variations in the caloric conditions of the huge water-masses of the North Atlantic was suggested by the observations of the "Challenger" nearly forty years ago, and has been confirmed during the recent cruise of the "Michael Sars," these two vessels having made investigations in the

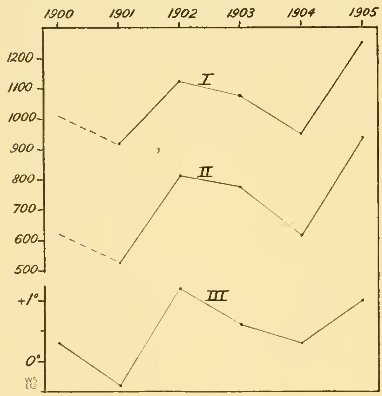


FIG. 209.

I. and II., the annual variations in the amount of heat in the "Gulf Stream" (Sognefjord section, May); III., variations in the air-temperature of Norway (November to April).

same oceanographical region. In July 1910 observations were made by the "Michael Sars" at Stations 60 to 65 in the vicinity of the "Challenger" Station 65 of June 1873. Now, the temperatures of the great depths beyond 1000 fathoms prove to be identical in these two years, showing that the thermometers worked properly, but in the upper layers it was much colder in 1910 than it was thirty-seven years before, the difference in

Comparison of "Challenger" and "Michael Sars" temperature-observations.

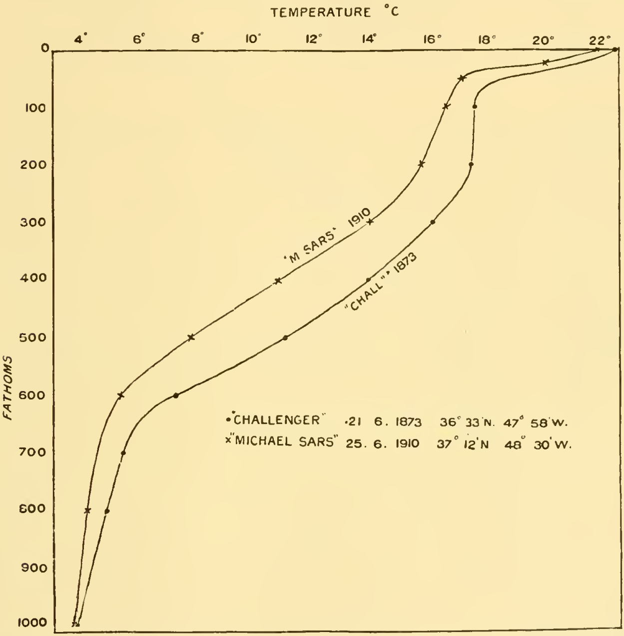


Fig. 210.—Comparison of the Temperatures taken by the "Challenger" in 1873 and by the "Michael Sars" in 1910.

some cases amounting to about 5° C. at a depth of 700–800 metres (400 fathoms). Fig. 210 shows the temperature-observations at the "Challenger" Station 65 and the "Michael Sars" Station 65, between the surface and a depth of 1000 fathoms.

Observations were taken at the "Michael Sars" Station 51 in June 1910, in the vicinity of the "Challenger" Station 354 in May 1876. Fig. 211 shows the conditions at these two stations, which varied only to a slight extent; at certain depths it was a little colder in 1876 than in 1910, at other depths a little warmer, but no general difference appears between the two series of temperatures—one series taken thirty-four years after the other. There have probably been many variations in the course of these years of which we have no knowledge. In this

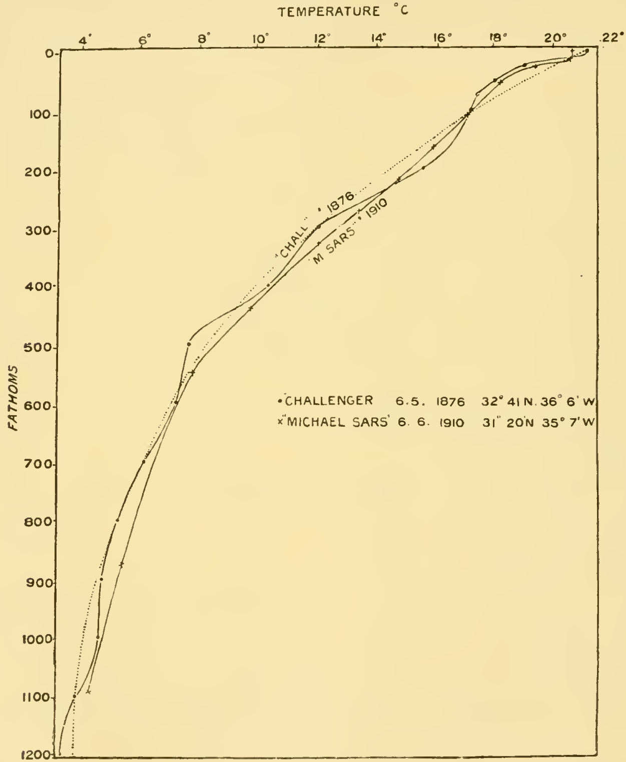


FIG. 211.—COMPARISON OF THE TEMPERATURES TAKEN BY THE "CHALLENGER" IN 1876 AND BY THE "MICHAEL SARS" IN 1910.

and in many other respects the Atlantic Ocean calls for further and more detailed investigation; as we said at the beginning of this chapter, very much more work will have to be done before we shall be able to solve the many interesting and important problems relating to the great ocean waters.

B. H.-H.

CHAPTER VI

PELAGIC PLANT LIFE

NOT many years have elapsed since the scientific world became aware that the sea contains plants in abundance floating on and beneath its surface, and that they build up the organic substances upon which marine animals depend. In the open sea the plants are too minute to be detected without the microscope; so that, until this instrument came to be regularly employed by biologists, it was impossible to know anything about them. Historical introduction.

The first to use the microscope for studying unicellular organisms in the sea was the celebrated Danish zoologist, O. F. Müller, who, in 1777, described one of the most important plants of our northern waters, namely, *Ceratium tripos*. He was succeeded by the microscopist Ehrenberg, who laid the foundation of our knowledge regarding the multiplicity of forms, their wide distribution, and their significance in the economy of nature; and also discovered the coverings of diatoms together with coccoliths and the skeletons of various unicellular animals (radiolaria, foraminifera) in deposits on the sea-bottom and in geological strata from previous ages. Ehrenberg aroused interest by pointing out the wonderful structure of these coverings, and improvements in the microscope have resulted in fresh wonders being disclosed, which have induced quite a number of capable amateurs to take up the study of diatoms. O. F. Müller. Ehrenberg.

Classification of these algæ dates from about the middle of the nineteenth century. It is based on the shape and structure of the cell-wall, less attention having been given to the living contents and to the biology. The pelagic forms have as a rule thinner coverings, and a more indistinct structure, than the robust species nearer the coast, and have therefore been less studied. However, occasional samples have now and then been collected from the surface with nets, and researches have been carried out by J. W. Bailey in the waters off Kamchatka, by Brightwell along Bailey. Brightwell.

Lauder. Cleve. Wallich. the shores of England, by Lauder at Hong-Kong, and by Cleve in the North Polar Sea and at Java. A regular gold mine in the way of rare pelagic forms was found by Wallich in the intestinal canals of salpæ, and this source has subsequently been utilised for procuring forms that our apparatus could not capture.

Nitsch. Claparède. Lachmann. Stein. Bergh. Pelagic algæ which have no skeletons of durable mineral constituents, such as silicic acid or lime, were in those days neglected. A few, no doubt, of the larger peridineæ were described by Nitsch, Ehrenberg, Bailey, Claparède, and Lachmann; but there was very little progress made, and it was not till 1883 that T. R. von Stein published his first comprehensive monograph, a great deal of the material for which had been taken from the stomachs of salpæ. R. S. Bergh had already issued, two years previously, a text-book on the organisation of these algæ.

"Challenger" Expedition. John Murray. Castracane. Since 1870 important expeditions have been undertaken, one object of which was to study the pelagic organisms systematically. The "Challenger" Expedition, in particular, collected quantities of material from all the seas of the world; though attention was still chiefly directed to those forms whose coverings are met with in deposits on the sea-bottom, that is to say, diatoms with their silicious coverings, and the remarkable little organisms forming the microscopic calcareous bodies which Ehrenberg had already designated coccoliths and rhabdoliths. Murray pointed out that coccospheres and rhabdospheres, as they were termed, are really self-existent organisms in the surface-layers. He could obtain them by allowing a glass of sea-water to stand for a few hours, so that they sank to the bottom and attached themselves to threads placed there for purposes of experiment; and he also found numbers of them in the stomach-contents of salpæ, of which they often formed an essential part. It was possible, too, by noting the occurrence of their coverings in the bottom-samples, to obtain definite information regarding their geographical distribution. He observed that, while they are abundant in all tropical and sub-tropical waters in the open ocean, they are not found in arctic and antarctic waters having a temperature below 45° F., nor are they to be found in the deposits of the polar oceans. Murray further ascertained that diatoms are irregular in their occurrence, and that they are more numerous in coastal areas than out in the ocean. Unfortunately Castracane, when examining the diatoms collected by the expedition, was unable to find any conformity in the distribution of the different species.

The other expeditions that were sent out about the same time as the "Challenger" carried out their investigations on similar lines. G. O. Sars, who was a member of the Norwegian North Atlantic Expedition in 1876–1878, made a study on board ship of the luxuriant plant life near the ice-limit, and remarked, like Œrsted before him, that plants are really the basis upon which the nutriment of animals is founded. It was not, however, till twenty years afterwards that an examination was made of the algæ in the comparatively small number of samples then collected.

G. O. Sars.

Œrsted.

Soon after 1880 Hensen commenced a physiological study of the sea, and essayed principally to estimate its production of nutritive substances at different seasons. As a result the plants came more into notice than they had previously done; and it is significant that Hensen found it necessary to introduce the new name of "plankton" to designate generally all pelagic organisms, both plants and animals, regarded as one universal community. The term "plankton" is now used for all floating organisms which are passively carried along by currents, while "nekton" —a term introduced by Haeckel—is used to designate all pelagic animals which are able to swim against currents. During Hensen's Plankton Expedition in 1889 Schütt made the first investigations regarding the general biology of the plankton-algæ. His ingenious descriptions and admirable drawings explained the different ways in which the algæ adapt themselves to their floating existence.

Hensen.

"Plankton."

"Nekton."

Schütt.

An endeavour was made by Hensen to find a method of calculating the quantity of pelagic organisms occurring in different localities. He constructed nets to be drawn up for certain distances through the water, that were supposed to filter the whole column of liquid through which they passed, and to retain all the organisms existing therein. The total amount of these organisms was then measured by determining the volume, and a most careful enumeration was made of the number of individuals belonging to each species. The nets were drawn vertically through the whole zone where plant plankton is abundant, that is to say, from a depth of 200 metres to the surface; and Hensen attempted to utilise the results for measuring the production of life in a column of water whose superficial area is one square metre. He tried at the same time to solve important problems, such as the rate of augmentation of algæ, or what proportion of individuals disappears owing either to consumption by other organisms or unfavourable conditions of existence.

Quantitative estimations.

Hensen's work must not be disparaged because his aspirations have been more difficult to realise than he at first imagined. The difficulties are far from insurmountable, while Hensen himself will be always looked upon as one of the founders of the science of marine physiology.

In the biology of the sea we have also to consider the geographical distribution of the different species and their dependence upon ocean currents. The Swedish scientists, Cleve and Aurivillius, brought these two questions into special prominence, though no doubt they had been previously considered by others. But with the hydrographical investigations of Otto Pettersson and others the whole subject assumed a new aspect. Thanks to improved methods they succeeded in following the movements of the water-layers, by determining their salinity, temperature, and other hydrographical characteristics; and from this time forward the plankton was also enlisted as a supplemental means of characterising water-masses of different origin. Cleve with his marvellous power of distinguishing forms was able in a short space of time to determine numbers of species, animals as well as plants, and it is to him we owe the foundation of our knowledge regarding the distribution of plankton-algæ.

Aurivillius.

Pettersson.

Since the international marine investigations were commenced about ten years ago, researches have been carried out in the Northern Atlantic, North Sea, and Baltic; and specialists from the different countries of North Europe have gradually extended our knowledge, as far as northern species are concerned.

International investigations.

Simultaneously great improvements have taken place in our methods of studying plankton. Lohmann has made it clear that the catches in the silk nets originally used incompletely represented the flora of the sea, owing to the fact that whole series of the most diminutive organisms slip through the meshes of even the finest straining-cloth. He devised methods for catching them by means of the filter and the centrifuge, and could thus estimate their numbers in a given quantity of sea-water. Coccolithophoridæ, which the "Challenger" Expedition claimed to have discovered, but which Hensen refused to recognise as self-existent plankton organisms, because he did not capture them himself, were now investigated, and Lohmann was able to declare confidently that they really are algæ, furnished with brown pigment granules, the physiological equivalent of chlorophyl, thus confirming the earlier discoveries of Sir John Murray, George Murray, Blackman, and Ostenfeld. Lohmann

Lohmann.

G. Murray. Blackman. Ostenfeld.

has further, by his quantitative investigations of the variations in the plankton of Kiel Bay and off Syracuse, taught us the value of exact studies of this description.

Our future investigations will have to be conducted on three main lines :—

(1) In the first place, much study must be devoted to the biology, in the restricted sense of the word, of the algæ. We will have to learn how the forms adapt themselves to their conditions of life, and in particular to their floating existence. Here, however, a great advance should most certainly be made, now that W. Ostwald has shown us a new factor affecting their floating power, namely, the varying viscosity of sea-water, and since the instructive writings of Wesenberg-Lund have directed our attention to the seasonal modifications which the species adopt to suit variations in viscosity. Ostwald. Wesenberg-Lund.

(2) In the second place, the distribution of the species throughout the seas of the world requires further investigation at different seasons, and this must be founded on a careful characterisation of the different species. In recent years the peridineæ, after a long period of neglect, have received due attention at the hands of Ostenfeld, Ove Paulsen, Pavillard, Jörgensen, Broch, and Kofoid. A great deal, however, still remains to be accomplished. Paulsen. Pavillard. Jörgensen. Broch. Kofoid.

(3) In the third place, we will have to deal with the laws of production in the sea. This great physiological question calls for observations on a very comprehensive scale, if we are to be in a position to discuss the interesting theories put forward by Brandt, Nathansohn, and Pütter. A brief discussion of their theories will be found at the end of this chapter. Brandt. Nathansohn. Pütter.

During the Atlantic Expedition of the "Michael Sars" we were able to make observations on all these three aspects of the subject; and in what follows I shall endeavour to summarise our results, and to consider, while doing so, the attitude at present taken up by the scientific world with regard to these three lines of investigation.

Most of the ocean plants exist in countless myriads of minute individuals, though they are invisible to the naked eye. Still, small as they are, they are in a way highly organised, and their organisation is in strict accordance with the particular conditions of life. On land a higher plant consists of a community of separate cells, each of which has a special function to perform in the service of the whole. It establishes an under- General biology of the pelagic algæ.

ground system of roots to collect moisture and nourishment from the soil, and its leaves are raised aloft on slender stems to derive benefit from the rays of light and build up organic substance out of carbonic acid and water. Ocean plants have no such *point d'appui*; they find their nourishment dissolved in sea-water and distributed uniformly all around them, and they get most benefit from the sunlight when they are regularly spread throughout the whole bulk of the water in the photic zone. Their diffusion is also their best defence against their enemies, for, while animals have no great difficulty in finding and consuming the larger plants, these creatures, scattered everywhere like dust amidst the immeasurable water-masses, are not so easily available. The majority of the floating plants pass their lives as single cells, though they are frequently far more highly organised than the single cells that go to form a higher plant.

Suspension organs.

As pelagic algæ have generally a greater density than the sea-water in which they live, they would sink out of range of the rays of light, and perish, if it were not for the fact that they are kept from descending either by their own exertions or by suspension organs which act as a parachute. The most noticeable features in their organisation are their different forms of structure, which are directly connected with the floating existence they lead. In what follows I shall describe the most important types, belonging to a limited number of classes, most of which have variously shaped pigment granules or chromatophores, consisting of brown colouring matter instead of green chlorophyl. Comprised in their number are diatoms, peridineæ, and brown flagellates, amongst which last we also include calcareous flagellates or coccolithophoridæ. In addition there are a few pelagic representatives of the green and blue-green algæ, which I will discuss separately.

Diatoms.

A diatom can be distinguished from other algæ by its silicated cell-wall. This is composed of two quite similar halves, or valves as they are called, that are united to one another like the top and bottom of a pill-box (see Fig. 212). Inside the valves the protoplasm lines the wall like a thin sort of bladder, while the nucleus is frequently in the very centre surrounded by a denser mass of protoplasm connected to the bladder by bridges or strings. The rest of the cavity is full of a clear cell-fluid. The pigment granules, which are organs of nourishment, enable the diatom to collect rays of light and build up organic substance out of carbonic acid. They usually lie in regular order along the cell-wall (Fig. 213, *a*); but if the light becomes too strong for them, they are able to huddle more closely together, either in the middle of the cell or

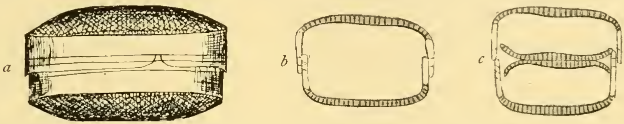


FIG. 212.—CELL-WALL OF A DIATOM (*COSCINODISCUS SUBBULLIENS*), $\frac{300}{1}$.
a, External view; *b*, vertical section; *c*, section in cell-division.

at some point where they can mutually protect each other from the harmful effects of the rays (Fig. 213, *b* and *c*). This has been demonstrated by Schimper. The assimilation of carbonic acid produces a fat oil, which may form into comparatively large drops. Schimper.

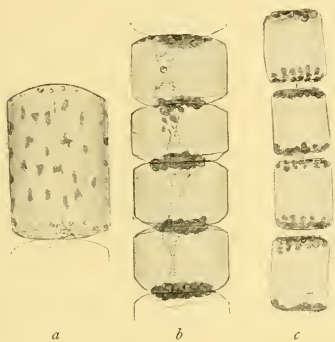


FIG. 213.
a, *b*, *Lauderia annulata*. *a*, Cell with the pigment granules (chromatophores) in normal position, collected early in the morning; *b*, chain from the surface of the sea, 3 P.M., chromatophores congregated at the ends of the cells; *c*, *Detonula schrœderi* in the same condition. All $\frac{440}{1}$.

Cells are produced by division. The nucleus and protoplasm divide into two parts, the valves are pushed a little apart, and two new valves develop within the old ones. Thus each of the daughter-cells gets one of the valves from the mother-cell and a new valve that joins on to it (see Fig. 212, *c*). When once the valves have acquired their shape they seem incapable of expanding, so that the cell generations will gradually become contracted in the plane in which division takes place. It follows that the cavity of the cell will also be diminished, though at the same time the perpendicular axis of the plane of division is frequently slightly prolonged. Algæ can, however, regenerate their original size, by throwing off their old valves, growing into a larger bladder with a thin expansible skin, and forming within it new valves that are two or three times as large as the old ones. This is the so-called auxospore development (see Fig. 214). Cell division.

Auxospore development.

Diatoms occur in quantities over the whole world in both

Distribution of diatoms.

fresh and salt water, and they are found not merely as floating forms, but also along the coasts, some of them attached to the bottom or to other algæ and animals; some are capable of motion, gliding over the mud in enclosed bays or among grains of sand near the seashore. The coast forms, however, are essentially different from the pelagic forms in their structure.

Littoral forms.

Littoral diatoms are apt to have a comparatively thick and extremely silicated cell-wall with the characteristic patterns, ribs, and pores, that have made them such an attractive object of study to amateur scientists. Bilateral symmetry prevails, especially amongst forms that are capable of motion, which are as a rule pointed at the ends like the bows of a boat. Diatoms of

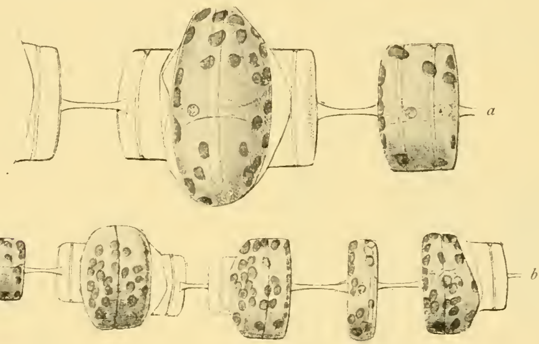


FIG. 214.—AUXOSPORE-FORMATION OF *THALASSIOSIRA GRAVIDA*.

a, Showing in the centre a newly-formed auxospore, the old cell-walls still lying outside ($\frac{600}{1}$); *b*, showing on the left a cell before auxospore-formation, succeeded by an auxospore during its first cell-division, the chain of five cells having originated from an auxospore ($\frac{500}{1}$).

this kind have a highly organised locomotion apparatus, which is differently constructed in the different genera, such as *Navicula* and *Nitzschia*.

Attached forms.

Attached forms show more variation. Symmetry with them depends upon the mode of attachment. *Licmophora* and *Gomphonema* are fastened at one end to a gelatine-like stalk, and their cells are wedge-shaped, narrow at the bottom and widening out towards the top. Others, like *Epithemia*, are convex on the one side and straight on the other, the straight side being the one by which they are attached. And there are others again that consist of more or less highly organised and often ramifying colonies, composed of series of cells, or sheaths of mucilage, within which the cells are able to move past one another.

Pelagic forms usually have thinner cell-walls, and the characteristic ornamentations on their silicated valves are not so prominent, though in their case too a high magnifying power will nearly always render them visible. The families that are endowed with locomotion organs are very scantily represented, and even amongst the few that are thus favoured, several species make use of them for quite a different purpose, employing them as organs to secrete mucilage and thus keep the cells united in chains. Most of the pelagic diatoms belong to families that lack organs of locomotion, though by way of compensation various types have highly developed suspension organs, which increase their superficies and consequently their friction against the surrounding water-masses. It is possible, too, that these algæ are able to reduce excess weight by evolving specifically lighter matter, such as fat, within the cells or air-bladders outside them, but this has not yet been properly investigated.

The suspension organs, however, have been most carefully studied, especially by Schütt, who was one of the members of Hensen's Plankton Expedition in 1889, and the different cell-forms, with their numerous contrivances for maintaining a floating existence, may be grouped under four heads:— Schütt.

Four types of suspension organs.

(1) *The Bladder Type.*—In these the cell is comparatively large, while the cell-wall and protoplasm are merely thin membranes round a big inner cavity which is filled with a cell-fluid of about the same specific gravity as sea-water. Among diatoms the best instances of this type are species of the genus *Coscinodiscus*, whose structure resembles cylindrical boxes, sometimes fairly flat-shaped, and sometimes more elongated and rounded at the top and bottom. In most forms the cell-wall is quite thin, though it is strengthened by means of a fine mesh-work of more or less regular hexagons. One of the biggest, *Coscinodiscus rex* (*Ethmodiscus rex*, *Antelminellia gigas*), is over a millimetre in diameter, and is quite a common form in the warmer parts of the Atlantic (see Fig. 215). A series of species with stouter structure, and more distinct ornamentations on the cell-wall, occur especially in the deeper water-layers, at about the lowermost limit of plant-life (100 to 200 metres), and belong to a characteristic twilight-flora, of whose existence Schimper became aware during the "Valdivia" Expedition.

(2) *The Ribbon Type.*—The surface is enlarged owing to the cell being flattened down into a plane, which is often bent or twisted to a certain extent. Diatoms of this type (see Fig. 216) are scarce. We have, along the coasts especially, a few species with flat cells, which are associated in ribbon-shaped colonies, such as *Fragilaria* and *Climacodium*. The cell-walls of these species are extremely thin, and not of a particularly distinct structure.

(3) *The Hair Type.*—The cells are very much prolonged in one direction, or else they are united in narrow, elongated colonies. Diatoms

Distribution of diatoms.

furnish many varieties of this type. Sometimes the length axis is situated in the division-plane of the cells, as, for instance, in *Thalassiothrix longissima*, one of the characteristic forms in colder seas; at other times division takes place across the elongated cell, as in the genus *Rhizosolenia*, of which there are many species (see Fig. 217). Hair-shaped cells of this kind create a great deal of friction when horizontal, but would sink rapidly when perpendicular, if it were not for the fact that they are either slightly curved, or else their terminal faces are sloping; so that

FIG. 215.—*COSCINODISCUS REX* ($\frac{60}{1}$).

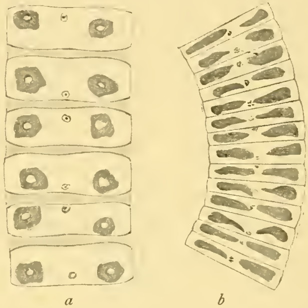


FIG. 216.—PELAGIC DIATOMS OF THE RIBBON-TYPE ($\frac{500}{1}$).
a, Chain of *Navicula vanhöffeni*, the cells connected by a band of mucilage; *b*, part of a chain of *Fragilaria oceanica*.

the resistance of the water soon restores them to an almost horizontal position, and they sink slowly in long spiral sweeps.

(4) *The Branching Type.*—The surface of the cell is enlarged by various kinds of hair-shaped or lamelliform outgrowths. To this type belongs the genus *Chætoceras* with its numerous species (see Fig. 218).

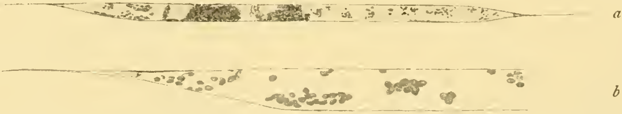


FIG. 217.—PELAGIC DIATOM OF THE HAIR-TYPE, *RHIZOSOLENIA HEBETATA-SEMISPINA*.
a, Entire cell ($\frac{200}{1}$); *b*, end of a cell ($\frac{500}{1}$).

Every cell has four long setiform outgrowths, and the cells are besides nearly always associated in chains, so that these setæ radiate in every direction. When the chain is straight and stiff it is frequently furnished with special terminal setæ, which are stiffer than the others, and act as a sort of steering apparatus.

In addition to the actual outgrowths from the cell many diatoms can secrete long filaments of mucilage from special secretion pores. These filaments act as an effective suspension-apparatus (see Fig. 219). During unfavourable conditions

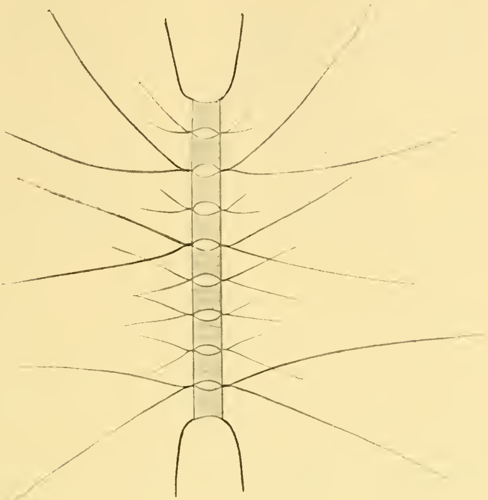


FIG. 218.—CHAIN OF *CHÆTOCERAS DECIPIENS* ($\frac{160}{1}$).

of existence, especially when there are considerable changes in the salinity, sufficient mucilage is secreted to form a protecting

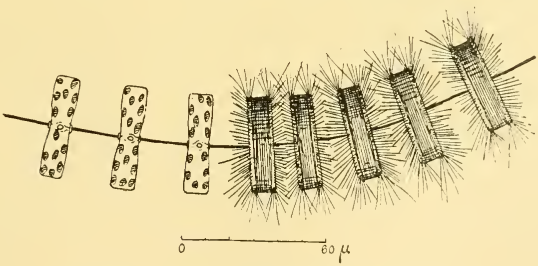


FIG. 219.—CHAIN OF *THALASSIOSIRA GRAVIDA* ($\frac{400}{1}$).
Showing on the right five cells with filaments of mucilage. (Mangin.)

sheath round the cells. This I have myself observed in the case of species of *Thalassiosira* on the Norwegian coasts.

Adjustment of their organisms to the conditions of their floating existence affects the whole structure of these algæ, though it is not always carried out to the same degree in the different genera and species. If we examine into their distribution we shall find that no particular region is distinguished by specially well-equipped species. Genera with the greatest numbers of species have their representatives in both the warmest and the coldest areas of the sea, and no essential difference in the development of their suspension-apparatus is to be found between the species of *Chætoceras* and *Rhizosolenia* which live near the confines of the polar sea, and their relatives in the tropics. The greatest abundance of forms is to be met with in coastal waters, where, too, the majority of the species have their home. I shall return later on to the special biology of these coast-forms.

Many species of diatoms show variations indicating that within certain limits the algæ can adapt their floating power to the demands made on them. Their tendency to sink increases with a rise of temperature, and decreases with an increase of salinity. It is not alone the specific gravity (density) of sea-water that is here the determining factor; no doubt we must bear specific gravity in mind also, but its variations are comparatively small. Ostwald has shown that the internal friction or viscosity of sea-water is the most important consideration, and this diminishes with an increase of temperature. Other things being equal, sea-water at 25° C. offers only half the resistance that it would at freezing-point. Salinity, on the other hand, is of less account. A rise of 1 per cent in the salinity will produce no more than an increase of 2 to 3 per cent in the internal friction, and as salinity in the open sea is subject to what are after all quite inconsiderable variations, it follows that it is really temperature which indirectly affects the development of the suspension-organs. In areas of the sea where there is a big difference in temperature between summer and winter, we find a number of species with distinct summer and winter forms, that have sometimes even been supposed to belong to totally different species. And the same variation occurs also in species with a wide distribution, the warm-water types corresponding to the summer forms, and the cold-water types to the winter ones. The summer forms have usually thinner cell-walls, and a more slender structure; their excess weight appears to be reduced, though at the same time their surface is comparatively larger. As, however, diatoms vary greatly in their dimensions throughout their life-cycle,

Viscosity of sea-water.

Summer and winter forms.

their cells diminishing by being divided and increasing again owing to the formation of auxospores (see Fig. 220), it is

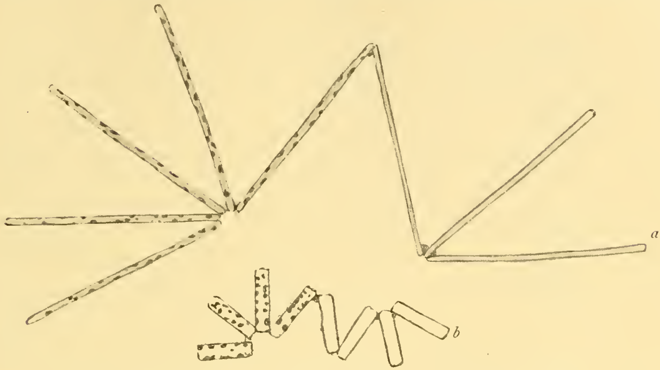


FIG. 220.—COLONIES OF *THALASSIOTHRIX NITZSCHIOIDES* ($\frac{800}{1}$).
a, With long cells shortly after auxospore formation; *b*, with shorter and thicker cells.

difficult to show in the case of many species to what extent variations are due to adaptation and regulation of their floating power, though in the case of some chain-forming species it is

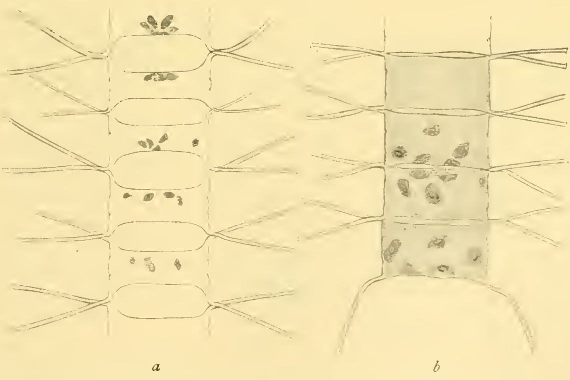


FIG. 221.—PARTS OF TWO CHAINS OF *CHÆTOCERAS DECIPIENS* ($\frac{440}{1}$).
a, From the Atlantic off the coast of Spain, April 1910; *b*, from Christiania-Fjord, March 1911.

evident enough. *Chætoceras decipiens*, one of the commonest species in the northern Atlantic, consists of straight chains of flattened, almost rectangular cells, every one of which is furnished with four long setæ. Each of these setæ is attached at the root to its fellow from the neighbouring cell, the result being the formation of the chain. The terminal faces of the cells are otherwise separate, so that there are openings between them. In the winter and spring *Chætoceras decipiens* is furnished with thick cell-walls and stout setæ, and the interstices between the cells are quite inconsiderable (see Fig. 221, *b*); but in summer the walls are thin and the setæ extremely fine, and the openings in the chain between the cells then become large, round or oval gaps, which are almost as big as the cells themselves (see Fig. 221, *a*). Corresponding variations occur in other species of *Chætoceras*, and in other diatoms, such as *Biddulphia aurita*. Along the arctic coasts, for instance, *Biddulphia* has a rather gross structure, and is almost cylindrical, with short conical projections at the corners, but off the south of Norway it has a comparatively much larger surface, and the corners develop into long, slender outgrowths.

We find a variation of a different nature in the case of

FIG. 222.—CELL OF *RHIZOSOLENIA HEBETATA-SEMISPINA* ($\frac{300}{1}$).
One end of the cell belongs to the typical arctic *hebetata* (on the right), the other to the Atlantic form *semispina*.

Dimorphism.

Rhizosolenia hebetata. It occurs in two perfectly distinct forms, that were formerly regarded as good species. The first, which belongs to arctic waters, is thick-walled and gross, and is the true *R. hebetata*. The second, *R. semispina*, has thinner walls and is proportionately longer, and it is furnished with a long hair-like point at each end. Its distribution extends over practically the whole Atlantic, though it is chiefly to be found in the neighbourhood of the cold currents. These two "species" can originate from one another reciprocally as the result of one cell-division. During the course of transition a cell may be *hebetata* at the one end and *semispina* at the other (see Fig. 222). Dimorphism of this kind is known, moreover, in the case of other species.

Still, in the open sea conditions of existence are comparatively uniform compared with what we find in coastal waters, where the temperature and salinity vary considerably. Most of the diatoms which belong particularly to the coastal waters

Resting-spores.

have a special adaptation, the so-called resting-spores, which must be regarded as a means of protection against such altered conditions. The contents of the cell can shrink into a denser mass in the middle, and become enwrapped in a new thick wall of characteristic shape within the old cell-wall, which is discarded as soon as the resting-spore is completely developed (see Fig. 223). The spores have now acquired an increased specific weight, as compared with their original cell, and sink down into deep water, where they may be found months after they have disappeared from the surface-layers. The majority of them, however, rest on the bottom in shallow coastal waters, until conditions of existence again occur which induce them to make a fresh start.

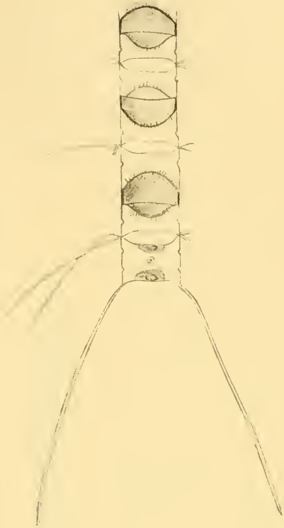


FIG. 223.—CHAIN OF *CHÆTOCERAS CONSTRICTUM*, WITH THREE RESTING-SPORES AND ONE NORMAL CELL (THE END-CELL OF THE CHAIN) ($\frac{440}{1}$).

The germination of the resting-spores has not yet been described, though Hensen states that Lohmann has observed the first stages on several occasions. It will be a great advantage when we can follow their development-history through all its stages, and study the conditions of existence that lead to germination. Resting-spores are unknown in the true oceanic species; but, as already stated, they are found in most of the species belonging to coastal seas. In some cases we were not aware of them till quite a short time ago. It is only recently that they have been discovered in *Leptocylindrus danicus* (see Fig. 224), in which the cylindrical cells are broken across in the process of spore-formation, so that the spores are liberated, and in *Chætoceras pseudocrinitum*, in which the resting-spores originate in auxospores.

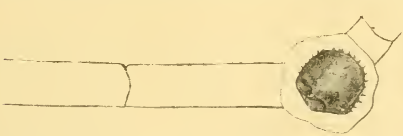


FIG. 224.—*LEPTOCYLINDRUS DANICUS*, WITH RESTING-SPORE ($\frac{1000}{1}$).

So far as we are able to ascertain, the auxospores of pelagic diatoms are always formed without any sexual act. There is, however, another kind of organ, the so-called microspores, Microspores.

Bergon. Karsten.

which, according to Bergon's investigations, would seem to be zoospores, and which Karsten assumes to be sexual cells. Karsten has observed the formation of microspores in an antarctic diatom, *Corethron valdiviæ* (see Fig. 225), and in the same microscopic preparations found amalgamations of small cells resembling microspores. We cannot yet, however, consider this conclusively settled. We do not know the life-history of the numerous small spores after they have emerged from the mother-cell. We can only hope that the centrifuge will enable us to study the most diminutive and sensitive cells immediately after capture, and that we shall thus succeed in solving this problem in the biology of diatoms.

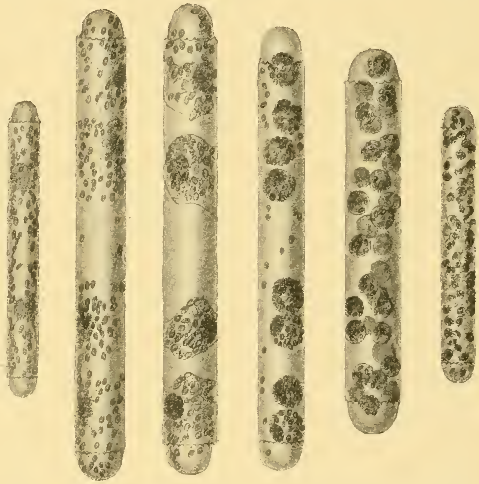


Fig. 225.—Microspore-formation of *Corethron valdiviæ* in different development stages ($\frac{332}{1}$).
Ripe microspores in the cell to the right. (Karsten.)

Peridineæ.

Peridineæ are mobile algæ furnished with two cilia. Several species can produce brilliant phosphorescence. Their cells are highly organised, with a distinct difference between the anterior and posterior ends, and between the dorsal and ventral faces. The cell-wall is built up entirely of organised matter, which dissolves soon after the death of the cell. Peridineæ are therefore not noticeable in the deposits of the ocean-bottom, which is one of the reasons why, until quite recently, they were but slightly and imperfectly known. A number of laminæ, characteristic in shape and position, compose the cell-wall. On the posterior side there is a characteristic furrow, with a pore for one of the cilia, which can be withdrawn spirally into a sheath (see Fig. 226). The ventral furrow is often protected by curtain-membranes. Another furrow encircles the cell, and is known as the ring-furrow. It is guarded by projecting borders on the anterior and posterior sides, called ring-borders. It is in this furrow that the second cilium lies and vibrates.

These principal organs appear in a great variety of shapes. The genus *Ceratium* has the anterior end drawn out into a long *Ceratium.* horn, which is open at the top; its posterior end has also nearly always two horn-like projections, which in most species bend in a forward direction. The species of *Ceratium* are well supplied with brown pigment granules, and they occur in the upper water-layers, where they constitute an essential part of the plant life. The horns must be regarded as suspension-organs, even though the mobility of the cell makes an adaptation of this kind less indispensable. We frequently find them, especially in the species of tropical seas, transformed into very consummate suspension-organs. Sometimes they are decidedly long and hair-shaped, sometimes flattened, and in a few species actually terminate in radiating branches. Kofoid has Kofoid. shown that the species of *Ceratium* can regulate their floating power, and that when, owing to the movement of the water masses, they enter colder or warmer layers of water, they can shed portions of their horns or prolong them at will (see Fig. 227). They have also still another mode of improving their floating power. The cell wall grows in thickness during the whole life of the algæ, and simultaneously ribs and pores are constantly developing; but as soon as the cell gets too heavy, one or even several laminæ peel off from the cell armour, and new extremely thin plates take their place.

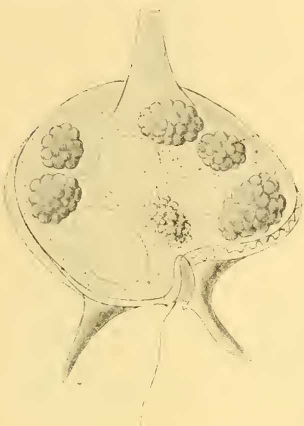


FIG. 226.—*PERIDINIUM DEPRESSUM* ($\frac{375}{1}$). (Schütt.)

The species of *Ceratium* are also formed by division, and with them, too, the daughter-cells each retain half of the membrane of the mother-cell, the other half being new. This does not, however, take place within the cell-wall of the mother-cell, and there is therefore no gradual diminution in the bulk of the individual. Sometimes the cells hang together in chains, and it is then quite evident that the direction and shape of the horns may vary considerably from one generation to another.

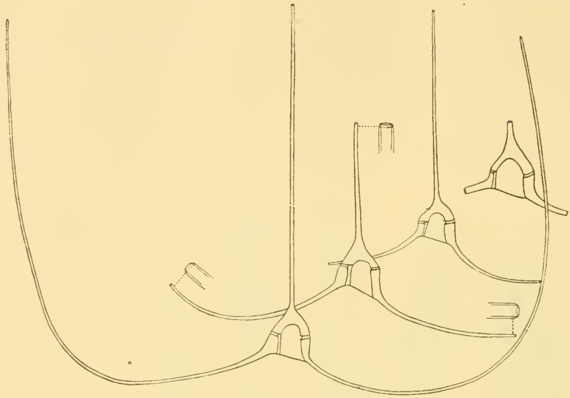


FIG. 227.—*CERATIUM TRICHOCEROS.*
Showing progressive and proportionate reduction of the horns in autotomy ($\frac{165}{1}$). (Kofoid.)

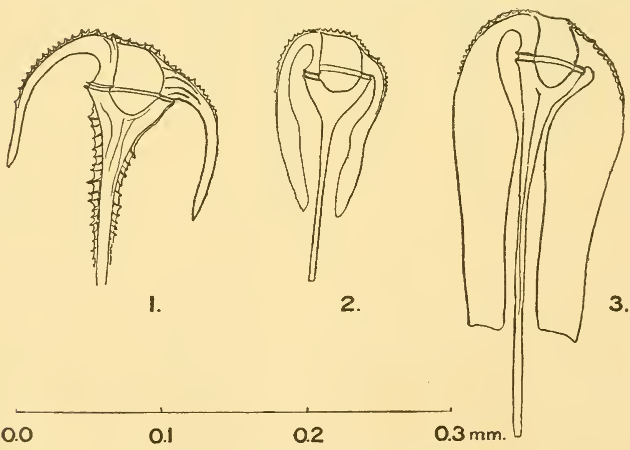


FIG. 228.—*CERATIUM PLATYCORNE.*
1, Forma *compressa*; 2, 3, forma *normalis.*

In other cases, where the cells separate immediately after division, it is more difficult to tell which variations are due to hereditary dissimilarities and which are the result of direct adaptations from one generation to the other. Still, now and then even this, too, is possible. I found during the Atlantic expedition of the "Michael Sars" that the subtropical *Ceratium platycorne*, both of the posterior horns of which are developed ordinarily into flat wing-like suspension-organs, changed gradually into a form with cylindrical horns belonging to the Gulf Stream in the Norwegian Sea, that I had myself previously described under the name of *Ceratium compressum* (see Fig. 228).

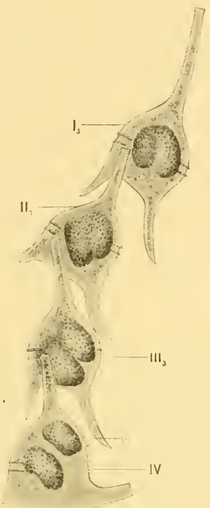


FIG. 229.
CHAIN OF *CERATIUM TRIPOS.*
Only one cell (IV.) shows the character of the type, the others (I.-III.) belonging to the type of *Ceratium californiense* ($\frac{270}{1}$). (Kofoid.)

Lohmann.

Jörgensen.

Discontinuous variations have been found as well as continuous ones in the species of *Ceratium.* Lohmann has shown that the ordinary Baltic form, *C. tripos*, can set up an intermediate generation of a totally different type, much smaller and with short, straight horns, corresponding to the forms described under the name of *C. lineatum.* Kofoid has met with similar variations in American species (see Fig. 229). The signification of these development forms has not yet been discovered. Jörgensen, who has recently published a monograph on the genus, is inclined to regard them as degenerate forms that have been produced under abnormal conditions of existence. It seems to me, however, more probable that these small, extremely mobile, cells are normal formations, which have a definite function to perform in the imperfectly known development-cycle of the species of *Ceratium.* It is still questionable whether peridineæ propagate sexually, even though Zederbauer claims to have discovered sexual propagation in the ordinary fresh-water form (*Ceratium hirundinella*). But, *a priori*, it is quite possible that the above described intermediate generation may be a sex-generation. Just as little as these "mutations" do we understand the significance of the gemmation which Apstein has lately described in *Ceratium tripos*, nor do we know what conditions of existence cause gemmation instead of normal cell-division.

Zederbauer.

Apstein.

Peridinium.

Another important genus with many species, *Peridinium*, differs in various ways from *Ceratium*, though systematically it is not far removed from it. The cells, however, lack the brown pigment-granules (at any rate, this is so in the case of marine species), and the contents are pale yellow or pink. It is improbable that it can assimilate carbonic acid, and it must therefore somehow or other obtain organic matter for its nourishment. Unfortunately nothing is known regarding its mode of nourishment. These forms do not live so close to the surface as the species of *Ceratium*, but all observations made hitherto indicate that they belong exclusively to parts of the sea to which light penetrates, where they exist along with the other algæ. Their cells are much grosser than those of the species of *Ceratium*, and the projections corresponding to the horns of *Ceratium* are short or entirely wanting. The membrane-curtains along the furrows are only slightly developed, and the cell itself is much more globular. The species of *Peridinium*, and some other genera (*Gonyaulax*, *Goniodoma*), have thus at best only imperfect suspension-organs, but the mobility of the cells makes up for this deficiency. The way they are formed, too, is different from what we notice in *Ceratium*. There is no proper cell-division, but the cell changes its contents to one, two, or four naked spores, which are shed out from their original covering (see Fig. 230). Each spore afterwards gradually evolves a new cell-wall for itself, within which it develops as the wall expands, and bands, due to accession of growth, intervene between the laminæ composing the structure. This has been demonstrated by Broch. The genus *Peridinium* includes a large number of species distributed throughout all the seas of the world, but the systematic arrangement of the species is extremely difficult, and has not so far been sufficiently investigated. A large amount of material has, however, been brought home by our expedition, and it is to be hoped that we shall now be able to ascertain the characteristics to which we can ascribe chief systematic importance. A good beginning, at all events, has been made by Kofoid and Broch.

FIG. 230.
GONYAULAX POLYGRAMMA.
The cell-contents form a zoospore, shed out from the bursting cell-wall ($\frac{640}{1}$). (Schütt.)

Broch.

Dinophysidæ.

The family Dinophysidæ possesses the most remarkable suspension-organs of all the peridineæ. In northern waters its representatives are limited to a number of species all resembling one another and all belonging to the same genus, namely, *Dinophysis*. The commonest of these, *D. acuta* (see Fig. 231), has a small tongue-shaped mobile cell without particularly well-defined suspension-organs. Its ring-furrow and protecting borders are situated at the forepart of the cell, and its sides are flattened to such an extent that the ventral furrow is on quite a sharp edge, where it is guarded by two membrane-curtains. The cell is formed by division, which takes place perpendicularly to the ring-furrow. Within the cell are several brown chromatophores, showing that *Dinophysis* is one of the peridineæ that assimilates carbonic acid. *Dinophysis.*

In warmer waters this funda-

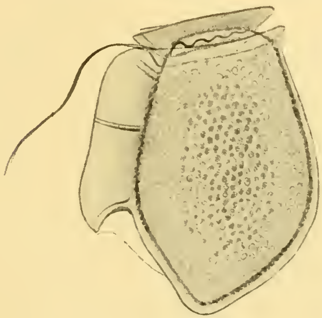


FIG. 231.—*DINOPHYSIS ACUTA.*
From the west coast of Norway ($\frac{600}{1}$).
(Jörgensen.)

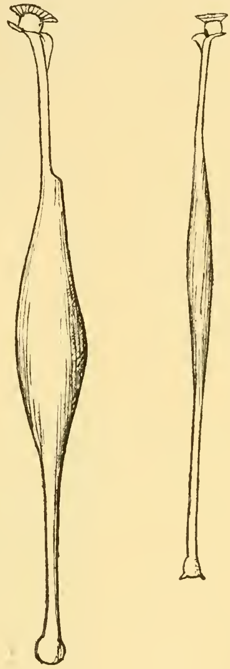


FIG. 232.
a, *Amphisolenia globosa* ;
b, *Amphisolenia tenella*, n.sp. ($\frac{600}{1}$).

mental type shows strange variations. *Amphisolenia* (see Fig. 232) has its whole cell drawn out to a hair, the ring-furrow is situated right in front on a little head, and the ventral furrow is on a narrow neck with slightly developed membrane-curtains like a kind of collar. The cell widens out slightly like a spindle in the middle, and posteriorly ends in a globular knob by way of balance, or in two or three ramifications. *Triposolenia* (see Fig. 233) has a similar anterior structure, but the middle part is *Amphisolenia.* *Triposolenia.*

more expanded, and the two bent legs which issue from it do not lie in quite the same plane, with the result that in sinking the cell describes very long sweeps. Besides these we get other genera, where the suspension-organs are not formed by the cell itself, but by the membrane-curtains. In *Ornithocercus splendidus* the ring-borders are transformed into an unmistakable parachute, stiffened by a network of ribs (see Fig. 234, *a*), and in some species, such as *O. steinii* and *O. quadratus*, the membrane-curtains are ventrally or posteriorly most highly developed (see Fig. 234, *b*). The majority of these more differentiated forms are without chromatophores, but some of them by way of compensation are in almost constant symbiosis with small brown naked cells that are probably immobile stages of brown flagellates. In *Ornithocercus magnificus*, for instance, we find these naked cells in the space between the ring-borders, where they are well protected against harm (see Fig. 235); and in a series of species of the remarkable tropical genus *Histioneis* this home of theirs is expanded posteriorly into a cavity which may be of considerable dimensions as compared with the cell. In *Citharistes* the cavity takes up the whole of what should be the central portion of the cell, and the cell-membranes are merely the outer skin like the shell of a guitar (see Fig. 236).

Ornithocercus.

Histioneis.

Citharistes.

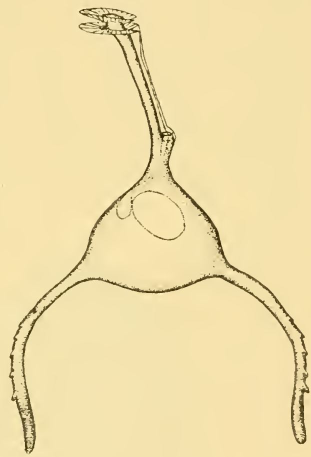
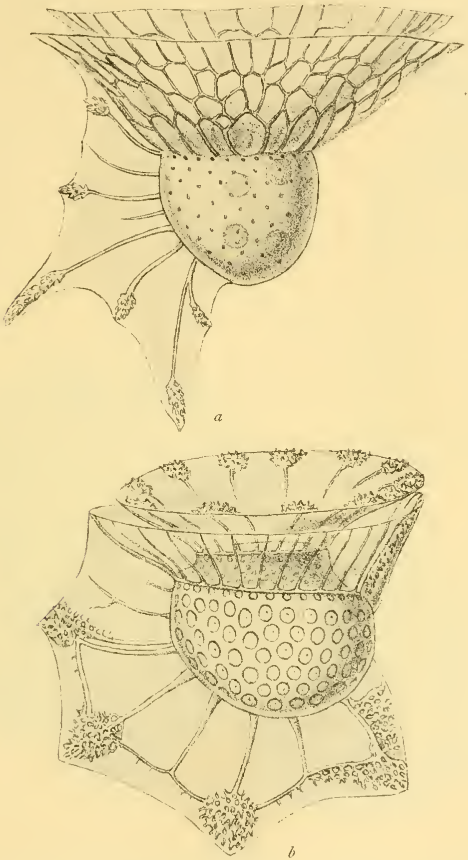


FIG. 233.—*TRIPOSOLENIA BICORNIS* ($\frac{540}{1}$). (Kofoid.)

Pyrocystis.

A remarkable subdivision of the peridineæ is the genus *Pyrocystis*, which Sir John Murray discovered during the "Challenger" Expedition. *Pyrocystis noctiluca* (see Fig. 237) has large globular cells with a thin layer of protoplasm along the cell-wall, a denser mass round the nucleus, and brown pigment granules. Murray stated that the genus was abundant in all tropical and subtropical waters, where the temperature exceeds 68° F., and where the salinity at the surface is not lowered by the presence of coast or river water. The cells have no organs of motion, but belong to the most brilliantly phosphorescent of the algæ; biologically they are of the "bladder-type." Other species are elongated (see Fig. 238), straight, or crescent-shaped. Within their cells they form big zoo-



a

b

FIG. 234.

a, *Ornithocercus splendidus* ($\frac{310}{1}$); *b*, *Ornithocercus steinii* ($\frac{500}{1}$). (G. Murray and Whitting.)

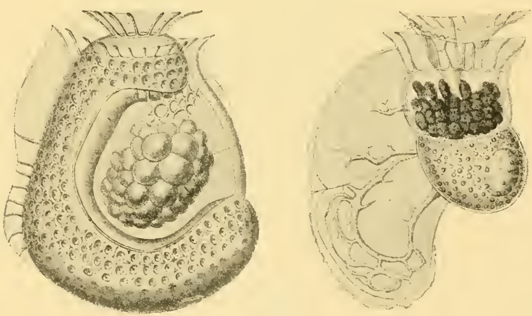
spores, built up exactly like the peridineæ type with a ring-furrow and two cilia, for which reason the species of *Pyrocystis* are included among the peridineæ, though their fully-developed cells are really of a quite different type.

Besides these highly-organised forms, which I have given as instances, the peridineæ include many with a far more simple structure. There are, especially in the samples collected by means of the centrifuge, numerous series of small forms, both coloured and colourless, and often with very poorly developed cell-walls. These, too, have already got or will shortly be given names, although many of them are probably nothing more than development-stages of the larger forms. We can recognise the whole series by their characteristic ring-furrow, so that we are seldom left in doubt as to the classification of even the simplest types. Still a good deal remains to be done before we can claim a thorough acquaintance with their development-history and systematic arrangement.

FIG. 235.
ORNITHOCERCUS MAGNIFICUS.
With brown flagellate cells in the space between the ring-borders ($\frac{480}{1}$). (Schütt.)

Coccolithophoridæ.

The third series of pelagic algæ consists of brown flagellates, the chief place amongst which is occupied by calcareous flagellates or coccolithophoridæ (see Fig. 239). Their cells are



a *b*

FIG. 236.
a, *Citharistes apsteini* ($\frac{788}{1}$); *b*, *Histioneis gubernans* ($\frac{675}{1}$), both with cells of brown flagellates in special chambers. (Schütt.)

generally nearly globular, with one or two cilia and one or two brown chromatophores, and they are protected by remarkable shields of lime which unite into a complete defensive covering, though sometimes with a big opening in front. The cell does not always occupy the whole internal space, but lies sometimes, as it were, at the bottom of a hollow hemisphere or up at the mouth-opening in a conical sac. The shields of lime can be dissolved by the weakest acids, and the cell then remains as an insignificant mass with undefined boundaries. Still, these shields are very characteristic, and have been found in such enormous quantities in the deposits on the ocean-bottom that they aroused the attention of scientists long before the algæ themselves were known. The commonest forms (*Coccolithophora*, *Pontosphæra*) have an almost globular lime-covering, and are therefore without special suspension-organs, though their surface is big in proportion to their bulk, if we consider their extraordinarily minute dimensions (5 to 20 μ

FIG. 237.—*PYROCYSTIS NOCTILUCA*. (From Chun.)

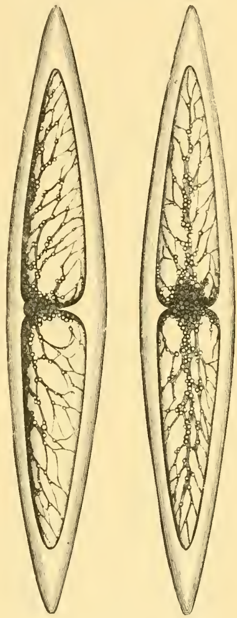


FIG. 238.
PYROCYSTIS FUSIFORMIS ($\frac{100}{1}$).
(From "Challenger" Narrative.)

in diameter). But in forms like *Rhabdosphæra* the calcareous shields have each a more or less large spike in the middle. In *Discosphæra* we find trumpet-shaped spines, in *Scyphosphæra* barrel-shaped outgrowths, and during the "Michael Sars" Expedition I succeeded in discovering even stranger forms. *Ophiaster* has a tuft of slightly spiral flexible calcareous filaments. *Michaelsarsia* carries in the front of its cell a sort of parachute or pappus of hollow jointed calcareous tubes arranged in a wreath. *Calciosolenia murrayi* resembles, to some extent, the shape and structure of *Rhizosolenia*, as the shields of lime are not rounded like those of most other species, but rhomboid and spirally bent, so that between them they form a cylindrical tube, pointed at either end, and furnished at the extremities with one or two fine calcareous setæ.

Notwithstanding their small dimensions these microscopic calcareous algæ occupy a very important place in the economy of the sea, and their shields of lime, which may be met with in geological deposits dating from as far back as the Cambrian period, show that they have retained their shape practically unaltered through immeasurable ages. They are almost entirely oceanic, and mostly belong to the warmer seas. In coastal waters, where the salinity is lower, they are scarcer, but the commonest species, the little *Pontosphæra huxleyi*, has been found even in the Baltic, and there were such immense quantities of it in the inner parts of the Christiania fjord during the hot summer of 1911 (5 to 6 million cells per litre) that the calcareous cells with their strong refraction gave the sea quite a milky appearance.

FIG. 239.—DIFFERENT TYPES OF COCCOLITHOPHORIDÆ. ($\frac{1000}{1}$).

1, *Michaelsarsia elegans*; 2, *Ophiaster formosus*; 3, *Rhabdosphæra claviger*; 4, *Syracosphæra prolongata*; 5, *Calciosolenia murrayi*; 6, 7, *Coccolithophora leptopora*; 8, *Pontosphæra huxleyi*.

Naked flagellates.

The naked flagellates in the sea are still only imperfectly known, though, no doubt, the part they play is quite a considerable one. In coastal waters they occur sometimes in such abundance that we have actually been able, even with our present defective methods, to discover and describe a number of species. In the open sea we are best acquainted with the passive and usually almost globular development-stages that live in symbiosis with various animals, and, in particular, with radiolaria. Of these radiolaria, which would seem from Brandt's investigations to derive special benefit from the assimilation-products of algæ, we occasionally get the colony-forming species and Acanthometridæ in such myriads among the surface-layers, that they contribute a very large proportion of the organic substance produced. I have previously stated that the brown algæ also regularly associate with a whole series of Dinophysidæ. Another family of brown flagellates includes the species of *Phæocystis*, which form large colonies visible to the naked eye, and enveloped in a loose slime (see Fig. 240). In cold waters these have actually been known to occur in sufficient numbers to stop up the meshes of silk nets, and render them ineffective in working.[1] Brandt.

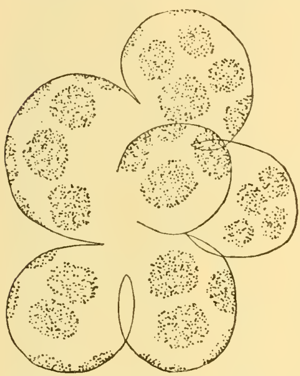


FIG. 240.—*PHÆOCYSTIS POUCHETI.* (Lagerheim.)

It is the brown algæ that, properly speaking, characterise the plant-world of the sea. Still there are two other important series, the cyanophyceæ and the chlorophyceæ, which preponderate in fresh water, and are, no doubt, represented in salt water also, though by only a few species.

The Cyanophyceæ are chiefly to be met with in warmer seas, if we except the brackish water forms that may be found along the coasts of North Europe in the height of the summer. The genus *Trichodesmium* appears as clusters of threads, composed of brownish-yellow or red cells, which are either parallel to one another, or twisted together, or matted and tangled, and radiating in all directions. Wille, who described these forms collected by the German Plankton Expedition in 1889, showed that all the types may belong to the same species, *Trichodesmium thiebaulti*, under different development-forms. The clusters may be seen sometimes when they collect near the surface in calm weather, and resemble yellowish-brown snowflakes. Like the different kinds of fresh-water forms, they can raise themselves in the water by means of vacuoles that, according to Klebahn, contain air. When abundant they sometimes Cyanophyceæ. *Trichodesmium.* Wille. Klebahn

[1] See Summary of Results Chall. Exp., p. 499, 1895.

cover the surface in one unbroken layer, a phenomenon which Œrsted observed in 1849, and which led him even then to look upon microscopic plants as the basis of production in the sea. Besides the species of *Trichodesmium* we have another genus, *Katagnymene*, with spiral series of cells in sheaths of slime. Mention must also be made of the remarkable little alga, *Richelia intracellularis*, described by Johs. Schmidt, which lives in cells belonging to various species of *Rhizosolenia* (see Fig. 241). These diatoms appear to have no difficulty in accommodating their guest, which apparently reproduces itself within the cell, and is thus transferred to new generations of the hospitable plant. The riddle is, how did it originally manage to get in? Most likely this happened at a stage when the *Rhizosolenia* had not yet developed the silicated cell-wall of the hermetically sealed chamber with which we are acquainted.

Œrsted.

Katagnymene.

Richelia.

Schmidt.

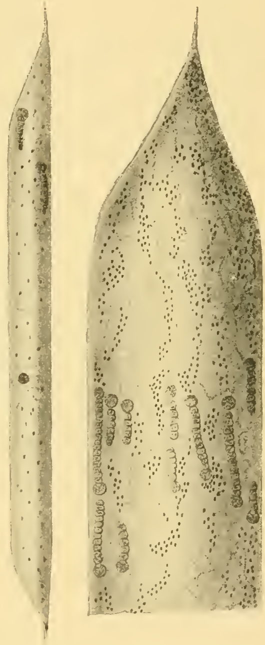


FIG. 241.—CHAINS OF *RICHELIA INTRACELLULARIS* WITHIN THE CELLS OF *RHIZOSOLENIA STYLIFORMIS*. (Karsten.)

The green colour which predominates in plants on land is practically only to be found at sea in the globular *Halosphæra viridis* (see Fig. 241). This has been described by Schmitz from Naples, where the people call it "punti verdi," that is to say, green spots. It is or may be lighter than sea-water, so that it floats quite close to the surface. On the other hand, Hensen's expedition found it at profound depths, even at 1000 metres, away down near the limit of the penetration of sunlight, but if this denotes anything in its life-history, it must be at any rate in a state of resting. *Halosphæra* is reproduced by zoospores, though we do not know how they proceed to form the small globular cells that little by little grow up to the normal size. The cell-wall is so firm and thick that its outer part is burst at last in the course of growth and discarded, and the inner elastic parts are thus enabled to expand. Cleve has also observed thick-walled

Halosphæra.

Schmitz.

Cleve.

resting-cells. *Halosphæra* occurs over the whole Atlantic Ocean, and follows the Gulf Stream to its farthest ramifications in the north near the coasts of Norway and Spitzbergen. In the North Sea there are quantities, especially in the winter, and they form their zoospores in May, and thereby commence their new generation.

Just as *Halosphæra* differs from all the rest of the pelagic algæ in having a pure green colour, so, too, it has its own special mode of reproduction. The other forms, whose development-history we know, are reproduced by division, and this goes on incessantly, the rate of increase depending upon different conditions of existence. *Halosphæra* does not undergo division, but continues to grow for a comparatively lengthy period, and then finally transforms all its contents, as has just been stated, into a great number of zoospores.

FIG. 242.—*HALOSPHÆRA VIRIDIS*, THROWING OFF ITS OLD CELL-WALL ($\frac{70}{1}$).

In addition to *Halosphæra viridis* there are one or two similar species that have been described, but they do not call for any particular discussion.

Floating seaweeds.

In the foregoing I have sketched the most important types of pelagic algæ and their biology, but the picture would not be complete if I omitted to describe the drifting species of seaweed. These do not really belong to the open sea. They grow along the coasts in the littoral zone, and their gas-filled bladders assist them in maintaining their position whatever be the state of the tide. The violence of the waves finally tears them loose, and then these same gas-bladders keep them for a long time floating on the surface. These patches of seaweed are to be met with in every coastal sea, the chief kinds along the coasts of North Europe being *Fucus vesiculosus* and *Ascophyllum nodosum*, and in the Mediterranean species of *Cystosira*. They may also drift right out into oceanic waters, and in the Sargasso Sea we have an immense eddy where the patches of weed often collect in enormous quantities. The prevailing weed is *Sargassum bacciferum*, but one frequently gets patches of *Ascophyllum nodosum* as well, the whole being derived from the coasts of Central America. The Sargasso weed is easily recognisable, owing to its berry-like bladders on special small side branches (see Fig. 243).

One cannot help being struck by the fact that the drifting Sargasso weeds are destitute of the ordinary organs of reproduction. This seems to be invariably the case with attached algæ that have been torn loose from their support. They continue to grow vegetatively, but are deprived of all power of forming new reproduction organs, until they can attach themselves afresh. The same holds good, too, with those strange broken-off masses of algæ that one finds drifting about along the bottom in bays, the constant movement of the water-masses preventing them from attaching themselves to the soft mud or sand.

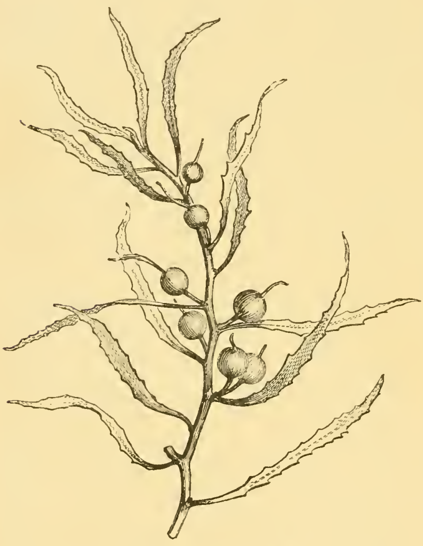


FIG. 243.—BRANCH OF *SARGASSUM BACCIFERUM*. (From Kerner.)

The Sargasso weed continues to grow as it drifts, but the gas-bladders are not formed in the same proportion as on the ordinary branches, the result being that one finds newly detached patches close up to the surface, whereas the older patches with a greater specific weight have sunk lower down. These last have, moreover, thinner branches and a lighter olive-brown colour. Finally, the power of floating ceases altogether, and the patches sink into deep water and perish. Their disappearance is, however, quite imperceptible, since fresh patches of weed are constantly arriving from the coast.

It is quite usual to find smaller algæ fastened to the Sargasso weed, and there is, besides, a characteristic animal-life amidst its branches, but none of these organisms properly belong to the ocean, notwithstanding their being found there so invariably.

This is true also of the attached algæ, which develop upon driftwood, vessels, and other large objects. They show that germs of littoral organisms abound in the open sea, and are far more numerous than our random samples would seem to indicate. In May 1904, when cruising in the Norwegian Sea, in lat. 67° N., where the bottlenose whales are annually shot, we came across some wadding from a whaler's gun drifting in the sea, the lower side of which was thickly overgrown with attached forms of littoral diatoms.

Castracane, after examining the first big collection of pelagic diatoms from all the seas of the world made by the "Challenger" Expedition, came to the conclusion that there was no essential difference between the flora of the different areas. In this, no doubt, he was right to a certain extent, since many species are very widely distributed; still a closer study has shown us that there are definite marine areas and conditions of existence in which they develop in vast numbers, whereas in other localities they occur perhaps in such small quantities that only their skeletons in the bottom-samples furnish evidence that they have actually been present. Besides, we often find that species with a wide distribution have different forms in the different areas, though we have not yet the means of deciding whether these forms diverge from the main type by virtue of hereditary characteristics, or whether they merge into one another through constant modifications. But in any case these forms are characteristic of the flora of a given locality, and any one who examines plankton-samples will become aware that it is nearly always possible to determine the area from which they have come. During the German Plankton Expedition under Hensen in 1889, Schütt convinced himself that the different currents had their characteristic flora, and he was at a loss to understand how it is that local boundaries of distribution can continue, seeing that the currents are ever carrying off the microscopic plant-life from one part of the ocean to another, and it might consequently be expected that all differences would be obliterated.

Geographical distribution of the pelagic algæ.

Schütt.

Schütt has also given a good description of the character of the plant-life in different parts of the Atlantic, but the honour of being the first to systematically investigate the distribution of all the different species, and the influence exerted upon them by ocean currents, must be assigned to the Swedish biologist Cleve. A chemist by profession, he had for many years made a

Cleve.

special study of diatoms before he commenced co-operating about 1890 with the well-known hydrographers, Otto Pettersson and Gustaf Ekman. They commenced their labours in the Skagerrack, that remarkable little sea where so many different water-masses meet and pass each other; and it very soon became clear that different currents might each possess synchronously its own particular flora, and therefore there was the possibility of ascertaining where the water-masses came from, by determining their flora.[1] All that was requisite was to know the distribution of the different species in contiguous parts of the sea. The investigations were accordingly extended, and samples were collected by ordinary steamers in the North Sea, the Norwegian Sea, and the Northern Atlantic, in addition to the collections that were gradually formed chiefly through the efforts of Swedish, Norwegian, and Scottish scientific expeditions. Cleve also studied the annual changes in the plankton, and had weekly collections made at selected stations on the Swedish coast. The scope of his investigations was further enlarged, for his unique knowledge of forms enabled him to determine, not merely all pelagic plants, but also little by little, a whole series of animal-families which proved no less useful than the algæ as "guiding forms" to determine the character and origin of the plankton.

O. Pettersson and G. Ekman.

Plankton-types.

Cleve believed that he could distinguish a series of plankton-types characteristic of defined marine areas. Particular species were therefore assigned by him to one or other of these main types. But whereas outside the Skagerrack each of the plankton-types had its own characteristic distribution, within this sea the same types were found to predominate, each in its own characteristic season. From February to April there were the same species that we have learnt to connect with the coasts of Greenland and Spitzbergen in the Polar Sea, and from May to June there was a plankton resembling that of the Western Baltic. During the course of summer and autumn there were, first of all, species like those belonging to the southern part of the North Sea, and afterwards Atlantic and more northerly forms. Cleve was led to conclude that these changes in the Skagerrack were due to the fact that it is supplied during the course of the year

[1] "While passing through the Japan Stream the tow-net observations indicated water from two different sources. When in the colder streams there were very many more small diatoms, *Noctilucæ*, and Hydromedusæ than in the warmer streams, where the same pelagic animals that were obtained all the way from the Admiralty Islands prevailed. Many similar instances occurred during the cruise, where the approach to land or the presence of shore water was indicated by the contents of the tow-nets" (Narrative of the Cruise, Chall. Exp., vol. i. p. 750, 1885; see also Summary of Results Chall. Exp., pp. 893 and 895, 1895).

in regular rotation with water-masses from the marine areas to which these plankton-types belong.

Subsequent investigations have shown that Cleve's view, which he endeavoured to apply even more widely, was preconceived. His eagerness to discover how far the distribution of particular species depended on sea currents, made him apt to forget that algæ are living organisms which are incessantly in process of formation. Accordingly, when the conditions of existence in the flowing water-masses gradually alter, it is the new conditions of existence that decide the character of the flora, since the species best qualified to endure them will very soon get the upper hand over the others. When, therefore, in a sea like the Skagerrack we find northern and southern forms alternating during the course of the year, we are not compelled to assume that the flora is being periodically recruited from different areas. The periodic alterations in the conditions of existence, and particularly in temperature and sunlight, which in our latitudes follow the course of the seasons, sufficiently explain why at one time northerly species predominate and thrive in low temperatures, and why southern forms succeed them and benefit by the warmth which they find necessary for their proper development. Of course it is absolutely essential that germs should be present ready to develop whenever the conditions of existence become favourable. A certain proportion of these, no doubt, may be introduced by currents from elsewhere, but there is nothing to prevent them from remaining in a particular area, even though the water-masses are in constant motion. Recent hydrographical researches have shown us that eddies are far more common than was at one time believed. Even in areas where huge masses of water are constantly streaming in one direction, which one might naturally suppose would carry away with them all germs belonging to a local flora, these eddies act as a retaining factor, preventing any complete replacement till germs sufficient to maintain the local flora have been transferred to the supplanting water-masses. In coastal seas, moreover, many of the species are able to evolve resting bottom-stages, which lie waiting to reproduce the local flora, as soon as the conditions of existence are congenial.

Still Cleve's investigations have been of great value, and his plankton-types provide us with a biological division of species which is yet in the main quite serviceable. All that we have to say by way of qualification is that Cleve looked upon his types as representing communities of species limited to definite marine areas, whereas in reality the areas of distribution of the different species encroach so upon each other, that a division of this kind is hardly practicable. This is true, not merely of the altering flora of ocean-currents, but also of the attached flora along the coasts and on land. Unless the areas are exceedingly remote from one another, the forms common to the areas usually exceed those peculiar to each area. Cleve's types, on the contrary, have no species in common, and therefore do not record the species in any definite area, but merely group them in accordance with their conditions of existence. If we adopt his principles we can certainly obtain a biological division of the species that is satisfactory in the main; but when we come to details it will, in some cases, be difficult to decide whether a species is to be assigned to this or to that type.

Biogeographically, the pelagic algæ may be divided, firstly according to the latitudes in which they are distributed, which is generally tantamount to saying according to their need of warmth and light, and secondly according to their occurrence along the coasts or in the open sea. This latter classification gives us the most distinct boundaries, and we will therefore consider it first. There is a whole series of species which unmistakably belong to coastal waters, and occur there in myriads at definite seasons of the year. Out in the ocean we do not find them, except when salinities or other physical properties indicate that they must have drifted from the coast. These have been termed neritic on the suggestion of Haeckel. Opposed to them are the oceanic species, which belong to the ocean and float over profound depths, from which occasionally they are swept by the currents into coastal seas and there usually perish.

Haeckel.

Neritic species.

It is possible to imagine various reasons why the neritic species keep in the vicinity of the coasts. Some may derive benefit from the low or fluctuating salinities, which enable them to outstrip the more easily affected forms. Others, perhaps, require the abundant supply of nourishment from the land in order to grow and multiply as fast as such organisms should do. There may be other species, again, whose development-history makes it necessary for them to remain on the bottom at one stage of their existence, like the hydroid medusæ and all pelagic young-stages of littoral animals. Most of the neritic algæ have a bottom-stage, in so far as they form resting-spores that sink to the bottom in the shallow coastal seas, where they rest until conditions of development become favourable again. This has been observed by many naturalists since Schütt first noticed in the Western Baltic that a species which begins to form resting-spores disappears shortly afterwards from the surface-layers. He showed, too, that the resting-spores sink down to the bottom, and, although their germination has not been carefully studied, we may be sure, all the same, that it does take place; further, when we subsequently find the same species once more in abundance, we have every reason for surmising that the resting-spores on the bottom were the principal source from which these forms have been derived.

Resting-spores.

Ability to form resting-spores must be of the utmost importance for the existence of the species in coastal waters. The chief difference between coastal seas and the ocean, so far as hydrographical conditions are concerned, lies in the extreme and rapid changes in such fundamental conditions of existence as salinity and temperature in coastal waters. Resting-spores, therefore, must be the means by which many species continue in coastal seas, notwithstanding the fact that there conditions of existence are only favourable for a limited portion of the year. The arctic diatoms, for instance, which are sometimes to be found in the plankton of the Skagerrack, are very easily affected by a rise in temperature, but their development takes place during the winter months from February to April, when the temperature is at its minimum. In the summer they are not to be seen, but their resting-spores are then most probably on the bottom. In the same way a whole series of warmth-loving species pass through the winter as resting-spores, and are to be found along our shores only in the warmest months of summer and autumn.

Neritic diatoms in the open sea.

The neritic species may often be met with a long way out at sea, still continuing to increase, though they are seldom in any great quantity. One of the few instances that I know of, where we regularly find an immense production of neritic diatoms in the open sea, is in the Gulf Stream north of Shetland and the Faroe Islands during May. I made this discovery as long ago as 1895, and it has often been confirmed since then during the international investigations. When the snows begin to melt in the spring, the surface-layers of water are carried far away out from the land, and the neritic algæ are taken with them. I shall presently show that it just happens to be in the spring that conditions of nourishment favourable to an abundant plant-life exist in the Northern Atlantic, and the somewhat exacting neritic species benefit accordingly. This explanation, at any rate, seems to me the most reasonable one.

Another well-known instance is in the Polar Seas during the summer. Close to the melting polar ice, where it meets the warmer water-masses, a rich flora of neritic diatoms sometimes develops, while littoral species form a brown layer over the floes and broken lumps floating between them.

Blessing.

Blessing, who took part in Nansen's expedition during 1893-1896, has given a good description of this latter phenomenon. We must look upon the Polar Seas as coastal waters in the biological sense. They have the extreme variations of temperature and salinity, and probably also the abundant supply of nourishment, that we would expect to find in a coastal sea. The resting-spores are enclosed in the ice, as I was able to show after examining the material collected by Nansen.

In the warmer parts of the Atlantic there are neritic diatoms nearly everywhere, but never in any great quantity, except where rivers enter the sea in the tropical regions. As a rule, too, they are smaller and weaker in structure than those we meet with in coastal waters under similar conditions of temperature. The cell-walls are very often only slightly silicated, and the form itself is so indistinct that it is difficult to distinguish species, which in their properly developed condition have unmistakable characters. It is not easy to tell whether this degeneration is merely a sign of insufficient nourishment, or whether other causes are also responsible. Certainly in one case want of nourishment is not entirely to blame. Out in the water-masses of the Atlantic to the south of Iceland we get a community of neritic diatoms that occur especially in the spring and autumn. Most of them are species of *Chætoceras*. The prevailing forms have been long ago determined, and are undoubtedly *C. schüttii* and *C. laciniosum*. Still they are so dwarfed in structure, and so much the reverse of typical, that one might very well say that they were separate species (see Fig. 244). During this last expedition of ours we succeeded in finding this diatom-flora again, though in smaller quantities, in the Gulf Stream off the east coast of North America, so that it is practically certain that the neritic diatoms of the Atlantic south of Iceland are derived from the American coastal sea. As they are borne passively northwards towards the shores of Iceland, they commence to develop at a great rate, with the result that the plankton in those parts frequently yields abundant though monotonously uniform samples of these degenerate forms. The altered conditions of existence, which obviously must have supervened, have thus resulted in an extensive production of algæ, though without investing them with their normal robust appearance. The strings of cells are of much smaller diameter than usual, so that the formation of auxospores cannot have taken place at the stage that is usual elsewhere. Wesenberg-Lund has told us that pelagic Wesenberg-Lund.

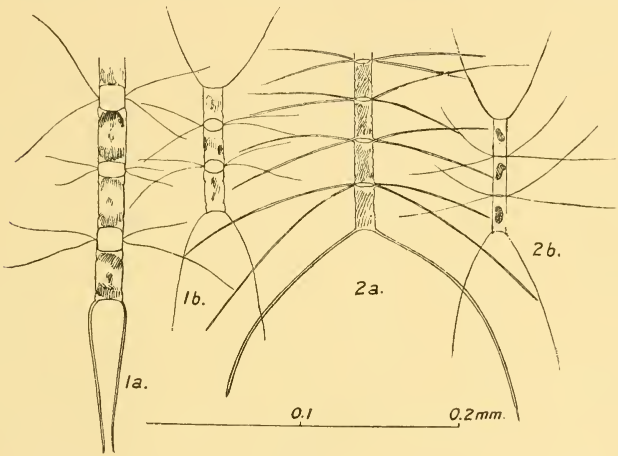


FIG. 244.
1*a*, *Chætoceras laciniosum* : 1*b*, forma *pelagica* ; 2*a*, *C. schüttii* : 2*b*, forma *oceanica*.

fresh-water diatoms, such as *Asterionella gracillima* and *Fragilaria crotonensis*, keep on reducing their dimensions in the Danish lakes for months, sometimes even for over a year, and then suddenly return to their maximum measurements, and that this is undoubtedly due to the formation of auxospores. All are not, however, affected alike by such a change, and the species occur thereafter in two different sizes, making it necessary to express the measurements of their cell-dimensions by means of divergent curves. This goes on uninterruptedly, moreover, and the smallest forms diminish and seem to degenerate more and more, until in Wesenberg-Lund's opinion they lose all power of regaining their normal dimensions and of reproducing their kind. The degenerate forms of neritic diatoms met with in the open sea appear to me to lack the stimulus which in some unknown manner leads to the formation of auxospores; consequently their ultimate extinction is only a matter of time, even though they may continue reproduction through a whole succession of generations. This is, of course, merely an unsupported surmise, for the few random investigations we have hitherto made do not afford sufficient material to settle questions of this nature at all definitely; but my idea is that the hypothetical views of an author are of more value than the enumeration of solitary facts that have no apparent connection.

Resting-spores in the open sea.

When the neritic diatoms evolve resting-spores out in the open sea, which occurrence we have been able to observe on more than one occasion, it might be supposed that the spores would be destroyed after sinking down to profound depths. This is not, however, necessarily always the case, since they appear to sink slowly, and remain within the region of light for weeks if not for months. The spores after leaving their cells are so minute that they are rarely caught in silk nets, so that little has been done as yet to throw light upon this question. But now that we have adopted the centrifuge-method it is possible to collect them, and we discovered numbers of resting-spores of species of *Chætoceras* in our centrifuge-samples from the Atlantic. In a litre of sea-water from Station 87 (lat. 46° 48′ N., long. 27° 46′ W.), from a depth of 100 metres, I secured altogether 1160 resting-spores belonging to three different species of *Chætoceras*, though the forms themselves were not present at that time in a vegetative state either in the surface-layers or deeper down. Most probably what we got were representatives from the last remnants of the diatom-masses that throng the surface-layers there during the spring.

Distribution.

Neritic species include a very large number of diatoms—a class by far the most characteristic in coastal seas. In the majority of these neritic diatoms we have now been able to prove the existence of resting-spores. The peridineæ, on the other hand, are mainly oceanic, especially the species of *Ceratium*. One of the best-known neritic peridineæ is the comparatively low species *Prorocentrum micans*; but there are probably, too, whole series of small forms, as yet imperfectly known, which prefer the neighbourhood of the coasts. The coccolithophoridæ, again, are undoubtedly oceanic, whereas most of the naked flagellates are most likely domiciled in shallower waters. *Halosphæra* is oceanic, and so also are the species of *Trichodesmium*; but there are several blue-green species that are brackish-water forms, and they must of course be accounted neritic (*Anabæna baltica*, *Nodularia spumigena*, *Aphanizomenon flos-aquæ*).

Several of the neritic algæ practically only occur locally. *Detonula cystifera*, for instance, appears in the Limfjord in Denmark and along the south coast of Norway, while *Lithodesmium undulatum*, *Coscinodiscus granii*, *Navicula membranacea*, and *Streptotheca thamensis* belong to the English Channel and to the southern portion of the North Sea. I could mention additional examples, but the greater number of them are far more widely distributed. It has been found possible to allocate all the species along the coasts of the Northern Atlantic to three comprehensive main groups, namely, the arctic, temperate, and tropical. This is perhaps rather an arbitrary arrangement, as these groups encroach to a very great extent upon one another; so that we get northern forms a long way south in the winter, and in the autumn the southern forms extend northwards. Further researches, too, might result in a stricter classification, while it is known that there are species which, biologically speaking, unite the groups, and might with equal reason be assigned to the one or to the other.

Arctic neritic species.

(1) *Arctic neritic species* are mainly those which Cleve termed Sira-plankton, and consist principally of diatoms. The characteristic forms are the species of *Thalassiosira* from which this name was derived. They are composed of long strings of short cylindrical cells united by a central thread of slime. *Thalassiosira hyalina* has its southernmost limit off the north of Norway, while *T. gravida* and *T. nordenskioldii* occur in winter as far south as Central Europe. A series of species belonging to the genera *Fragilaria*, *Achnantes*, *Navicula* and *Amphiprora* are also distinctly arctic forms, and are characterised by having their cells bound together like ribbons. These include *Fragilaria oceanica*, *F. islandica* and *F. cylindrus*, *Achnantes tæniata*, *Navicula septentrionalis*, *N. vanhöffenii* and *N. granii*, and *Amphiprora hyperborea*. The usually predominant genus *Chætoceras* is only represented by two purely arctic species, namely, *Chætoceras furcellatum* and *C. mitra*. We must likewise add the well-known *Biddulphia aurita*. Besides these diatoms, there are the peridinean *Gonyaulax triacantha*, and the brown flagellate *Phæocystis poucheti*, with its naked cells in large slimy round or lobate colonies.

Temperate neritic species.

(2) *Temperate neritic species* are even more numerous. The warmth-loving species fall under Cleve's designation of Didymus-plankton, with *Chætoceras didymum* as the most characteristic form. It is, however, a better arrangement, perhaps, to associate with them a series of other species with a slightly more northerly character, that cannot be really

called arctic. Here, too, diatoms predominate, and *Chætoceras* takes first place. The commonest forms include :—

(*a*) Northerly : *Chætoceras teres*, *C. constrictum*, *C. diadema*, *C. debile*, *C. crinitum*, *C. pseudocrinitum*, *C. scolopendra*, *C. sociale*, *C. simile*, *Rhizosolenia setigera*, *Thalassiosira decipiens*, *Coscinosira polychorda*, *Leptocylindrus danicus*.

(*b*) Southerly : *Chætoceras weissflogii*, *C. contortum*, *C. didymum*, *C. laciniosum*, *C. schüttii*, *C. curvisetum*, *C. cinctum*, *C. anastomosans*, *C. radians*, *Lauderia annulata*, *Cerataulina bergonii*, *Biddulphia mobiliensis* and *B. regia*, *Eucampia zodiacus*, *Ditylum brightwellii*, *Guinardia flaccida*, *Asterionella japonica*, the peridinean *Prorocentrum micans*, and the brown flagellate *Phæocystis globosa*.

Tropical neritic species.

(3) *Tropical neritic species* have had far less study devoted to them ; still we may denote by this term a whole series of species that have their northernmost limit on the coasts of the Mediterranean. Of these we may mention :—

Chætoceras furca, *C. diversum*, *C. femur*, *Hemiaulus hauckii* and *H. heibergii*, *Detonula schröderi*, *Asterionella notata*, *Rhizosolenia cylindrus*.

Neritic diatoms in the Antarctic.

The neritic flora off the coasts of the Atlantic in the southern hemisphere has also been comparatively little studied as yet. Still we are justified in saying that the neritic diatoms of the antarctic, from the ice barrier northwards, differ in the main from species belonging to the northern hemisphere. The difference indeed is so great, that hardly a single species is common to both arctic and antarctic waters. The investigations of Cleve, Karsten, and Van Heurck show that the following neritic diatoms may be considered characteristic of the antarctic :—*Chætoceras radiculum*, *Mœlleria antarctica*, *Eucampia balaustium*, *Fragilaria antarctica*, *Thalassiosira antarctica*, and probably several others whose biology is as yet only slightly known.

Oceanic species.

Oceanic plankton algæ are much more widely distributed than neritic algæ, and it would almost seem from our material that each species may be met with in all the seas of the world, wherever there are favourable conditions of existence. The diatoms are apt to occur irregularly. Sometimes we find enormous quantities of them, and at other times they may be so scarce that it is difficult to detect them. The peridineæ are more evenly distributed, and this is true especially of the species of *Ceratium*, which are fairly abundant and hardly ever absent from oceanic-samples, unless perhaps in arctic waters. They may well be used as guiding forms to express the character of the plankton. It is possible that the different species and varieties of the genera *Peridinium* and *Gonyaulax* might be employed with equal advantage, but they are more difficult to determine, and so little studied as yet that the determinations of Hensen and Karsten are unserviceable. Owing to so little being known about their distribution, I have decided to ignore them for the present.

The oceanic species may also be divided into three main groups :—

(1) *Arctic forms*, corresponding to Cleve's Tricho-plankton and Chæto-plankton. Most of them occur also in antarctic waters. Arctic oceanic species.

Diatoms : *Thalassiothrix longissima*, *Coscinodiscus subbulliens*, *Chætoceras criophilum*, *C. boreale*, *C. convolutum*, *C. atlanticum*, *C. decipiens*, *Rhizosolenia hebetata* (*semispina*), *Nitzschia seriata*.

Peridineæ : *Ceratium arcticum*, *C. longipes*, *Dinophysis granulata*.

(2) *Temperate-Atlantic forms*, corresponding to Cleve's Styli-plankton and Tripos-plankton. The latter of these two designations comprises a small community of species, which are less exacting as regards salinity, and are therefore produced in quantities along the coasts of North Europe. Temperate oceanic species.

Diatoms : *Rhizosolenia styliformis*, *R. acuminata*, *R. alata*, *Coscinodiscus radiatus*, *C. centralis*, *C. stellaris*, *Chætoceras densum*, *C. dichæta*, *Corethron criophilum*, *Dactyliosolen antarcticus*, *Thalassiosira subtilis*, *Coscinosira œstrupi*, *Asteromphalus heptactis*, *Bacteriastrum delicatulum*, *B. elongatum*.

Peridineæ : *Ceratium tripos*, *C. bucephalum*, *C. azoricum*, *C. macroceros*, *C. intermedium*, *C. lamellicorne*, *C. reticulatum*, *C. fusus*, *C. furca*, *C. lineatum*, *Dinophysis acuta*, *D. hastata*, *D. homunculus*.

Coccolithophoridæ : *Coccolithophora pelagica*, *Pontosphæra huxleyi*.

Chlorophyceæ : *Halosphæra viridis*.

(3) *Tropical-Atlantic forms*, corresponding to Cleve's Desmo-plankton, and comprising a series of species, especially peridineæ and coccolithophoridæ. Cleve's guiding form is the blue-green alga *Trichodesmium thiebaultii*. The following are some of the commonest :— Tropical oceanic species.

Diatoms : *Coscinodiscus rex*, *Planktoniella sol*, *Gossleriella tropica* (see Fig. 245), *Rhizosolenia castracanei*, *Chætoceras coarctatum*, *Asterolampra marylandica*, *A. rotula*.

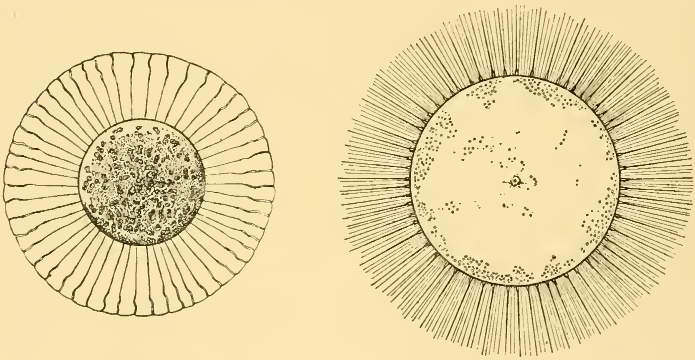
Peridineæ : species of *Ceratium* of all groups (*prælongum*, *cephalotum*, *gravidum*, *candelabrum*, *pennatum*, *extensum*, *palmatum*, *massiliense*, *carriense*, and several others), species of *Oxytoxum* and *Podolampas*, *Ceratocorys horrida*, species of *Phalacroma*, *Dinophysis schüttii* and *D. uracantha*, species of *Amphisolenia* and *Triposolenia*, *Ornithocercus magnificus*, *O. quadratus*, *O. steinii* and *O. splendidus*, *Pyrocystis noctiluca* and *P. fusiformis*.

Coccolithophoridæ : *Coccolithophora leptopora*, species of *Syracosphæra*, *Calciosolenia murrayi*, *Michaelsarsia elegans*, and many others.

The boundaries of the areas populated by these communities of species are as variable as the limits of distribution for the species themselves. Our investigations at different seasons, both in coastal waters and in the North Atlantic, have shown us that the flora of each locality is constantly changing. One species succeeds another as month follows month, and different societies predominate in the same locality at different seasons.

Flora of west coast of Norway.

Along the west coast of Norway, for instance, we find a flora during the winter, from December to February, scanty in numbers, but consisting of many species, and mainly composed of true Atlantic forms (Styli-plankton), which reach their northernmost limits in the dark months of the year. About March or April the temperature attains its minimum, and great quantities



a *b*

FIG. 245.
a, *Planktoniella sol*, and *b*, *Gossleriella tropica*, from the Atlantic. (Schütt.)

of diatoms are then produced, which are mainly arctic. Sometimes these are almost entirely neritic, and sometimes there is a considerable addition of oceanic species. As often as not it is the species of *Thalassiosira* and *Coscinodiscus* which first appear, and then comes *Chætoceras*, *C. debile* being usually the form found on the west coast, *C. constrictum* preferring the Skagerrack. In May the predominant form is generally *Leptocylindrus danicus*. We next get a period in June when the prevailing forms are oceanic, *Ceratium longipes* at that time attaining its maximum development and characterising the flora. In August the warmth-loving peridineæ begin to be more and more numerous, *Ceratium fusus*, *C. furca*, and *C. tripos* being then much in evidence, and continuing to increase until October. Finally, in November we get a comparatively large amount of southern neritic species (Didymus-plankton), made up to a great extent of forms of distinctly foreign origin. As the dark months of winter approach, however, their numbers rapidly decline.

In the open sea, too, our investigations appear to indicate that the southern forms reach farthest north in the autumn, say about November, while during the months of spring, from April to May, northern forms extend very far south. We have not as yet made investigations at different seasons in the tropical parts of the Atlantic ; consequently we cannot say whether there is an annual cycle of plant-development in a region where the conditions of existence seem to vary so little. It would be an excellent thing if researches of this nature could be undertaken. Flora of the open sea.

Supposing that the ocean-currents do exercise a direct influence upon the character of the plankton in the tropics, it is fair to imagine that it must be in the direction of periodicity. Lohmann has put forward the suggestion that the changes in pelagic animal life near the coasts of South Europe are connected with a cyclic movement of the water-masses. When these reach their northernmost point the conditions of existence will affect the organisms, so that the water-masses that pass through this region in the winter are likely to have a different fauna from that of the water passing through in summer. Elsewhere it is very difficult to tell what changes in the plankton are due to the direct influence of ocean-currents, and what changes are the result of altered conditions of existence partly due to ocean-currents and partly to other causes. It has often been observed, not only by Cleve and Hensen, but also during previous researches made by the "Michael Sars" and during the "Challenger" and "Valdivia" Expeditions, that the plankton changes its character the moment one passes the boundary between two currents. Thus an examination of the plankton may serve as a check on purely hydrographical investigations, which aim at ascertaining the boundaries of currents by means of observations of their temperatures and salinities. Perhaps the best guiding forms are the species of *Ceratium*, and strangely enough it is very often the species that systematically are the nearest related, which replace each other as we pass from one area to another. Many of them are so closely related that it is only for the sake of convenience that we regard them as distinct species, and there is always the possibility that they may be able to pass directly from one form into the other, even if we cannot actually prove Ocean-currents and the plankton.

that they do so. There is a series of closely related species, for instance, grouped round *Ceratium macroceros*. *Ceratium arcticum* is the farthest outpost in the direction of the polar sea, and shows the greatest variation. Its three horns are extremely divergent; the centre one, which points forward, is slightly bent, and so also are the other two. Near the southern limit of the species there are more and more instances, in a series of transition forms, where the two posterior horns bend forward, till we get to *Ceratium longipes*, the characteristic form of the Norwegian Sea and North Sea during the first half

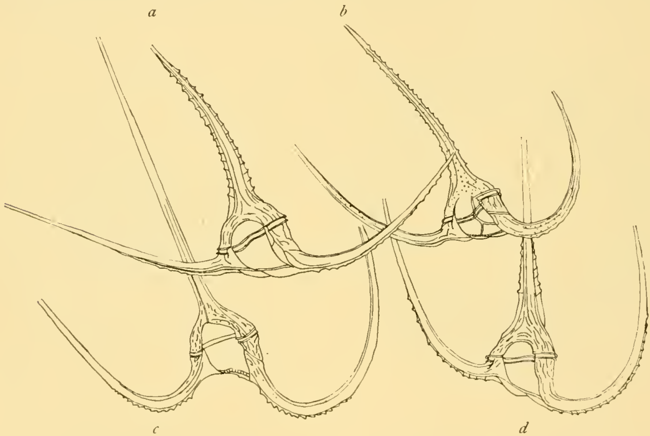


FIG. 246.—SPECIES OF *CERATIUM* BELONGING TO THE TYPE OF *C. MACROCEROS*, NORTHERN SPECIES.
a, *C. arcticum*; *b*, *C. longipes*; *c*, *C. macroceros*; *d*, *C. intermedium* ($\frac{187}{1}$). (Jörgensen.)

of summer. In this case, the posterior horns are bent quite forward, so that their extremities are parallel with the frontal horn. In the Gulf Stream we get *C. intermedium*, which has a straight frontal horn, like the other members of this type, and all three of its horns are much longer and more slender than those of the two northern species. At the eastern limit, where fresh water from the Baltic and the coasts of North Europe reduces the salinity, and where, too, the high summer temperatures diminish the viscosity of the surface-layers, there is a species with an even better suspension-apparatus, namely *C. macroceros* (see Fig. 246). Its frontal horn is particularly long and thin, and the posterior horns first bend a little backwards, and then sweep round to the front, sometimes in a direction parallel to the frontal horn, and sometimes with a moderate amount of divergence. We have already mentioned that *C. arcticum* and *C. longipes* belong to the Tricho-plankton and that *C. intermedium* and *C. macroceros* are Styli-plankton. We have finally a whole series of variations belonging to the tropical Desmo-plankton, namely *C. vultur*, *C. pavillardii*, *C. trichoceros*, and *C. tenue*, which we reproduce from Jörgensen's excellent monograph (see Fig. 247), and many others. They illustrate the different tendencies to variation. In similar fashion there are series of variations which group themselves round the other main types of the genus.

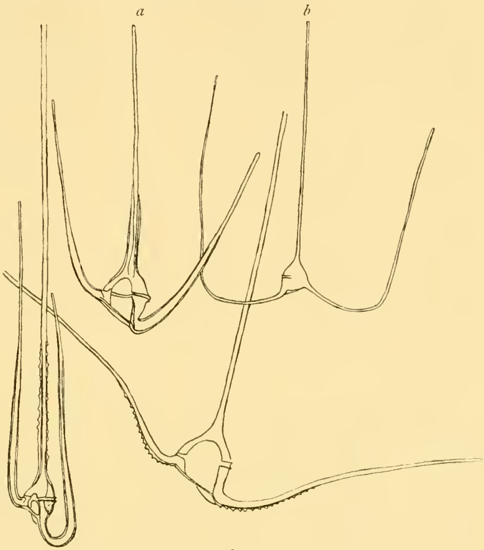


FIG. 247.—SPECIES OF *CERATIUM* BELONGING TO THE TYPE OF *C. MACROCEROS*, TROPICAL SPECIES.
a, *C. pavillardii* ($\frac{94}{1}$); *b*, *C. trichoceros* ($\frac{94}{1}$); *c*, *C. vultur*, var. *japonica* ($\frac{94}{1}$); *d*, *C. tenue*, var. *buceros* ($\frac{210}{1}$). (Jörgensen.)

Guiding forms like these are of very great assistance in defining the boundaries of adjacent currents which have a different biological character. But we need to exercise the utmost care in drawing conclusions as to the origin of ocean-currents from the composition of their pelagic flora, and it must not by any means be taken for granted that areas where the same species occur are necessarily united by a continuous stream connection. We have repeatedly made discoveries which go to indicate that most plankton-species of any consequence are to be found scattered about here and there outside their proper domain, so that these stray individuals might easily originate an abundant flora whenever conditions of existence became favourable.

Cleve, who looked upon the dispersal of organisms by currents as the chief factor in affecting the character of the plankton, was at first of opinion that he could fix the north-western boundaries of the Gulf Stream by noting the distribution of *Rhizosolenia styliformis*, the guiding form in his Styli-plankton. But he, too, found that its area of distribution extends northwards in the course of spring and summer, and that the swarms of *Rhizosolenia* actually outdistanced the speed of the current. The wider distribution of the algæ was evidently, therefore, due not alone to the increased volume of the current, but also to a rapid propagation produced by summer warmth outside the influence of the current, the algæ apparently having been already present in this area in small quantities.

Bipolarity of oceanic diatoms.

I may further instance the close agreement between oceanic species in arctic and antarctic waters. *Thalassiothrix longissima* and *Rhizosolenia semispina* (*hebetata*) are the two most characteristic forms among algæ along both the polar boundaries of the Atlantic, though they have also been found in small quantities at various localities in the tropics. I personally came across them on several occasions during the "Michael Sars" Expedition, and it requires, in my opinion, no special theories to account for this "bipolarity." There is quite sufficient connection between the two oceans to enable a few germs which are exceptionally tenacious of life to pass from the one to the other, and this would amply explain the agreement. Characteristically enough there is no similar agreement between arctic and antarctic waters when we come to the neritic forms, and this is probably because they are less adapted to travel over such immense distances. It may be, too, that their tendency to evolve resting-spores is an obstacle to long passive wanderings.

As a means of determining the direction and velocity of currents pelagic algæ will be found of very little use. Their continued existence during the progress of the current must always depend upon their persistence in reproduction, and this again is dependent upon conditions of existence and competition with other species. It is not mere coincidence that the microscopic flora of the warm Atlantic extends farthest north during the dark winter months, when no other species are much inclined to develop, and there is therefore no competition of any consequence, the character of the flora consequently remaining for a long time unaltered. Large animals, such as medusæ and salpæ, or the larvæ of bottom-animals like *Phoronis*, will be found far better indicators of the currents. Ostenfeld has, however, encountered one solitary case where plankton algæ could be employed for this purpose. *Biddulphia sinensis* (Fig. 248), a neritic diatom from the coasts of the Indian Ocean, was met with in the North Sea for the first time in 1903, to begin with in the southern parts, and then gradually farther and farther north, until at last it was discovered on the west coast of Norway at Bergen. Its travelling rate corresponds to the values which have been otherwise obtained for the velocities of the current along the coasts of Denmark and Norway. Latterly, it has found a fixed distribution-centre in the north-eastern corner of the North Sea, whence it extends still farther northwards every autumn. The velocity of the current could hardly be determined from the observations of these last few years, as there is always the possibility that this diatom has more than one centre of distribution, but its annual wanderings clearly indicate the direction of the current.

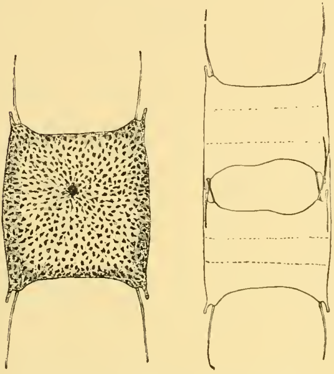


FIG. 248.—*BIDDULPHIA SINENSIS* ($\frac{110}{1}$). (Ostenfeld.)

Phytoplankton collected during the "Michael Sars" Expedition.

A large quantity of plankton algæ has been collected during the "Michael Sars" Expedition along the whole route, and will contribute valuable information regarding the distribution of the different species. We have been particularly successful in our study of the coccolithophoridæ, owing to the improved methods we were able to adopt. I shall deal separately with their distribution in what follows, and at the same time give some particulars of their quantitative occurrence. Part of the material is still incompletely examined. The difficult species of *Peridinium* in particular, and of a few other genera, will require a separate monograph for their special treatment; we have secured immense numbers of these forms. In other respects our observations practically confirm the views regarding the distribution of species that we owe chiefly to Cleve.

I shall now give a preliminary description of the character of the plankton along our route, founded upon an examination of material from representative stations, and upon observations of the living organisms on board ship.

The coast banks of North Europe. (Stations 1-10, 9th-20th April.)

All our first stations about the middle of April, with the exception of Stations 1 and 5, that were close in to land and had a less abundant flora, had an extremely plentiful diatom-plankton, such as we only get in the waters of North Europe during the spring. Our experiments with the closing-net, which, thanks to the fine calm weather, were made with the utmost exactitude at Stations 3 and 10, showed that by far the larger number were to be found between the surface and a depth of 100 metres, though even at a depth of 100 to 150 metres there were still quite considerable quantities. The character of the flora was mainly northern, especially in the case of the oceanic species. Among the principal forms we got *Rhizosolenia hebetata* forma *semispina* and *Nitzschia seriata*. Neritic diatoms were also numerous, and some had resting-spores. They are of a distinctly southern character compared with the species which occur, for instance, along the coasts of the North Sea; further, they belong to a local flora, which does not seem to have any direct connection with the North Sea. On the whole, these neritic diatoms are so small in their dimensions that they show signs of an "oceanic degeneration."

Besides them, there was an addition of subtropical species, especially in the deeper layers, and especially at the southernmost stations, Nos. 9 and 10, consisting of both diatoms and peridineæ, not in any great quantity, but still occurring regularly. These are the northernmost outposts of the Desmo-plankton, including such species as *Planktoniella sol*, *Ceratium gibberum*, *Dinophysis schüttii*, and *D. uracantha*.[1]

The coast banks of South Europe and North Africa. (Stations 11-41, 21st April-22nd May.)

Throughout the stretch of sea along the coasts of South Europe and North Africa our investigations were carried on comparatively close to the coast, and the plankton was generally found to be poor both in quality and quantity as soon as we stood at all far out from the land. It was then composed

[1] As representing this area, I here give a list of species from Station 7, depth 0-20 metres:—

Oceanic diatoms: *Chætoceras decipiens*, *C. densum*, *C. convolutum*, *C. peruvianum*, *C. atlanticum*, *C. dichæta*, *Coscinodiscus centralis*, *C. marginatus*, *Euodia cuneiformis*, *Thalassiosira subtilis*, *Asteromphalus heptactis*, *Rhizosolenia alata*, *R. semispina*, *R. stolterfothii*, *R. shrubsolei*, *R. acuminata*, *R. amputata*, *Dactyliosolen antarcticus*, *Nitzschia seriata*, *Thalassiothrix longissima*.

Neritic diatoms: *Chætoceras diadema*, *C. schüttii*, *C. contortum*, *C. coronatum*, *C. scolopendra*, *Bacteriastrum varians*, *Eucampia zodiacus*, *Thalassiothrix nitzschioides*, *Cerataulina bergonii*, *Dactyliosolen tenuis*, *Thalassiosira decipiens*, *T. excentrica*, *T. nordenskioldii*.

Peridineæ: *Ceratium tripos* forma *atlantica*, *C. lamellicorne* forma *compressa*, *C. azoricum*, *C. furca*, *C. arietinum*, and several others.

Coccolithophoridæ: *Distephanus speculum*, *Coccolithophora pelagica*.

of oceanic species, that we subsequently met with in the central parts of the ocean, though there was not more than a mere selection of the very commonest forms. It was here that we first became aware of the immense contrast between the scanty plant life and the teeming animal life. Sir John Murray and I examined the stomach contents of the salpæ abounding in the Strait of Gibraltar, and could see that they lived almost entirely on small forms like coccolithophoridæ and tiny peridineæ, which were too diminutive for our silk nets to capture. Radiolaria, however, both Acanthometridæ and colony-forming species, in symbiosis with brown flagellates, were present sometimes in such quantities that their assimilation of carbonic acid played no small part in proportion to that of the scanty plant plankton. Close in to the shore, on the other hand, there was abundance of plankton, and we got quantities of neritic diatoms off Lisbon, in the Strait of Gibraltar, and at several places on the coast of Morocco down to Cape Bojador. Different species predominated in the different samples, but *Lauderia annulata* was the commonest form everywhere.

No one accustomed to the plankton algæ of northern waters, with their numerous dark-brown chromatophores, could fail to be struck by the fact that the species never had more than a few small chromatophores, and thus had a pale appearance. In the diatoms the strong light frequently had the effect of making the chromatophores group themselves in the centre of the cell, or in *Lauderia annulata* at the terminal faces where the cells in the chain touch each other. This was invariably the case in plankton near the surface, though deeper down the position of the chromatophores might be normal.[1]

The Central Atlantic from the Canaries to the Azores, and from the Azores to the Newfoundland Bank. (Stations 44-69, 28th May-29th June.)

On this cruise we made acquaintance with the tropical Atlantic plankton in all its abundance. For a northerner it was most fascinating to study the many strange forms, especially of peridineæ. Every fresh batch disclosed species that were new or rare, or else remarkable stages of development. The

[1] The following list is from a sample pumped up from the surface, off the south coast of Portugal, on 24th April 1910 :—

Diatoms: *Lauderia annulata* (the prevailing form, found with auxospores), *Thalassiosira subtilis*, *T. gravida*, *Stephanopyxis turris*, *Paralia sulcata*, *Coscinodiscus concinnus*, *Leptocylindrus danicus*, *Rhizosolenia alata*, *R. shrubsolei*, *R. styliformis*, *R. stolterfothii*, *R. delicatula*, *R. robusta*, *Chætoceras densum*, *C. schüttii*, *C. didymum*, *C. curvisetum*, *C. decipiens*, *C. lorenzianum*, *C. diversum*, *Eucampia zodiacus*, *Hemiaulus hauckii*, *Biddulphia mobiliensis*, *Bacteriastrum varians*, *Nitzschia seriata*.

Peridineæ: *Ceratium lineatum*, *C. macroceros*, *C. fusus*, *C. furca*, *C. candelabrum*, species of *Peridinium*, *Gonyaulax spinifera*, *Diplopsalis lenticula*, *Dinophysis acuminata*, *D. rotundata*, *D. acuta*; *Coccolithophora pelagica*.

multitude of species was surprising, though none of them was very numerously represented. Every day one might sit and examine some unique microscopical form, which might be lost only too easily, and consequently had to be drawn there and then. And whereas in the north there are large quantities of every species, so that it is easy to investigate them in all their stages of development and variation, this multiplicity of forms in the tropics renders it incomparably harder to find out what stages of development belong to the same species, or how the boundaries between the different species are to be fixed.

The various stations did not differ much from one another, if we except Station 59, near Fayal in the Azores, where there were numbers of neritic diatoms, and Station 66, close to the Newfoundland Bank, where there was an addition of arctic forms. On the whole, the multiplicity of species increased as we went westwards. Possibly considerable differences may be revealed when the material has been completely treated, but all the species occur too sparsely in these samples to justify one in drawing conclusions from negative results.[1]

The Tropical Atlantic flora much resembles the plankton flora of the Indian Ocean observed by Karsten. In the Pacific there would seem, according to Kofoid, to be an even greater multiplicity of species, but I found several of the new species obtained by him during the "Albatross" Expedition, and it is probable that more and more of these rare Pacific species will gradually be found within Atlantic waters also.

In conclusion, it should be stated that, as far as quantity is concerned, the smallest plankton organisms, Lohmann's Nanno-plankton, play a far more important rôle than the whole of the other species caught in our silk nets, which will be subsequently discussed in their proper order.

[1] To show the character of the flora I append a list of species found at Station 64, lat. 34° 44′ N., long. 47° 52′ W., in a closing-net sample from a depth of 200 metres to the surface:—

Diatoms: *Coscinodiscus rex*, *C. lineatus*, *Euodia cuneiformis*, *Planktoniella sol*, *Gossleriella tropica*, *Thalassiosira subtilis*, *Asterolampra marylandica*, *Rhizosolenia castracanei*, *R. acuminata*, *R. styliformis*, *Bacteriastrum elongatum*, *Hemiaulus* sp., *Chætoceras dichæta*, *C. tetrastichon*, *C. peruvianum*, *C. coarctatum*, *C. furca*.

Peridineæ: *Ceratium pentagonum*, *C. teres*, *C. candelabrum*, *C. gravidum*, *C. fusus*, *C. extensum*, *C. pennatum*, *C. gibberum*, *C. buceros*, *C. platycorne*, *C. azoricum*, *C. tenue*, *C. pavillardi*, *C. karsteni*, *C. declinatum*, *C. gracile*, *C. arietinum*, *C. macroceros*, *C. massiliense*, *C. arcuatum*, *C. carriense*, *C. reticulatum*, *C. trichoceros*, *C. palmatum*, *C. limulus*, *C. pulchellum*, species of *Peridinium*, *Diplopsalis lenticula*, *Blepharocysta splendor maris*, *Ceratocorys horrida*, *Goniodoma polyedricum*, *G. fimbriatum*, *Gonyaulax polygramma*, *G. joliffei*, *G. pacifica*, *G. fragilis*, *G. mitra*, *Protoceratium reticulatum*, *Podolampas elegans*, *P. palmipes*, *P. bipes*, *Oxytoxum scolopax*, *O. reticulatum*, *O. cristatum*, *O. milneri*, *O. tesselatum*, *Dinophysis uracantha*, *D. schüttii*, *D. schröderi*, *Phalacroma argus*, *P. doryphorum*, *P. cuneus*, *P. rudgei*, *Amphisolenia palmata*, and another new species, *Ornithocercus quadratus*, *O. magnificus*, *O. steinii*, *O. splendidus*, *Pyrocystis lunula*, *P. noctiluca*, *Hexasterias problematica*.

Cyanophyceæ: *Trichodesmium thiebaulti*.

The plankton of the cold water on the Newfoundland Bank was very poor in species, *Ceratium arcticum* and *Peridinium parallelum* being the commonest forms. There were, besides, a few diatoms, such as *Chætoceras atlanticum*, *C. criophilum*, and *Rhizosolenia semispina*, all well-known species in the Norwegian Sea. In the harbour of St. John's, on the other hand, we found the plankton quite abundant, consisting of northern forms, both neritic and oceanic: the species of *Chætoceras* (*decipiens*, *debile*) predominated.

The Newfoundland Bank. (Stations 70-79, 30th June -10th July.)

Our northern section across the Atlantic contributed largely to our knowledge of the distribution of species, since it showed

The northern Atlantic section. (Stations 81-92, 12th-24th July.)

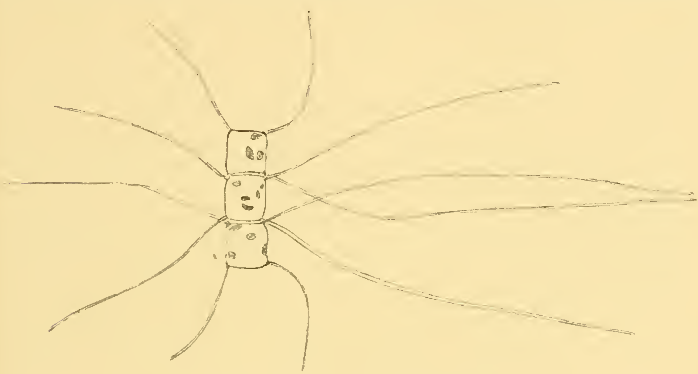


FIG. 249.—*CHÆTOCERAS PERPUSILLUM* ($\frac{600}{1}$).

us that a great many tropical forms are still to be found in lat. 45–50° N. These particular waters had been very little studied previously, and it was extremely interesting to follow all this Atlantic flora on its passive journey northwards. On the whole, its character remains unchanged, though of course the number of species becomes considerably reduced. During the first half of the section, on the western side of the mid-Atlantic ridge, there were a few small degenerate neritic diatoms belonging to the species which occur in the Atlantic water-masses south of Iceland: namely *Chætoceras schüttii*, *C. laciniosum*, and others. It seems unquestionable that they are derived from the American coast, and follow the current as far as Iceland. At Station 85 I also came across a remarkable little *Chætoceras*, that Cleve found in 1897 in the Skagerrack and named *Chætoceras perpusillum*

(Fig. 249), which had not been met with subsequently. The whole structure of this diatom shows that it, too, is most probably a neritic form, and it must therefore have a wider distribution than was commonly supposed.[1]

As we neared the coast banks of Europe we found the number of species growing distinctly less, though on the other hand the quantity of the plankton increased.

Law of production of organic substance in the sea.

The plants of the sea like those of the land build up all the organic substance which forms the chemical foundation of life. If we wish to know clearly when and how and under what conditions vigorous production takes place, or what prevents the development of an exuberant plant-life, we must first acquire the means of estimating the amount of vegetation in the different parts of the sea.

Hensen.

Hensen was the first to take up this problem, the solution of which depends on three assumptions: (1) it is absolutely essential to have apparatus that can capture all the organisms living in a specified quantity of water, (2) the plankton must be supposed to be uniformly distributed in the sea, so that the catch represents a reasonably extensive area; and (3) a scientific examination of the catch must supply a really correct picture of the amount of plants and their capacity of production.

Hensen's net.

The apparatus employed by Hensen and his assistants consisted of extremely fine straining-cloth, with meshes 0.04 to 0.05 mm. in diameter. He made the mouth of his net small in proportion to the filtering silk surface, to ensure as far as possible the immediate filtering of all water that came in through the opening, his object in this being to ascertain approximately how much water was filtered, when the net was drawn through the sea for a calculated distance. Experiments showed that in

[1] As illustrating a haul on this section I append a list of the species found in the closing net at Station 81 (lat. 48° 2′ N., long. 39° 55′ W.), from a depth of 50 metres to the surface:—

Diatoms: *Coscinodiscus excentricus*, *Euodia cuneiformis*, *Planktoniella sol*, *Coscinosira æstrupi*, *Thalassiosira subtilis*, *Corethron criophilum*, *Rhizosolenia styliformis*, *R. shrubsolei*, *R. fragillima*, *R. alata*, *R. semispina*, *Bacteriastrum delicatulum*, *B. elongatum*, *Chætoceras atlanticum*, *C. boreale*, *C. mediterraneum*, *C. peruvianum*, *C. criophilum*, *C. decipiens*, *C. contortum*, *C. schüttii*, *C. curvisetum*, *C. laciniosum*, *C. furcellatum* (a resting-spore), *Thalassiothrix longissima*, *T. nitzschioides*, *Nitzschia seriata*.

Peridineæ: *Ceratium lineatum*, *C. candelabrum*, *C. pentagonum*, *C. gravidum*, *C. fusus*, *C. pennatum*, *C. tripos*, *C. azoricum*, *C. gibberum*, *C. platycorne*, *C. arcticum*, *C. intermedium*, *C. macroceros*, *Protoceratium reticulatum*, *Peridinium oceanicum*, *P. depressum*, *P. divergens*, *P. conicum*, *P. ovatum*, *P. tristylum*, and some others, *Diplopsalis lenticula*, *Pyrophacus horologium*, *Goniodoma polyedricum*, *Gonyaulax polygramma*, *Podolampas elegans*, *P. palmipes*, *Oxytoxum scolopax*, *O. diploconus*, *Ptychodiscus carinatus*, *Dinophysis acuta*, *D. schüttii*, *D. rotundata*.

Flagellates: *Phæocystis poucheti*.

Silicoflagellates: *Dictyocha fibula*.

Chlorophyceæ: *Halosphæra viridis*.

Cyanophyceæ: *Trichodesmium thiebaulti*.

practise his net could not filter the whole of the water which ought to pass through; it was possible, however, to work out a coefficient for each size of net, namely a fraction indicating what proportion of the total quantity of water had actually been filtered. Hensen trusted chiefly to vertical hauls, since he was anxious to know definitely the exact distance through which the net had passed. He lowered his apparatus open, but with a heavy weight attached, so that it went down end-first and therefore caught nothing until hauling in began. Initial investigations aimed at ascertaining the total quantity of plankton in the photic zone, and accordingly the net was drawn in one haul from a depth of 200 metres right up to the surface, or from the bottom to the surface in water shallower than 200 metres, the idea being to find out the quantity of plankton in a column of water of known depth 1 metre square.

It is not, however, sufficient merely to compare the total quantity of plankton present in different localities; it may be just as important to know what there is at different depths, not only because we have to consider the effect of light, let us say, upon plant production, but because there may be layers of water, such as we find especially in coastal areas, totally distinct in hydrographical characters, and with different conditions of existence. Hensen made vertical hauls from different depths, and had recourse to subtraction when estimating the plankton of the deeper layers, but since that time closing-nets have been introduced, and we are able now to get samples from any layer we wish to study. C. G. Joh. Petersen constructed a closing-apparatus to go with Hensen's vertical net, and Nansen also designed a vertical closing net which was invariably used by the "Michael Sars," and found to be handy and reliable. Provided only the bag be long enough in proportion to the opening, it will act successfully from a quantitative point of view, though we did not employ it much for this purpose, as we had better methods of our own for estimating quantity. Otto Pettersson obtained his estimates of quantity by attaching silk nets to a large current-meter, which recorded the velocity of the current, and thus indirectly supplied approximate figures denoting the amount of water filtered. A series of very interesting determinations, from samples secured in this way, has been described by Broch.

Petersen's closing apparatus.

Nansen's closing net.

Pettersson's method of attaching nets to current-meter.

Broch.

The net-method was found unreliable as time went on. In the first place, it does not fairly represent the total quantity of plankton, since many of the smaller forms pass altogether, or to a very great extent, through the meshes; and, secondly, the meshes become gradually clogged with the slimy little algæ, or animals, so that the coefficient of filtration does not remain constant. Even during the course of a single haul we occasionally noticed that everything worked well to begin with, but that the cloth became more and more stopped up, until at last filtration ceased entirely. In other words, it is sometimes impossible to tell how much water has been filtered, and consequently the catch is practically valueless from a quantitative point of view.

Filtering method.

An endeavour was made to overcome this last difficulty by filtering a quantity of water, previously measured, either through silk nets, or through an even less porous filter-material, such as taffeta, or hardened filter-paper, or sand, an additional advantage being that by this means the very smallest organisms could be retained. Water-samples were secured by water-bottles or by pumps. Lohmann, who did much to perfect the pump-method, was not only able to get his water-samples from any depth desired, but could obtain samples representing a column of water from the surface down to a specified level. The pump was made to work in connection with a long, flexible hose, the mouth of which was lowered as far down as considered necessary, and then drawn gradually up towards the surface as pumping proceeded. The pumped-up water thus represented proportionally the whole distance through which the hose passed before reaching the surface. These samples were afterwards filtered by Lohmann, and the results compared with catches obtained by vertical hauls with the silk nets.

Lohmann's pump method.

The methods of capture had thus been greatly improved, and it was possible to obtain the smallest organisms, but for practical reasons it was necessary to limit the quantity of water filtered on each occasion. This forced us to turn our attention to the second question, namely the regularity with which organisms are distributed in the sea. Fortunately, the researches of Hensen and his assistants, as well as those of Lohmann and myself, have all gone to show that the distribution of the pelagic plants, at any rate, is extremely regular. The samples from adjacent localities with similar life-conditions have yielded very concordant results. I do not consider it any exception to this statement that in tropical waters dense masses of *Trichodesmium* sometimes collect as water-bloom in certain areas and not in others, or that diatoms near the edge of the polar ice occur in more or less local swarms, for I consider it more than probable that these irregularities

Distribution of pelagic plants extremely regular.

arise because the conditions of existence vary in closely adjoining areas. Lohmann has found that at certain seasons 10 to 15 c.c. of sea-water amply suffice to give a representative sample of the total plankton, but it is evident that only the commonest organisms floating in the sea in any locality do occur so densely and regularly that we can be sure of securing them, or even of catching enough for ascertaining their comparative frequency, in a water-sample consisting of only a few litres of water or less. The more scattered or mobile the individuals are, the larger masses of water must we examine to get a knowledge of the quantity present in any locality.

No universal method of estimating quantity of plankton.

It follows, therefore, that we must abandon all thought of a universal method. Fine silk nets give us complete collections of the larger Ceratia and diatoms, but are of no use for the smallest species, for which we are obliged to have recourse to more delicate methods of filtration, and to the centrifuge. The larger forms, too, will be found in our silk nets in sufficient quantities, if they are at all abundant, but where they are scarcer than, say, fifty specimens to the litre, the centrifuge cannot be depended on. Besides amongst these larger organisms some species are so scanty that even a vertical haul with the big net yields insufficient material, so we have been compelled to adopt the special methods described in this volume.

Determinations of volume and weight.

Various methods have been employed for estimating the quantity of plankton on the basis of catches made. We can allow the whole sample to sink to the bottom of a measuring glass, and appraise its volume, or we can weigh it while the organisms are saturated with water or spirit, or we can weigh the dry substance. Such determinations of volume and weight give us our first rough idea of the variations in the quantity of plankton, but there are many sources of error which it is unnecessary to discuss here. The worst fault is that measurements of this kind group into a whole the most diverse values, such as plants and animals, producers and consumers, one-celled organisms that are constantly reproducing themselves, and multicellular animals with a longer duration of life, or, again, organisms with slow and others with rapid metabolism. If we want to know a little about the conditions of development of organisms, we must have a method of investigation that allows us to trace the growth and retrogradation of each of the different species by itself, and counting then becomes the only method possible, as Hensen has continually asserted. Counting is a method that requires much time, and also absolute accuracy in

Counting necessary.

determining the species whose development we desire to trace; consequently most of those who endeavour to work at these interesting questions will be forced to confine themselves to definite problems, and content themselves with tracing the growth of a limited number of species. No doubt a man like Lohmann may be able to know all the species within certain limits, and may actually calculate by counting what each of them contributes to the total plankton volume, but speaking generally a "universal method" that will give us the total quantity of all the plants and animals of the sea in curves and tables is unattainable.

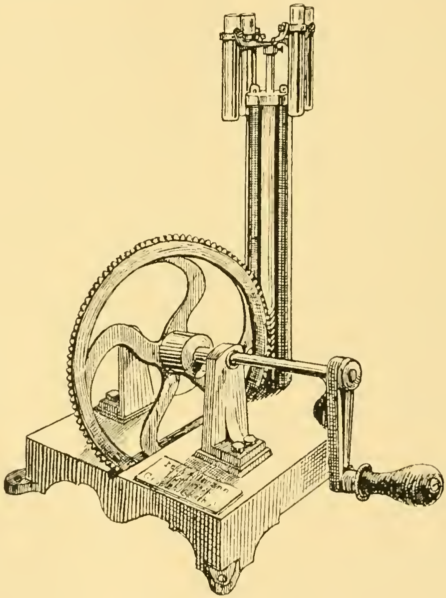


Fig. 250.—Lohmann's Hand-centrifuge.

Quantitative investigations on board the "Michael Sars."

During the "Michael Sars" Expedition our quantitative investigations yielded really remarkable results. Lohmann had succeeded by means of a centrifuge in determining the quantity of plankton in quite small samples of Baltic water, and we felt confident, therefore, that this excellent method ought also to prove serviceable in the open sea. We very soon found, however, that the algæ there were too scarce for our little hand-centrifuge (Fig. 250) to be of much utility; there was so little to be found at the bottom of the centrifuge glasses (Fig. 251) that we obtained a hopelessly inadequate idea of the plant life, whereas in the stomachs of salpæ we might, perhaps, get a quite abundant flora of small forms. Fortunately, we had taken with us a big centrifuge to be worked by steam (see Fig. 91, p. 105), and in its six glasses we could centrifuge at one time as much

Centrifuge.

as 1200 c.c. of sea-water. It made 700 to 800 revolutions per minute, and after eight minutes the plants were all collected at the bottom of the glasses. Our next proceeding was to pour away the clear water, and after rinsing the deposit, to put it in a smaller glass with a tapering bottom, where it was subjected to the action of a small hand-centrifuge. In this way we collected all the contents of, say, 300 c.c. of sea-water in one drop, which we examined in a counting chamber beneath the microscope, and noted carefully each single organism. As a rule we had to centrifuge the whole 300 c.c., but, if the plankton was very abundant, 150 c.c. or even 100 c.c. might suffice. Examination with the microscope is always more difficult when the organisms in the counting chamber lie close together.

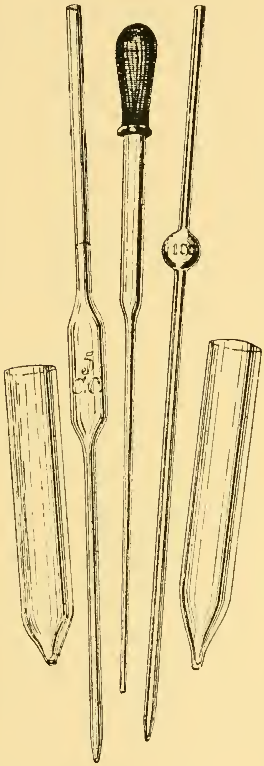


Fig. 251. — Centrifuge Glasses and Pipettes for use with Lohmann's hand-centrifuge.

Smallest organisms the most abundant in the open sea.

These investigations were carried out all the way from the Canaries to Newfoundland, and thence to the Irish coast banks, and resulted in our discovering that the smallest organisms which pass right through the silk nets are far more abundant than the others in the open sea, while the larger diatoms and peridineæ would appear to be so scanty that the total of all their species together only amounts to about ten per litre. Despite this fact, however, we found in the samples taken with our nets that there were at least fifty species of these larger forms at every station, so that as far as species go the flora is exceedingly rich.

Amount of plant life at different depths.

We were also able in this way to determine the occurrence of algæ at different depths. Samples from the surface, and from 20, 50, 75, and 100 metres were taken regularly, and we also examined samples now and then from still greater depths. We found, invariably, however, that the plant life below 100 metres was extremely scanty. The maximum in the ocean nearly always lay at about 50 metres, which is what Lohmann also found in the case of the Mediterranean coccolithophoridæ. At the surface there was less than down in the 20 to 50 metres zone, though the plankton nearly always approached its maximum value as soon as we reached a depth of 10 to 20 metres. At 75 metres the quantity diminished to about half of that found at 50 metres, and at 100 metres it had dwindled to at most a fifth. These were the values on our southern section. On the northern crossing the quantity of plankton fell away even more rapidly as we went deeper down; at Station 92, where there was a slight admixture of coast-water near the surface, and the lighter surface layer was separated from the pure Atlantic water somewhere between 25 and 40 metres, there were upwards of 250,000 plant cells per litre in the surface layer; whereas at 50 metres the plankton was less abundant than at any of our previous stations, and only amounted to 2213 cells per litre.

Schimper's observations in the Antarctic.

These results quite bear out the most valuable investigations so far made regarding the vertical distribution of algæ in the ocean, namely Schimper's observations in the Antarctic during the "Valdivia" Expedition. He found that the entire production was practically limited to the uppermost 200 metres, that the bulk was to be found above 100 metres, and that the maximum lay between 20 and 80 metres, or to be more precise, between 40 and 60 metres. We were able to confirm this, after comparing the volume of the samples taken with nets on those few occasions when there was a sufficiently large quantity of plankton at our stations to make such volume-measurements of any real value. There was, however, a different vertical distribution everywhere along the coasts where diatoms abounded, for then the exuberant plant production was limited to the surface layer, which was mixed with fresh water from the land.

Number of individual plant-cells at 50 and 75 metres at Station 64.

As illustrating our investigations at a station in the warmest part of the Atlantic, I give particulars of what I found at Station 64 (lat. 34° 44′ N., long. 47° 52′ W.) in water-samples from 50 metres (150 c.c.) and 75 metres (300 c.c.). The figures denote the number of individuals per litre.

	Cells per litre. 50 m.	75 m.
Coccolithophoridæ :—		
Pontosphæra huxleyi, Lohm.	300	173
Syracosphæra echinata, n.sp.	287	123
„ *spinosa*, Lohm.	193	33
„ *ampulla*, n.sp.	93	40
„ *lævis*, n.sp.	147	83
„ *blastula*, n.sp.	...	3
„ *pulchra*, Lohm.	160	100
„ *robusta*, Lohm.	80	67
Calyptrosphæra oblonga, Lohm.	593	370
Coccolithophora leptopora, Murr. and Blackm.	33	7
„ *pelagica*, Wallich	73	53
„ *wallichii*, Lohm.	7	...
„ *lineata*, n.sp.	7	...
Rhabdosphæra styliger, Lohm.	33	37
„ *claviger*, Murr. and Blackm.	...	7
Discosphæra tubifer, Murr. and Blackm.	107	93
Scyphosphæra apsteini, Lohm.	...	23
Calciosolenia murrayi, n.sp.	7	13
Ophiaster formosus, n.sp.	...	7
Undetermined coccolithophoridæ [1]	887	497
Total coccolithophoridæ	3007	1729
Pterospermataceæ :—		
Pterosperma disculus, n.sp.	...	20
Peridineæ :—		
Protodinium	1853	1007
Amphidinium gracile	33	37
Oxytoxum scolopax	7	3
„ *hjorti*, n.sp.	...	3
Dinophysis, sp.	7	...
Exuviælla, sp.	...	3
Other peridineæ	300	350
Total peridineæ	2200	1403
Diatoms :—		
Nitzschia seriata	...	3
„ sp.	7	33
Rhizosolenia calcar avis	14	43
Thalassiothrix frauenfeldi	...	7
Silicoflagellates :—		
Dictyocha fibula	43	93
Other plant-cells	447	377
Total plant-cells	5718	3708

I have previously given a list from this station of the species found in a vertical haul with the silk net. The number of

[1] Mainly young stages, which could not be determined with certainty; to a great extent they belong no doubt to *Coccolithophora leptopora*.

Plankton less abundant in the open sea than in coastal waters.

species is very considerable, yet the total quantity of individuals is surprisingly small compared with what we might find, for instance, off the coasts of Europe. In the Skagerrack one often gets plant-cells in tens of thousands or even hundreds of thousands in every litre of sea-water from the upper layer, and, what is more, they are much larger and more nutritive than the stunted forms which make up the bulk of this ocean plankton.

It cannot be denied that our investigations are as yet too incomplete to justify us in framing laws for plant production in the ocean. Still the great expeditions which have made researches in the open sea have given us a general conception of the conditions prevailing over wide stretches of water at certain seasons; on the other hand, careful investigations of the variations in the plankton throughout the year have been carried out at a number of coast stations, while our international researches have resulted in a great deal of material being collected at all seasons from the North Sea and adjoining areas. Though these investigations have not all been devoted to studying quantity, they have nevertheless enabled us to form some idea of the annual variations.

Plankton less abundant in tropical than in temperate seas.

One thing at any rate we may learn even from this incomplete material. The development of the plankton is much more irregular than it would be if merely such simple factors as warmth and light controlled production. It is not in the warmest waters that the greatest amount of organic substance is to be found. On the contrary we get larger masses of plants in temperate seas than we have ever yet come across in tropical or subtropical areas,[1] at any rate so far as the open ocean is concerned. Even when we come as far north as the coast of Norway we find that it is not in the hottest months of summer that the plankton attains its maximum, but in the early part of the spring or the end of autumn. Now it is certainly true that the quantity of vegetable matter present at any given moment is no direct measure of production. According to the law of Van 't Hoff, metabolism always takes place quicker *ceteris paribus* at a high temperature than at a low temperature, and a plant-cell in the tropics may perhaps produce more organic matter than a similar cell would do in the North Sea in the same space of time. The small tropical plants may

Van 't Hoff.

Metabolism more rapid in warm water than in cold water.

[1] The "Challenger" met with diatoms in the Arafura Sea in as great abundance as in the Antarctic regions, but neritic in character (see lists of species in Summary of Results, Chall. Exp., pp. 515 and 733).

pass more rapidly through their life-cycle, and their numbers may be more drawn upon by the abundant animal life; consequently considerable additions to their apparent total may be necessary, if we wish to estimate properly the importance of plant life in the tropics, as compared with that in higher latitudes. We must remember, moreover, when dealing with observations made in coastal waters all the year round, that the different species have a natural periodicity that may be connected with unknown internal factors in their cycle of life, as well as with the influence of currents which at one time carry the surface-layers away from the coast and at another time towards it. All the same there are many irregularities which cannot be explained as being solely the result of the actual physical conditions of existence. Besides light and warmth we might perhaps be apt to think of salinity, which, in the course of its variations, influences both the density and the osmotic tension of the sea-water. Though we are aware that a low or greatly varying salinity is injurious to many pelagic organisms, there are others which thrive remarkably well and multiply exceedingly under such conditions, as for instance the diatom *Skeletonema costatum* and the peridinean *Ceratium tripos* forma *subsalsa*. Results, in fact, are often the reverse of what one might expect. The flora of brackish-water bays, which is poor in species, may develop into even greater masses than we find synchronously in the open sea, where no osmotic changes have disturbed the vital activity of the numerous species belonging to the community of oceanic algæ.

We cannot get away from the view, which was first confidently put forward by Brandt, that certain indispensable nutritive substances occur so sparsely that, according to Liebig's minimum law, they act as factors which limit production. Liebig found that the growth of plants on land depends on the amount of the requisite nutritive substances present, the determining substance being the one of which at any moment there is least in proportion to the needs of the plant. As long as a particular nutritive substance occurs "in minimum," plant production will be proportionate to the available quantities of it, even though there be a superabundance of all other essentials.

Brandt.

Liebig's minimum law.

If this law is made to include all necessary conditions of life, it will be found to apply universally to all organisms both on land and in the sea, in which case that condition of existence, whether it be physical or chemical, which occurs "in minimum," will be the factor of limitation. We must remember, however, that production at a given moment need not necessarily be proportionate to the conditions of existence prevailing. There may be after-effects of a previous set of conditions. Indeed it is possible to point to places totally destitute of vegetation, owing to former unfavourable circumstances having destroyed all germs, while new germs have not yet found their way there. Still this is the only reservation we need to make, when asserting the universality of this natural law.

The necessary nutritive substances which are most likely to occur "in minimum" in the sea are nitrogen, phosphoric acid, and, in the case of diatoms, silicic acid; all others occur even to superfluity. Brandt in his works on metabolism in the sea discusses at some length the importance of nitrogen, phosphoric acid, and silicic acid, and his assistants at Kiel have carried out a number of tests to ascertain the extent to which these substances are present in sea-water. Not only the nitrogenous compounds (organic compounds, ammonia, and nitrates), but also phosphoric acid and silicic acid, occur in extremely minute quantities, so that it is particularly difficult to get accurate values representing them. We have therefore, unfortunately, no proper conception as yet of the way in which these substances vary in different parts of the sea. According to Raben's latest investigations the total quantity of combined nitrogen (ammonia, nitrates, and nitrites) in true North Sea water varies between 0.110 mg. and 0.314 mg. per litre, of which 0.047 to 0.124 mg. is saline ammonia, the whole being reckoned as free nitrogen. Even if we assume that the quantity of nitrogen in the Atlantic is considerably less, these values are high compared with the quantity of nitrogen to be found combined in the cells of the plankton-algæ. It seems, therefore, hardly possible that the nitrogenous compounds are entirely consumed by the algæ. It is, however, quite conceivable that the variations in the total quantity of nitrogen, or in the quality of such compounds as are easiest to absorb, may hasten or retard the augmentation of the algæ. The same is the case with silicic acid, which Raben found to vary between 0.30 mg. and 1.03 mg. per litre in thirty samples from the North Sea. The quantity of phosphoric acid, according to Raben's investigations, is as a rule below 1 mg. per litre, though it slightly exceeds the quantity of nitrogen.

Raben.

Brandt starts by discussing the occurrence of nitrogenous compounds in the sea. He calculates that large quantities of combined nitrogen are carried out from the land by the rivers, as organic nitrogenous compounds, ammoniacal salts, and nitrates. The result would be a constant increase, until at last the sea became poisoned, were it not that it is continually being absorbed by living organisms, or else being restored in some form or other to the atmosphere. We now know that there is very little combined nitrogen in the sea, so that it must evidently be used up as fast as it arrives. The consumers of nitrogen are first and foremost the seaweeds growing along the coasts, and the floating algæ of the open sea, but besides them there are also bacteria, which exist in all sea-water, as shown by Fischer. Their competition with the algæ for the nitrogenous compounds is not of any great consequence, so long as they do not interfere with the circulation of nitrogen otherwise than by disintegrating organic compounds so as to form ammonia, or by binding ammonia and nitrates in their cells as albumen.

Fischer.

Nitrifying and denitrifying bacteria.

From the bacteria-life of the soil, however, we are acquainted with another kind of nitrogenous metamorphosis produced by bacteria. There are nitrifying species which oxidise ammonia into nitrites and nitrates, without requiring organic substance to enable them to live; there are further whole series of other species which can reduce nitrites and nitrates, and give off nitrogen in a free state. Their action drives out of the natural circulation larger or smaller quantities of this valuable nutritive substance, scarce enough already, which all plants generally utilise to the uttermost. How great the loss is, as compared with the metamorphosis in other respects, and under what conditions it takes place, are questions that require our most careful attention before considering anything else.

Baur.

Baur, and others after him, succeeded in finding several kinds of these denitrifying bacteria in the sea, where they appeared to be widely distributed. It was found, too, that they produced free nitrogen with greater rapidity when the temperature was high (20° to 30° C.) than when it was low. Brandt, accordingly, put forward the hypothesis, that to the activity of these bacteria is due the fact that the abundance of plant life does not increase as we approach the tropics, but on the contrary very often decreases. This theory has now for some years been considered the only explanation of the irregular distribution of the plankton, but recent researches have shown that it is untenable.

The denitrifying bacteria require organic substance for their existence. If they are to give off free nitrogen, they must have nitrates or nitrites, though denitrification is as little a vital necessity for them as alcoholic fermentation is for the fermentation fungi. Feeding them with sugar and ammoniacal salts will result in their multiplying to an unlimited number of generations, without exhibiting their power of denitrification. They can attack nitrates whenever met with, utilise their oxygen, and give off nitrogen, but denitrification is not of any particular importance, provided the bacteria find sufficient free oxygen in their surroundings. It is only when this fails that they attack nitrates to any great extent. Given the requisite quantity of oxygen they will enter the regular circulation, and no nitrogen worth mentioning will be produced even where denitrifying bacteria are living and multiplying.

This is the case at any rate in the soil, where denitrification is of no importance, unless nitrates are brought into contact with considerable quantities of easily disintegrated organic substance. In the sea the quantity of organic substance is generally so small that a cubic centimetre of salt-water from the open sea rarely contains more than 50 to 100 living bacteria cells, while the nitrogenous compounds occur for the most part as ammonia or inorganic compounds, and not as nitrates or nitrites. It is more than likely that nitrates are not formed to any great extent in sea-water. Nitrifying bacteria are met with occasionally in the mud along the coasts, but they have not been proved to exist in the open sea ; in any case they have not the same importance there that they possess on land, where numbers of them are present in every single gram of cultivated earth. So it is probable that the small quantities of nitrates and nitrites in the sea-water are brought either from the land, or in a minor degree from the atmosphere as the result of electrical discharges. Most of the combined nitrogen of the sea occurs as organic compounds or as saline ammonia, neither of which can be reduced by denitrification. Supposing then that denitrification does play any noticeable part, it will only be in more or less enclosed bays and fjords, where there is a comparatively large amount of organic substance, a plentiful supply of nitrates from land, and so little circulation that there may be a lack of oxygen. In the open sea it is negligible.

Nathansohn. We must look for other conditions to explain the apparent irregularities in the distribution of the plankton. Nathansohn was the first to notice that vertical currents are bound to exercise considerable influence. If it be true that one or several of the necessary nutritive substances may be present in such small quantities as to act as factors that limit the development of the vegetation, then the more or less considerable exchange taking place between the illumined surface-layers and the vast water-masses of the deep is certain to produce a great effect. All the forms of animal life inhabiting the sea below 200 metres live solely upon organic substances which are due to plants in the surface layers; that is to say, they either feed directly upon the plant-cells which sink downwards, or upon the inanimate remains or excrements of the animals living up above, or else upon other animals which, in their younger stages, have inhabited the surface-layers and fed on the plants they found there. A large proportion of the produce of the surface-layers must thus be continually descending into the deep sea, and these nutritive substances are therefore withdrawn from their regular circulation in the photic zone. Down in deep water, no doubt, the destructive metabolism of animals will set free these nutritive substances, so that eventually carbonic acid and ammonia will be produced; still these gases can only regain the photic zone by very slow degrees if diffusion is their sole means of conveyance. If, however, whole masses of water are brought up from the deep sea to the surface, the nutritive substances contained in them will once more enter into circulation, and cause an abundant plant life to develop. Nathansohn has pointed out that marine areas where such ascending currents occur, and where the surface-layers are replaced by water from the deeper layers, are well known to be extremely prolific, not merely in plankton, but also in larger organisms. In anticyclonic systems like that of the Sargasso Sea, on the other hand, where, conformably to the laws of ocean-currents, the water-masses cannot ascend from the deep sea, but where the surface-layers sink downwards, the plankton is much less plentiful than in any other similar area where investigations have been made. Our researches in the Atlantic during the summer of 1910 have done a great deal to settle this question. I shall first of all, however, refer to a series of investigations which bring quite another light to bear upon the question, and show what difficulties we have to face.

Ascending currents.

In 1907 Professor Nathansohn and I commenced to study the Christiania fjord, and subsequently I continued these investigations alone. My previous observations had taught me that the pelagic algæ in this fjord attain their maximum between

Pelagic algæ of Christiania fjord.

March and May, and that they occur in rather smaller quantities from June to August. From September to October there is again a maximum, but from then onwards they decrease rapidly and reach their minimum between December and January. It is not surprising that the plankton is scanty during the dark period of the year, but the unmistakable secondary minimum in the summer months must be due to some special cause, which it should be possible to discover by studying carefully the whole year round the variations in quantity and the fluctuations in the outward conditions of existence. It struck me that the factors at work might be analogous to those which cause the differences in production met with in different regions of the great oceans.

Method of estimating the quantity of plankton.

To ascertain the quantity of plankton present we employed the method introduced by Sedgwick and Rafter for drinking-water tests in North America, which has been described by Whipple. A litre of water is filtered through a fine grade of sand, and the algæ that collect on its surface are rinsed off. To the rinsed-off water containing the algæ, filtered water is added until the whole comes to exactly 10 c.c. We then transfer 1 c.c. of this with a pipette to a counting-chamber 5 cm. long, 2 cm. broad, and 1 mm. high, which exactly holds it. For examination we use a microscope which magnifies to 40 or 50 times the natural size. A thorough knowledge of the species is requisite to enable us to enumerate them correctly. When counting species represented by many individuals we require a micrometer, with a larger or smaller number of millimetre squares marked off by lines, placed in the eyepiece of the microscope.

We soon found that our task was more difficult than we had at first imagined. The quantity of plankton fluctuated greatly in the course of short periods of time, yet the variations could not be ascribed directly to conditions of existence, since these remained fairly constant. The temperature in the surface-layers rose steadily during March to May from 1.5° C. to 6.3° C., the quantity of chlorine was about 16 per thousand, and according to Nathansohn the quantity of free ammonia in filtered samples of sea-water was between 0.0175 mg. and 0.031 mg. per litre, and of ammonia in organic combined form between 0.105 mg. and 0.217 mg. per litre. Of nitrates and nitrites he only found infinitesimal quantities up to 0.009 mg., set down as ammonia. *Chætoceras constrictum*, one of the commonest diatoms in the spring plankton of the Christiania fjord, furnished the following figures, denoting the number of living cells in every litre of surface-water near Dröbak :—

1907.	27/III.	30/III.	2/IV.	9/IV.	15/IV.	20/IV.	4/V.	6/V.	1/VI.	19/VI.
Chætoceras constrictum	20,850	45,850	12,750	59,730	760	44,425	192,500	95,480	1280	0

A quite satisfactory explanation presented itself, however, for the variations turned out to be closely connected with the direction of the winds and currents. The outflowing current in the surface-layers might reduce the quantity of plankton to a mere fraction of the normal amount in the course of a day or two, while the inflowing current might perhaps double the quantity in a few hours. The current exerts so great an influence because the abundant plant life is limited to a thin surface-layer which is sharply differentiated both in salinity and temperature from the water-masses below. On 28th March 1907, for instance, the temperature from the surface down to 20 metres was 2.6°–3.6° C., and the quantity of chlorine worked out at 16.74–17.62 per thousand ; from 40 metres down to the bottom at 80 metres the temperature was 6.2° C., and the quantity of chlorine was 18.73 per thousand. The outflowing current carries the surface-layers with their algæ out of the fjord, and the infertile deep water may be sucked up to perhaps 5 metres below the surface. The inflowing current, on the other hand, heaps up the fertile surface-waters. We found, on examining the plankton at different depths, that the bulk of the plants was limited to a very thin surface layer, say 5 metres in depth, after the current had set outwards, whereas subsequent to the inflow of the current they were as abundant down to 30 or 35 metres as at the surface.

At a place like this it was difficult to trace any regular connection between the local conditions of existence and the development of plankton-algæ, in view of the fact that currents caused variations of even greater extent than those actually due to conditions of existence. We had therefore to conduct our investigations on other lines. Supposing it were possible to determine the rate of growth of the algæ we should get a better measure of production, and probably also of the influence due to vital conditions, than variations in the total amount could give us. The number of individuals at any given moment depends not merely upon the rate at which production has taken place, but also upon how many have perished or been carried away; and the causes bringing about diminution, which we may perhaps term factors of loss, may vary without being in any way directly connected with the conditions of existence of the plankton. There is one genus, at any rate, whose rate of augmentation can be approximately determined. The species of *Ceratium* only divide their cells at night, so that if we make our investigations early in the morning we can tell which cells have been divided during the night and which remain entire. In a sample of surface-water on 10th September 1907 we found 300 whole cells and 161 half cells of *Ceratium tripos*, the latter consisting of 79 anterior parts and 82 posterior parts. The number of cells, then, had in twenty-four hours increased from $300+\frac{161}{2}=380.5$ on 9th September to $300+161=461$ on 10th September. The addition is accordingly $\frac{161}{2}=80.5$ individuals, and the percentage of the total amount on 9th September works out at $\frac{100 \times 80.5}{380.5}=21.2$ per cent.

This was the plan we adopted for calculating the augmentation of the species of *Ceratium* at Dröbak during the whole of their vegetation period in 1907, and we also recorded the average number per litre at different depths during the whole year.[1] The following tables show our chief results:—

[1] Similar investigations in the case of *Ceratium tripos* were carefully carried out during 1908-1909 by Apstein in the Baltic. The values he obtained for percentages of augmentation on the whole accord as nearly with mine as might be expected.

[Table

Number of Cells per litre of Surface-Water at Dröbak.

Date, 1907-8.	15/IV.	4/V.	1/VI.	19/VI.	6/VII.	20/VII.	1/VIII.	15/VIII.	30/VIII.	10/IX.	23/IX.	7/X.	28/X.	3/XI.	17/XI.	1/XII.	22/XII.	3/I.	9/II.
Ceratium tripos	60	22	20	840	333	172	343	573	337	1098	837	1433	13860	2149	899	2345	379	30	19
Ceratium fusus	...	66	180	...	111	234	305	246	581	1610	1553	8747	10230	506	83	30	17	6	...
Ceratium furca	...	22	...	...	16	55	400	72	58	350	443	1750	4460	536	24	12	21	18	...
Ceratium longipes	260	330	260	60	...	...	...	2	...	10	12	408	3000	440	661	1406	125	21	...

Percentage of Augmentation at the Same Place.

Date, 1907.	6/VII.	19/VII.	25/VII.	5/VIII.	22/VIII.	31/VIII.	10/IX.	23/IX.	6/X.	13/X.	20/X.	3/XI.	17/XI.
Ceratium tripos	6.5	13	8.3	12.9	23.8	28.8	21.2	13.7	8.7	5.8	2.6	2.1	0.3
Ceratium fusus	...	...	...	10	27	38.6	15.2	9.6	10.7	3.1	1.6	2.4	...
Ceratium furca	...	...	...	...	30.7	22.1	37.4	21.8	14.2	6.1	5.8	...	...
Temperature	14.0	16.0	15.5	15.8	15.1	13.9	13.0	12.4	11.5	11.6	11.3	7.95	5.7

The figures in the tables clearly indicate that, though the rate of increase is highest in August, the number of cells of *Ceratium* in the fjord makes no great advance before October. Throughout the whole summer the number continues at about the same level, in spite of a comparatively rapid production. This affords a further indication that in the Christiania fjord variations in the current and other factors of loss exert a greater influence than the variations in the conditions of existence which affect rate of increase.

The fact that we find in the Christiania fjord, and assuredly also in many other places along the coasts of North Europe, that the plankton is less abundant in the summer months than in spring, does not necessarily imply any unfavourable change in the conditions of existence due to summer. It may be caused by the melting of the snow in spring, and by the river water all through the summer driving the surface-water and its plant-life away from the coast, so that the production near land barely replaces the loss. In the autumn it would seem as if the prevalent sea-winds heap the surface-layers together along the coast, and thereby accumulate large quantities of plankton.

What effect these movements of the surface-water have upon the occurrence of the plankton we are as yet unable to say definitely, but they must be taken into consideration. We were obliged, therefore, to abandon our original intention, which was to ascertain the importance of such conditions of existence as dissolved nutritive substances, and particularly nitrogenous compounds.

Cultivation experiments.

I made a series of cultivation experiments, however, under conditions of existence resembling the natural conditions as nearly as possible. Stoppered glass bottles holding two and a half litres were kept just floating at the surface, by being filled with about two litres of sea-water ; the amount of plankton present was carefully checked in advance, and then one bottle was left in its original state, while in the other two small quantities of chloride of ammonium or calcium nitrate were placed. After an interval of 3 or 4 days the plankton in all the bottles was once more examined, and it was generally found that most of the species had augmented best when nitrogenous nutriment had been added. The addition had naturally to be made with the utmost care, since anything over 0.5 mg. per litre generally had a poisonous effect. The following table shows the result of one of these experiments :—

NUMBER OF CELLS PER LITRE.

	Before experiment on 21/VIII.	Three Days Later (24/VIII).	
		In Original State.	With addition of 0.5 mg. NH_4Cl per litre.
Ceratium tripos .	583	640	696
„ *fusus* .	543	649	833
„ *furca* .	155	149	196
Prorocentrum micans	1052	548	1464
Dinophysis acuminata	219	107	226
„ *rotundata*	33	30	42
Rhizosolenia alata .	157	232	345
Cerataulina bergonii	2840	3381	7214

Experiments with pure cultures of different plankton-diatoms, made by Allen and Nelson at Plymouth, show that they do not thrive without a regular supply of nitrogenous compounds. The plan of working which they adopted may also be employed with advantage when we wish to ascertain what concentration of dissolved nitrogenous compounds induces the plankton-algæ to augment most rapidly. This is the first thing to find out if we desire to know whether a want of dissolved nutritive substances is the limiting factor of production. It is quite possible that augmentation diminishes from lack of nitrogen long before the total amount of this essential has been fully consumed; yet augmentation must not fall below a certain minimum if the species is to hold its own, because of the larger or smaller number of individuals that are constantly perishing. Questions like these can only be settled by experiment, so that the cultivation method of Allen and Nelson is bound to be of great assistance to us eventually. But in the meantime our comparative investigations over large areas of the sea are also of considerable value.

Allen and Nelson.

I have already stated that plant life in the Christiania fjord was limited to a very thin surface-layer, which, owing to its lesser density, was differentiated from the deeper infertile water-masses, and this was practically the case along all the coasts where plankton-algæ were plentiful. Out in the open sea, on the other hand, where there are not such marked differences in salinity, temperature, and density be-

Plankton extends deeper, but is less abundant, in the open sea than in coastal areas.

tween the surface water and the deep water, the pelagic algæ extended deeper; at 50 metres, for instance, the quantity was still near the maximum, and even as deep as 100 metres or more the number was considerable. This, at any rate, was what we found in the case of the diatoms that abounded at our first stations off the Irish coast-banks and in the Bay of Biscay, and this too was what Schimper discovered in the Antarctic. It is also a regular rule that plankton is far more plentiful along the coasts than in the open sea, and, judging from investigations hitherto made, the proportion between what is produced in a typical coastal area and what is developed in typical oceanic water-masses would be more accurately expressed by 100 : 1 than by 2 : 1. For this the best explanation which I can give is that the open sea generally suffers from a want of one or more nutritive substances required by the plants, for though these are brought down to the sea in comparatively large quantities by the rivers, they are almost entirely consumed by the plant life of the coastal areas.

This is why the abundant plant life of the coastal seas is confined to the surface-layers, since the water-masses lying below remain separated, and consequently cut off from the plentiful supply of nutritive substances which regulate the augmentation of plants. But out in the open sea there is another important source of nutriment to be taken into account. Nathansohn has pointed out that pelagic animals are constantly taking nutritive matter down into deep water, and that for the time being it is accordingly withdrawn from the plants, even though the metabolism of the animals and the action of bacteria liberate it once more in inorganic form. These nutritive substances may rise to the surface-layers again by diffusion, but the process will require a long time. They may also accompany the ascending water-masses where off-shore winds bring about up-welling, in cyclonic current systems, and where the surface-layers, becoming chilled, sink and make room for warmer layers from below. Wherever vertical circulation takes place, and it is assisted in its action by storms and waves, the temperature and salinity will be extremely uniform from the surface down to a depth where the water-masses have such a high salinity that their greater density sets a limit to circulation. Conversely uniformity in temperature and salinity may be taken as a sign that vertical circulation has just taken place. This was the condition of affairs at our stations to the south-west of Ireland (see Fig. 252), where we

Vertical circulation.

found abundance of plankton in April 1910, algæ being present in large quantities as deep down as they have been known to occur, that is to say as far down as sufficient light penetrates. We can appreciate the difference between these conditions and the conditions in coastal areas like the Christiania fjord, if we remember that the nutritive substances in the first case may rise up from the deep water, while in the second they are derived from the surface through the admixture of fresh water.

Vertical circulation is regulated by differences in temperature at the surface, due to summer and winter, which are sufficient to increase the density of the upper layers till it equals the density lower down, and if circulation is to have any effect in the open sea, the surface-layers must be able to sink to a depth of at least 200 to 300 metres. The greater the difference in temperature between summer and winter, the more effective will vertical circulation generally be.

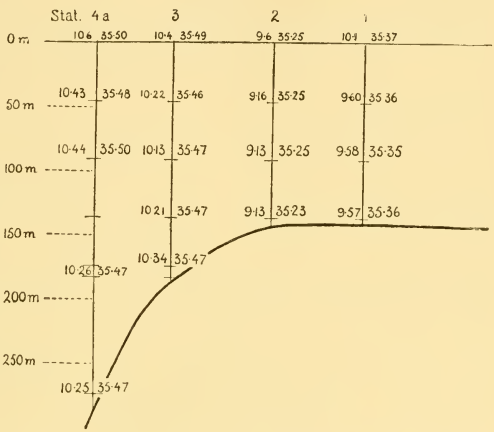


Fig. 252.—Hydrographical Section off the Irish Coast (April 1910).
Temperature and salinity nearly uniform from the surface down to a depth of 250 metres.

Assuming, then, that our view is correct, namely that plant production in the sea is mainly regulated by the amount of dissolved nutritive substances, we must expect to find plankton produced in abundance in coastal areas to which large rivers convey nourishment from the land, and in oceanic areas where vertical circulation takes place on a large scale, or where ascending currents bring up the deeper water-masses. Where vertical circulation is the controlling influence, the greatest profusion will be at seasons when the temperature of the surface reaches its minimum; that is to say, generally in winter, or in higher latitudes in the early months of spring. It would be possible to test the truth of this theory if we could carry out systematic quantitative plankton investigations all through the winter, in combination with hydrographical researches, in parts of the Atlantic like the sea round the Azores, where the plankton is known to be scanty during the summer, but where during the course of winter vertical circulation might be expected to create different conditions of existence.

Whipple. In this connection it should be mentioned that the influence of vertical circulation upon the production of plankton-algæ in fresh water has long been known to biologists. It has been pointed out by Whipple, who showed that the maxima of diatoms in particular coincide with the seasons when vertical circulation takes place, namely autumn and spring. And in the sea, too, it seems that diatoms, with their power of rapid augmentation, are the first to respond to improved conditions of nourishment.

Which of the essential nutritive substances are the chief limiting factors in the sea, it is impossible to say as yet. Probably, however, nitrogen is the most important, and next to it, perhaps, more especially in the case of diatoms, we may put silicic acid. Brandt and Nathansohn have both discussed the occurrence of these substances, but we need further and more conclusive information than what we now possess. Nathansohn has likewise considered the possibility of carbonic acid occurring "in minimum." This seems paradoxical, of course, since there are comparatively large quantities of it in sea-water. Still the greater part is combined in the form of carbonates, and only a very small portion is set free by dissociation at any given moment, so as to become available for the plants. How much there is in this form will depend on the alkalinity of the sea-water and on the temperature. When the free carbonic acid is used up by the plants, fresh quantities will gradually be absorbed from the atmosphere, though this may take place so slowly that there need not necessarily be any equilibrium between the carbonic acid tension in the atmosphere and at the surface of the sea. It is accordingly quite conceivable that the shortage may for a time be considerable enough to stop the algæ from assimilating carbonic acid. When the temperature is high the quantity of free carbonic acid in the sea-water will *ceteris paribus* be less than when it is low, and this also may help to explain the relatively poor production in warm seas. Variations in the tension of carbonic acid, however, have not as yet been sufficiently studied.

The organic substances built up by pelagic algæ unquestionably form the chief basis, and in the open sea practically the sole basis, of nutriment for all the pelagic animal life, as well as, through their pelagic forms, for the fauna of the sea-bottom. It is not, however, quite so certain that all the different algæ are equally useful as food to the animals which live on plant stuffs. Brandt's chemical studies of plankton organisms have distinctly shown that nutritive value does not necessarily correspond to volume. Diatoms, with their long silicated setæ, or with big bladder-shaped cells that merely enclose a thin layer of protoplasm along the inner side of the wall, have little nutritive value compared to the majority of the peridineæ, in which most of the cell-chambers are full of protoplasm. The dry substance of diatoms, according to Brandt's analyses of plankton samples, chiefly *Chætoceras*, contains 10 to 11.5 per cent albumen, 2.5 per cent fatty matter, 21.5 per cent carbohydrates, and as much as 64.5 to 66 per cent ash, 50 to 58.5 per cent of this last being silicic acid. Another sample, largely consisting of *Ceratium tripos*, had a totally different composition, the dry substance containing 13 per cent albumen, 1.3 to 1.5 per cent fatty matter, 80.5 to 80.7 per cent carbohydrates (half of which was chitin), and not more than 5 per cent ash.

Chemical composition of plankton samples.

We are still without systematic studies of the nutriment of plankton animals, and consequently do not know for certain whether some families of plants are preferred to others. The contents of the intestinal canals of salpæ make it evident that these animals at any rate collect all the different small organisms to be found in their neighbourhood. In warmer waters the greater part of their stomach-contents consists of coccolithophoridæ and other tiny forms, but we find besides representatives of all the plankton-algæ. Small peridineæ, for instance, like *Gonyaulax polygramma*, are seldom wanting. In fact, Stein, the well-known specialist on protozoa, who had no plankton-catches to aid him in his researches, got the best part of his material from the stomachs of salpæ, and was thus able to write his valuable initiatory monograph on peridineæ. And this, too, was the plan adopted at first for studying diatoms, so that our knowledge of pelagic genera like *Asteromphalus* and *Asterolampra* is largely due to the examination of the stomachs of salpæ. During the cruise I invariably examined the stomach-contents of salpæ, and obtained thereby plenty of small forms, coccolithophoridæ especially, for comparison with the material in the centrifuge samples. As we approached the coast of Europe, however, the contents took on another character, for at Station

Food of *Salpa*.

97 most of the forms were diatoms, and to a great extent consisted of *Rhizosolenia alata*. Generally speaking we discovered that salpæ do not trouble to make any selection. Lohmann's studies of *Appendicularia* have shown us that these animals get their nutriment by means of a filter apparatus, which allows only the minutest organisms, coccolithophoridæ in particular, and small peridineæ, to enter the digestive canal.

Food of *Appendicularia*.

Food of Copepods.

The chief consumers of plants in the sea are undoubtedly copepods. Their conditions of nutriment, however, have so far been principally studied by means of their excrements, which sink down in the shape of small elongated lumps, and are often brought up in numbers by the silk nets. Still, in these excrementa all the softer components have been digested, and the shells that can be identified do not necessarily always belong to species which are an indispensable part of their nutriment. Undoubtedly the calcareous shields of coccolithophoridæ occur too frequently for their presence to be ascribed to chance, indicating, moreover, that the digestive juices of copepods cannot have an acid reaction. In addition we very often meet with more or less bent and distorted coverings of peridineæ, and in northern waters the excrements contain stiffer forms like the little *Dinophysis granulata* in a practically unchanged condition. In localities where diatoms predominate, the excrements consist largely of bent and broken bits of species like *Rhizosolenia semispina* and *R. alata*. Even if Hensen's view be right that diatoms supply far less nutriment comparatively than the other classes of plants in the plankton, it is at any rate quite certain that the animals do feed on them, and especially when they are plentiful. In the Norwegian Sea I have several times observed that where diatoms abounded there might perhaps be only a few copepods and other plankton animals; still the copepods were there, and in large numbers too, just below the diatom zone, and their excrements consisted to a great extent of the silicious coverings of diatoms.

Proportion of plants and animals in the plankton.

Hensen noticed that the plants in the sea are often so scanty that it is hard to understand how all the animals get enough nourishment, and this is even more difficult to comprehend when we consider that the plants have directly or indirectly to support every single animal from the surface right down to the bottom. In many cases, perhaps, the plants may be more abundant than a cursory examination would seem to indicate; and the most diminutive forms, which are still practically unknown to us, undoubtedly exist in sufficiently large numbers to play a momentous part in the general economy. Still careful study distinctly reveals the fact that the plants of the sea are in striking disproportion to the animals. The most reliable results so far obtained are those due to Lohmann's researches in Kiel Bay. He studied the quantities of all the plankton organisms for a whole year with great thoroughness, and calculated the volume of the various groups in the plankton of the different water-masses at all seasons. To us his most interesting discovery is that the plants on an average made up 56 per cent and the animals 44 per cent of the total plankton. In the winter months the plants were easily outnumbered by the animals, and from December to February they formed scarcely a third of the total plankton. In the summer, on the other hand, they predominated, and made up sometimes even as much as three-quarters of the whole. Plants which are reproduced by division must necessarily decrease rapidly whenever vigorous augmentation ceases, if animals are constantly consuming numbers of them.

Life-cycle of animals.

The life-cycle of animals, with its growth-period in youth and propagation in maturity, is more complicated than that of plants, and gives them a better chance of withstanding unfavourable conditions of existence. A lower temperature necessarily reduces their intensity of breathing, and thus diminishes their consumption of nourishment, and it may be also that they can go without feeding for a comparatively long time, during which they live upon reserve matter that they have accumulated at more favourable seasons. Damas made some interesting studies of the life-cycle of the larger copepods, and found that propagation may require a higher temperature than what is necessary for conserving vital energy, and that therefore these forms can delay their propagation until the conditions of existence become more favourable, so that the young animals may have the rich nutriment required for their growth. *Calanus finmarchicus*, the commonest large copepod of the Norwegian Sea, abounds wherever the temperature is over 2° C., in both its half-grown and full-grown stages, but propagation does not begin till the temperature rises to 4° C., either owing to warmer water-masses arriving from the south, or to heating at the surface from the atmosphere.

Relation between production and consumption of algæ.

Lohmann has endeavoured to calculate the relation between the augmentation of the algæ and their consumption by animals throughout the year in Kiel Bay. He assumes that there is a daily accession of 30 per cent to the volume of the algæ, and that this can be consumed by the animals without harm to the plant aggregate. He further assumes that copepods and other multicellular animals require per day a quantity of nutriment equal to a tenth of their own volume, whereas protozoa need half their own volume. In view of what I have previously stated regarding the variations in the rate of production of *Ceratium*, I have no hesitation in declaring that the augmentation of the algæ varies within wide limits, and the same is undoubtedly also the case with the nutriment-requirements of the animals. Still I am quite ready to concede that Lohmann's assumptions may apply to the average conditions. The following table compiled by him, and showing values in cubic millimetres of plankton per 100 litres of sea-water, will doubtless be of interest :—

	Daily Augmentation of Producers available for Nutriment.	Daily Nutriment-requirement of Animals.	Surplus or Deficiency.
August .	35	6	+ 29
September	27	8	+ 19
October	14	5.5	+ 8.5
November .	9	4.5	+ 4.5
December .	3.5	2.5	+ 1.0
January .	3	1.8	+ 1.2
February .	1	1.8	− 0.8
March .	3	2.4	+ 0.6
April . .	13	2.0	+ 11
May . .	14	5.5	+ 8.5
June . .	20	4.0	+ 16
July . .	17	4.5	+ 12.5
August .	16	4.3	+ 11.7

According to this table the surplus plant substance is not large, and in February there was actually a deficiency. It is possible, too, that Lohmann's assumptions are on the optimistic side, and that he has put the production-capacity of the plants too high, and the nutriment requirements of the animals too low.

Organic matter in sea-water.

Pütter, after studying the quantities of oxygen consumed by different marine animals, both benthonic and pelagic, considers that the augmentation of the plant aggregate by no means suffices as nutriment for the animals. If his view is correct, there must, of course, be other sources of nutriment, both to replace the loss of organic substance which the animals incur by breathing, and also to supply building material for their growth and propagation. Pütter has endeavoured to find out whether organic matter dissolved in the sea-water does not provide this. He investigated its amount, and got surprisingly high values. Improved methods have enabled Raben to check his experiments; in water from Kiel there were 10.9 to 13.9 milligrams, or on an average 12.25 milligrams, of organic combined carbon per litre of sea-water, and at a station in the Baltic 3 milligrams. These are really high values, if we compare them with the quantities of organic substance we are able to point to in the form of living organisms. Lohmann's studies show that the total amount of the organic combined carbon in the plankton at Laboe in Kiel Bay varied during the year between 12.7 mg. and 189.8 mg. per 1000 litres of sea-water. According to Raben's investigations at a place close by, the mean value of organic combined carbon in dissolved form is 12,250 mg. per 1000 litres, or in other words about sixty times as much. Pütter.

Too little is known, unfortunately, about the occurrence of organic matter, and there are many difficulties to be overcome before we can look for conclusive results. Perhaps the most discouraging thing is that even the best filters allow a good many organisms to pass through them. The water-samples to be examined ought possibly to be freed from all suspended insoluble matter by means of the centrifuge, but even this method will not always give entirely satisfactory results, since some of the algæ (cyanophyceæ, *Halosphæra*) are lighter than sea-water, while the nimbler animals will swim up from the bottom before one can separate the clear water from the deposit. Pütter's hypothesis, however, certainly deserves to be further tested. If it be really true that in the salt-water of the open sea there is organic substance in sufficient quantities to be compared with what is combined in plants and animals, then this substance must be due to the production of plants. We will accordingly be forced to conclude that the pelagic algæ distribute to their surroundings through their surface comparatively large quantities of organic substance, and that their production is thus in actual fact much more considerable than we are led to believe, when we merely measure what they store up in their cells during growth and augmentation. Even if it seems strange biologically that they should evince such want of economy in regard to valuable nutritive matter, it would be unwise to reject the hypothesis, and the best plan is to await the results of continued investigations. Some biologists favour the theory and others oppose it; some of them have published the results of special studies, particularly of the nutrition-processes of animals, all of which have been of service to the cause of science, though they have not succeeded in deciding this question.

Lohmann and C. G. J. Petersen have maintained that organic detritus may be of intrinsic importance for the nutriment of animals, as well as plants, and they have demonstrated that organic detritus from the land is present in fairly large quantities in waters like the Baltic or off the coasts of Denmark. We have reason, therefore, to expect extremely interesting results from the work of the Danish biologists on organic detritus in the water and in the deposits at the bottom of the sea. But out in the open sea this detritus is only met with in inconsiderable quantities, as our centrifuge-samples showed us on board the "Michael Sars." I do not, of course, include inanimate organic substances, such as excrements or the empty chitin-coverings of copepods, which form a part of the circulation of nutritive substances through the pelagic organisms. Organic fragments, not actually derived from pelagic organisms, either do not occur at all in the open sea, or, if they do, are not worth taking into consideration.

H. H. G.

CHAPTER VII

FISHES FROM THE SEA-BOTTOM

Zoologists on both sides of the Atlantic have long been engaged in collecting facts regarding the occurrence of fishes and other organisms which inhabit the Northern Atlantic and adjacent waters. In recent times special expeditions have offered opportunities of collecting according to definite plans, and the American expeditions in the "Blake" and the "Albatross," and the European ones in the "Challenger," in the "Travailleur," the "Talisman," and the "Princesse Alice" have added essentially to our knowledge. As a consequence a very large amount of material has been accumulated, but as yet this material has not been utilised for the purpose of drawing up a general account of the distribution of the different animal-communities.

Any attempt to review our knowledge, or to summarise the voluminous literature on this subject, would extend this book beyond all reasonable limits, and I shall therefore restrict myself to certain important and characteristic main lines in the distribution of Atlantic fishes and other animals, relying principally on the captures made during the cruises of the "Michael Sars." The material gathered during these cruises is so large that a representative view may now be obtained, and while confining myself to our own observations I hope to give some information of real value. My aim, then, will be to describe the geographical distribution of the fishes, as this group has been made the special object of our researches; other groups of animals will be mentioned only in order to illustrate the surroundings and the animal-communities associated with the different fishes.

In dealing with animal geography one must always presuppose a knowledge of a vast number of animal forms. The animals inhabiting the depths of the sea are strange to all but a few specialists, and are known only by Latin names, of which most zoologists even are ignorant. Nevertheless these names must be used if the reader desires to penetrate into the general laws which govern the distribution of animals in the ocean. In order to overcome this difficulty I commence this chapter with systematic lists recording the different species of fishes, and the details of their capture, accompanied by outline drawings of the most important species. By means of these lists the reader may easily obtain information as to what group in the system a certain fish belongs, and further details will be found in the literature of the subject.[1]

Bottom-fishes collected by the "Michael Sars."

During the many cruises of the "Michael Sars" probably all the species of fish which live in the Norwegian Sea and the North Sea have been captured, but only the commonest species will be treated of here. Nearly all the fish caught during the Atlantic cruise in 1910 will, however, be mentioned, or at all events as many as the present state of the work will permit.

The following list includes all the forms captured by us in the Atlantic which, according to our experience, must be considered as living mainly along the bottom.

1. List of Fishes caught by the "Michael Sars" along the Sea-Bottom in the North Atlantic

This list includes 138 different species belonging to almost all the most important groups of bottom-fishes. Thirty-two species belong to the order Plagiostomi, fishes with a cartilaginous skeleton, and 106 to the order Teleostei, fishes with an ossified skeleton.

The Elasmobranchii.—Our list includes of the order Plagiostomi the two sub-orders, Selachii (sharks) and Batoidei, with the family Raiidæ (rays), besides the order Holocephali with the Chimæridæ.

Seventeen species are sharks (Selachii), including the large Atlantic *Notidanus*, the small but numerous Scylliidæ, which also go into the Norwegian Sea. Of the large group of the Spinacidæ, *Acanthias vulgaris* is caught by the nets of the fishermen in the North Sea; it follows the herring shoals, and is therefore called dog-fish by the fishermen.

The two genera *Centrophorus* and *Spinax* include deep-sea fishes living on the slope. *Centrophorus* is confined to the Atlantic only, and so is *Centroscyllium*; *Spinax niger* is caught in the Norwegian fjords also. Two teeth of extinct species of sharks, *Carcharodon* and *Oxyrhina*, were

[1] See, for instance, A. C. L. G. Günther, *An Introduction to the Study of Fishes*, chap. xxi., Edinburgh, 1880; Francis Day, *The Fishes of Great Britain*, Edinburgh, 1880-84; Boulenger and Bridge, *Fishes*, in the *Cambridge Natural History*, 1904. The lists are arranged according to the system proposed by Boulenger.

found in deep water by the "Michael Sars," similar to those found in such great numbers by the "Challenger" in the Pacific.

Twelve species are rays (Raiidæ). *Raia microocellata* and *R. miraletus* are true Atlantic species, caught by the "Michael Sars" only south of the Canaries. The other species are caught also in the Norwegian Sea.

Of the family Chimæridæ, *Chimæra monstrosa* is recorded from the Norwegian Sea, from the extreme north of Norway, from the whole of the Atlantic down to the Cape of Good Hope, from Sumatra and Japan. *C. mirabilis* was discovered by the "Michael Sars" in 1902, south of the Faroe Islands, in deep water. *Hariotta raleighana*, in appearance a most remarkable deep-sea fish, was previously known from the Atlantic slope off the United States.

THE TELEOSTEI are represented in our list by no less than eight sub-orders.

The Malacopterygii include salmon-like fishes; two species of the genus *Argentina* live near the continental edge or the deepest part of the coast-banks of the Norwegian Sea and the Atlantic. The family Alepocephalidæ includes true deep-sea fishes, black in colour, known from the greatest depths of the ocean, but not recorded from the Norwegian Sea. They are salmon-like in form, and attain the dimensions of a small salmon.

The Apodes, or eel-like fishes, include a great number of deep-sea fishes belonging to the family Synaphobranchidæ. *Synaphobranchus pinnatus* is known from all the oceans of the world, and was caught in deep water by the "Michael Sars" at many stations. The family Murænidæ includes shore-fishes; the splendid *Muræna helena* was caught off the African coast.

The Haplomi and the Heteromi include true deep-sea fishes, the genera being *Bathysaurus*, *Bathypterois*, the new genus *Bathymicrops*, *Halosauropsis*, and *Notacanthus*. None of them are known from the Norwegian Sea, but some have a world-wide distribution, and have been caught at the very greatest depths where trawlings have been taken.

The Catosteomi and Percesoces are only represented by one species each; both coast-fishes. *Centriscus scolopax* is a brightly-coloured little coast-fish with a pipette-like rostrum.

The Anacanthini are represented in our list by no less than 36 different species, 19 of Macruridæ, and 17 of Gadidæ. These two families are very nearly related. The Macruridæ include the most important and numerous bottom-fishes on the continental slopes and over the abysmal areas of the ocean. The Gadidæ are the most numerous and economically the most important food-fishes in northern and subtropical waters. The Macruridæ have representatives which live in very deep water only, others which are confined to certain geographical areas of the slope, and so on; these will be treated in greater detail later. Of the Gadidæ the genus *Gadus* has a number of species (for instance, the cod, the haddock, the whiting, the pollack, the saithe) which are characteristic of different parts of northern waters, while the genus *Merluccius* is the most important food-fish on subtropical coast-banks. The genera *Molva* (ling) and *Brosmius* (tusk) inhabit the deepest parts of the coast-banks, and the genera *Mora*, *Lepidion*, and *Halargyreus* the uppermost part of the continental slope.

The Acanthopterygii.—Fifty-one species belong to this very important and large group of highly developed fishes, most of which are true coast-bank fishes, only a few of them being known from the uppermost part of the slope.

Most of these fishes, the Serranidæ, Sciænidæ, Pristipomatidæ, Sparidæ, Mullidæ, Caproidæ, Labridæ, Scorpænidæ, Triglidæ, Trachinidæ, Uranoscopidæ, and Callionymidæ, are brightly-coloured fishes, with hard ossified scales and spines of moderate size, living in shallow water, or deeper, on the coast-banks, with a maximum distribution in warm subtropical waters. The northern limit of their distribution differs for different species, several extending even to the southern warmer parts of the bays and fjords of Scandinavia; other families, *e.g.* Cottidæ and Blenniidæ, have representatives in the Arctic (*Triglops*, *Lumpenus*). None of these families have, however, any economical importance in the Norwegian Sea or North Sea.

The family Pleuronectidæ, or flounders, includes very important food-fishes. The plaice, flounder, sole, dab, megrim, halibut, all belong to this family. *Hippoglossus*, *Pleuronectes*, and *Zeugopterus* are northern genera; *Solea* is the most important genus in the Atlantic, *Solea vulgaris* being of importance also in the southern parts of the North Sea.

The Scombriformes, to which belong the genera *Trachurus* or *Caranx*, *Scomber*, *Thynnus*, are mostly pelagic, but are also caught very near to the shore. The mackerel, the tunny, the horse-mackerel are all economic species of great importance.

Class—PISCES

Sub-Class—ELASMOBRANCHII

Order—PLAGIOSTOMI

Sub-Order—SELACHII

NOTIDANIDÆ

Notidanus griseus, Cuv. (six-gilled shark), 1902, Faroe-Shetland channel (Fig. 253).

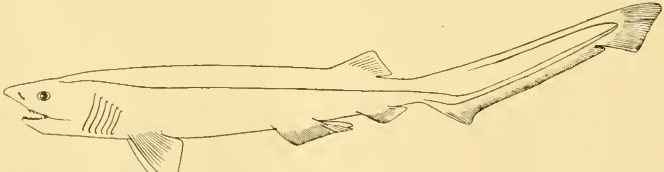


FIG. 253.
Notidanus griseus, Cuv. (After Bonaparte.)

Scylliidæ

Scyllium canicula, Cuv. (rough hound), 1910, Stations 3, 14, 20, 39.
Pristiurus melanostomus, Bonap. (black-mouthed dogfish), 1902, Faroe-Shetland channel; 1910, Stations 1, 21.
Pristiurus murinus, Coll., 1902, Faroe-Shetland channel, 1100 to 1300 metres.

Carchariidæ

Mustelus vulgaris, Müll. and Henle (smooth hound), 1910, Station 13.

Lamnidæ

Carcharodon, fossil tooth, 1910, Station 48 (see Fig. 254).
Oxyrhina, fossil tooth, 1910, Station 48.

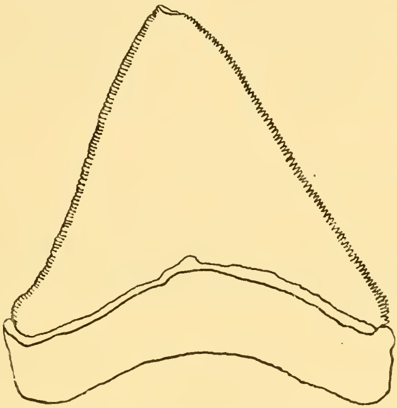


Fig. 254.
Carcharodon megalodon, Fossil Tooth. Station 48. (After Zittel.) This figure shows a Carcharodon tooth from Tertiary deposits; those dredged from the deep-sea deposits have never the base preserved (see Fig. 126, p. 156).

Spinacidæ

Centrina salviani, Risso, 1910, Station 13.
Acanthias vulgaris, Risso (dog-fish), 1902, Faroe Bank, 390 metres; Faroe-Shetland channel; 1910, Stations 1, 3, 20, 39 (see Fig. 255).

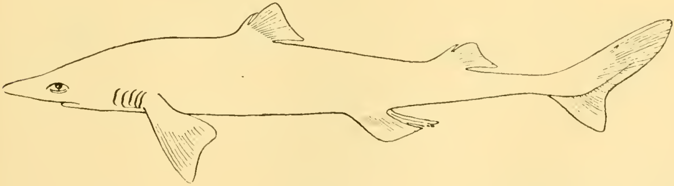


Fig. 255.
Acanthias vulgaris, Risso. (After Smitt.)

Centrophorus crepidater, Boc. and Cap., 1902, Faroe Bank, 750 metres.

Centrophorus squamosus, Gmel., 1902, Faroe Bank, 390 to 750 metres (see Fig 256).

FIG. 256.
Centrophorus squamosus, Gmel. (After Jensen.)

Centrophorus calceus, Lowe, 1902, Faroe Bank, 750 metres.

Centrophorus coelolepis, Boc. and Cap., 1902, Faroe Bank, 750 metres.

Spinax niger, Bonap., 1902, Faroe Bank, 426 metres; 1910, Station 21.

Spinax (*Etmopterus*) *princeps*, Coll., 1902, Faroe-Shetland channel and Faroe Bank.

Centroscyllium fabricii (Reinh.), 1902, Faroe-Shetland channel and Faroe Bank.

RHINIDÆ

Rhina squatina, Duméril, 1910, Station 39.

Sub-Order—BATOIDEI

RAIIDÆ

Raia clavata, L. (thornback ray), 1902, Faroe Bank, 130 metres; 1910, Stations 1, 3, 13, 14, 20, 39 (see Fig. 257).

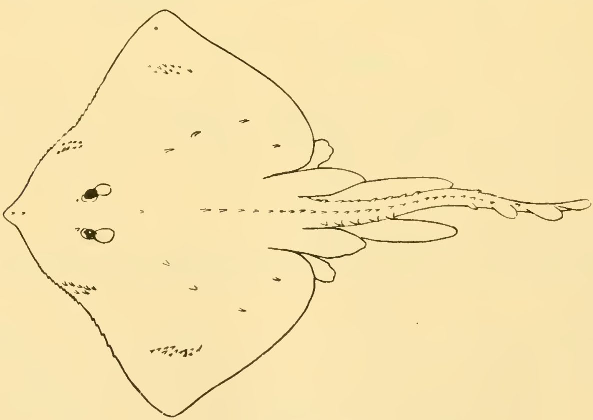


FIG. 257.
Raia clavata, L. (After Smitt.)

Raia punctata, Risso, 1910, Stations 37, 38, 39.

Raia microocellata, Montagu, 1910, Station 37.

Raia alba, Lacép., 1910, Station 37.
Raia miraletus, L., 1910, Station 39.
Raia fyllæ, Ltk., 1910, Stations 25, 95.
Raia circularis, Couch, 1910, Stations 3, 13, 39 (see Fig. 258).

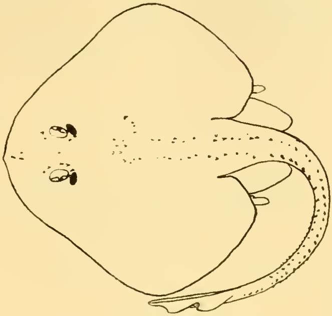


FIG. 258.
Raia circularis, Couch. (After Smitt.)

Raia batis, L. (skate), 1902, Faroe Bank, 130 metres; Faroe-Shetland channel.
Raia vomer, Fries, 1902, Faroe Bank, 750 metres; 1910, Station 3.
Raia nidrosiensis, Coll., 1910, Station 4.
Raia fullonica, L., 1902, Faroe Bank, 390 metres; 1910, Station 21.

MYLIOBATIDÆ

Myliobatis aquila, Cuv. (whip-ray), 1910, Station 36.

Order—HOLOCEPHALI

CHIMÆRIDÆ

Chimæra monstrosa, L., 1902, Faroe Bank, 435 metres; 1910, Station 21.
Chimæra mirabilis, Coll., 1902, Faroe-Shetland channel; 1910, Station 4 (see Fig. 259).

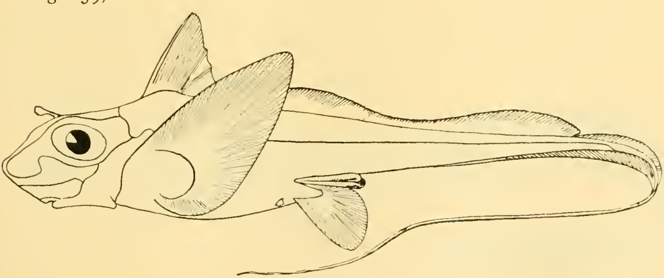


FIG. 259.
Chimæra mirabilis, Coll. Nat. size, 76 cm.

Hariotta raleighana, G. and B., 1910, Stations 35, 101 (see Fig. 260).

FIG. 260.
Hariotta raleighana, G. and B. (After Goode and Bean.)

Sub-Class—TELEOSTOMI

Order—TELEOSTEI

Sub-Order—MALACOPTERYGII

SALMONIDÆ

Argentina silus, Nilss., 1910, Station 39 (see Fig. 261).
Argentina sphyræna, L., 1910, Stations 1, 3.

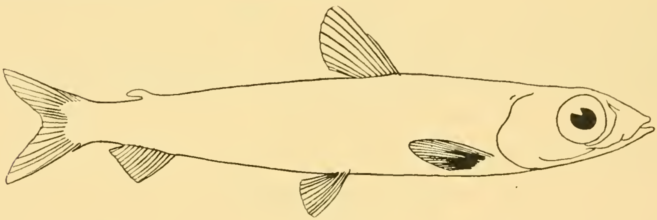


FIG. 261.
Argentina silus, Nilss. (After Smitt.)

ALEPOCEPHALIDÆ

Alepocephalus giardi, Koehl., 1902, Faroe-Shetland channel; Faroe Bank, 750 to 840 metres (see Fig. 262).

FIG. 262.
Alepocephalus giardi, Koehl. (After Collett.)

Bathytroctes rostratus, Günth., 1910, Stations 29, 56.
Conocara macroptera, Vaill. (G. and B.), 1910, Station 25 (see Fig. 263).

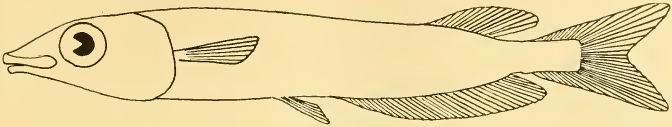


FIG. 263.
Conocara macroptera, Vaill. Nat. size, 20 cm.

Sub-Order—APODES

SYNAPHOBRANCHIDÆ

Synaphobranchus pinnatus, Gron., 1902, Faroe-Shetland channel; Faroe Bank, 750 metres; 1910, Stations 4, 24, 41, 53, 88, 95, 101 (see Fig. 264).
Histiobranchus sp., 1910, Station 88.

FIG. 264.
Synaphobranchus pinnatus, Gronov. Nat. size, 31 cm.

MURÆNIDÆ

Muræna helena, L., 1910, Station 38 (see Fig. 265).

FIG. 265.
Muræna helena, L. Nat. size, 102 cm.

Sub-Order—HAPLOMI

SCOPELIDÆ

Bathysaurus ferox, Günth., 1910, Stations 25, 35, 53, 95 (see Fig. 103, *a*).
Bathypterois longipes, Günth., 1910, Station 53.
Bathypterois dubius, Vaill., 1910, Stations 23, 41 (see Fig. 266).

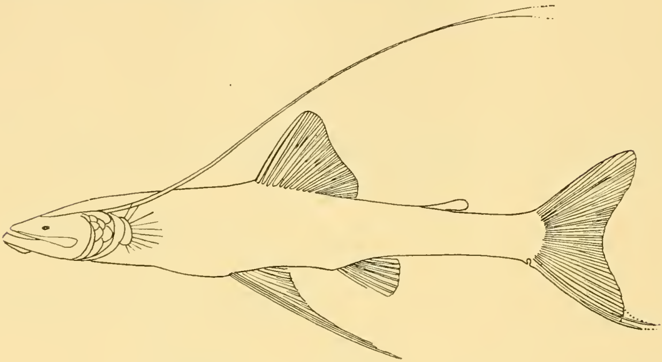


FIG. 266.
Bathypterois dubius, Vaill. Nat. size, 17 cm.

Benthosaurus grallator, G. and B., 1910, Station 53.
Bathymicrops regis, n.g., n.sp., 1910, Station 48 (see Fig. 305).

Sub-Order—HETEROMI

HALOSAURIDÆ

Halosauropsis macrochir, Günth. (Coll.), 1910, Stations 35, 53, 88, 95 (see Fig. 103, *b*).

NOTACANTHIDÆ

Notacanthus bonapartii, Risso, 1902, Faroe-Shetland channel; Faroe Bank, 840 metres (see Fig. 267).
Polyacanthonotus sp., 1910, Stations 53, 95.

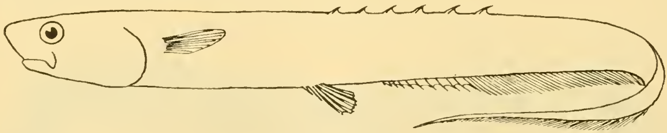


FIG. 267.
Notacanthus bonapartii, Risso. (After Goode and Bean.)

Sub-Order—CATOSTEOMI

CENTRISCIDÆ

Centriscus scolopax, L., 1910, Station 39 (see Fig. 268).

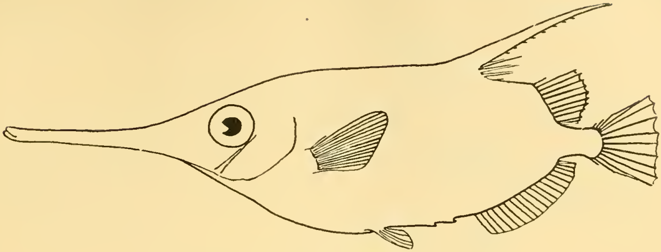


FIG. 268.
Centriscus scolopax, L. Nat. size, 16 cm.

Sub-Order—PERCESOCES

ATHERINIDÆ

Atherina presbyter, Cuv. and Val., 1910, Station 36.

Sub-Order—ANACANTHINI

MACRURIDÆ

Trachyrhynchus trachyrhynchus, Günth., 1910, Stations 4, 23.
Trachyrhynchus murrayi, Günth., 1902, Faroe-Shetland channel; Faroe Bank, 840 metres (see Fig. 269).

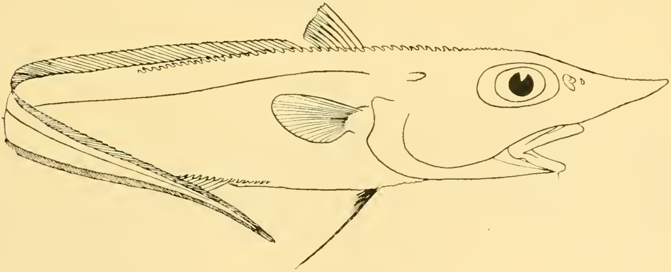


FIG. 269.
Trachyrhynchus murrayi, Günth. (After Günther.)

Macrurus (*Cœlorhynchus*) *talismani*, Collett, 1902, Faroe-Shetland channel; 1910, Stations 4, 24, 41.
Macrurus (*Cœlorhynchus*) *cœlorhynchus*, Risso and Bonap., 1910, Station 21.
Macrurus sclerorhynchus, Val., 1910, Stations 25, 41, 88, 95, 101.
Macrurus æqualis, Günth., 1902, Faroe Bank, 750 metres; 1910, Stations 4, 23, 25, 35, 41 (see Fig. 270).
Macrurus zaniophorus, Vaill., 1910, Stations 4, 41.
Macrurus güntheri, Vaill., 1902, Faroe-Shetland channel.
Macrurus (*Coryphænoides*) *rupestris*, Gunn, 1902, Faroe-Shetland channel; Faroe Bank, 750 to 840 metres.

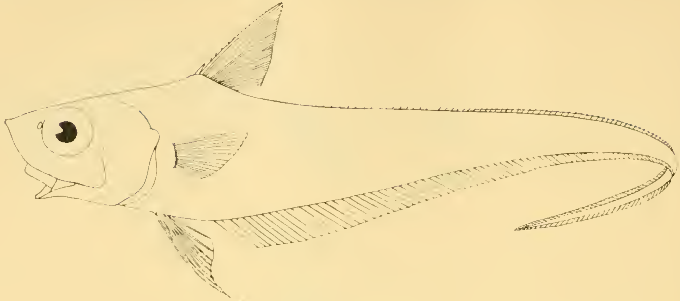


FIG. 270.
Macrurus æqualis, Günth. Nat. size, 23 cm.

Macrurus (*Coryphænoides*) *asperrimus*, Vaill., 1910, Station 41.
Macrurus (*Cetonurus*) *globiceps*, Vaill., 1910, Station 41 (see Fig. 271).

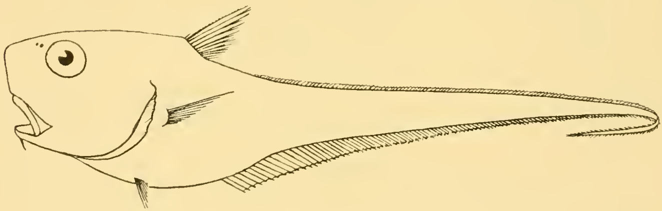


FIG. 271.
Macrurus (*Cetonurus*) *globiceps*, Vaill. (After Vaillant.)

Macrurus (*Chalinura*) *brevibarbis*, G. and B., 1910, Station 10.
Macrurus (*Chalinura*) *murrayi*, Günth., 1910, Stations 25, 95.
Macrurus (*Chalinura*) *simulus*, G. and B., 1910, Station 53.
Macrurus (*Malacocephalus*) *lævis*, Lowe, 1910, Station 21.
Macrurus (*Nematonurus*) *armatus*, Hect., 1910, Stations 10, 35, 53, 88 (see Fig. 272).

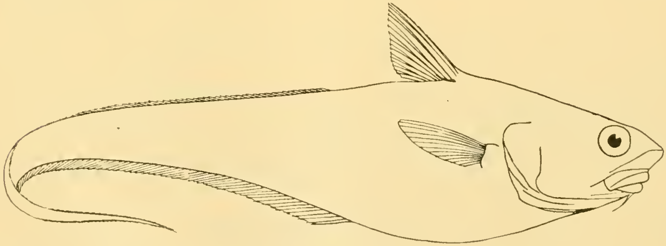


FIG. 272.
Macrurus (*Nematonurus*) *armatus*, Hect. (After Günther.)

Bathygadus longifilis, G. and B., 1910, Stations 23, 24, 41 (see Fig. 273).
Bathygadus melanobranchus, Vaill., 1910, Stations 23, 41.

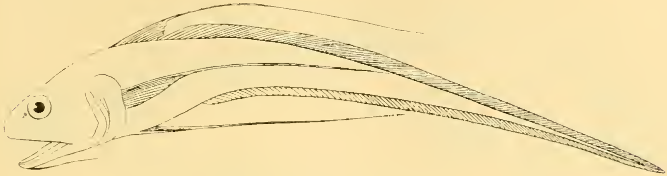


FIG. 273.
Bathygadus longifilis, G. and B. (After Brauer.)

GADIDÆ

Gadus callarias, L. (cod), 1910, Rockall (see Fig. 274).

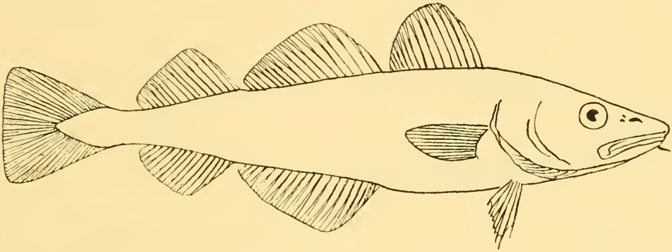


FIG. 274.
Gadus callarias, L. (After Smitt.)

Gadus æglefinus, L. (haddock), 1902, Faroe Bank, 130 metres; 1910, Station 3.
Gadus merlangus, L. (whiting), 1910, Station 14.
Gadus luscus, L. (bib), 1910, Station 14.
Gadus esmarki, Nilss., 1910, Station 1.
Gadus poutassou, Risso, 1910, Stations 1, 3.
Gadiculus argenteus, Guichenot, 1910, Stations 3, 21, 96.
Merluccius vulgaris, Flem. (hake), 1910, Stations 1, 3, 14, 20, 21, 36, 39 (see Fig. 275).

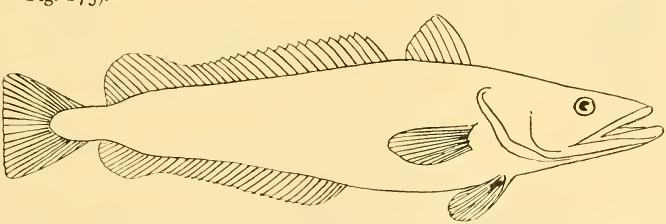


FIG. 275.
Merluccius vulgaris, Flem. (After Smitt.)

Phycis blennioides, Brünn, 1910, Stations 1, 3, 21 (see Fig. 276).

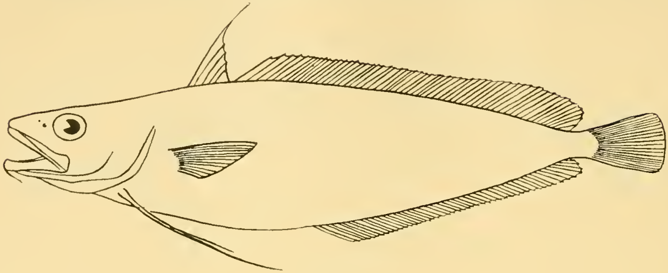


FIG. 276.
Phycis blennioides, Brünn. (After Smitt.)

Molva molva, L. (ling), 1902, Faroe-Shetland channel; Faroe Bank, 350 to 440 metres (see Fig. 277).

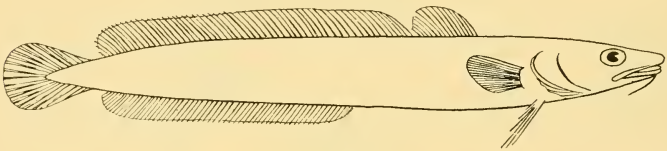


FIG. 277.
Molva molva, L. (After Smitt.)

Molva byrbelange, Walb., 1902, Faroe Bank, 840 metres.
Molva elongata, Risso, 1910, Station 21.
Brosmius brosme, Ascan (tusk), 1902, Faroe-Shetland channel; Faroe Bank, 550 to 440 metres.
Mora mora, Risso, 1902, Faroe Bank, 750 metres; 1910, Stations 4, 23, 41 (see Fig. 278).

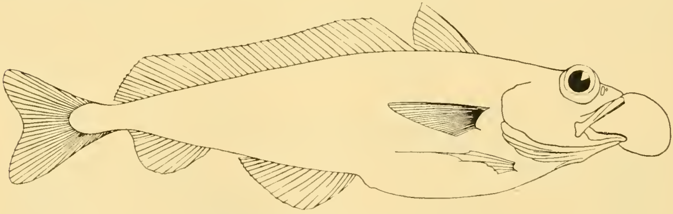


FIG. 278.
Mora mora, Risso. Nat. size, 45 cm.

Antimora viola, G. and B., 1910, Stations 4, 95, 101 (see Fig. 279).
Lepidion eques, Günth., 1902, Faroe-Shetland channel; Faroe Bank, 750 metres; 1910, Station 4 (see Fig. 280).

Halargyreus affinis, Coll., 1902, Faroe-Shetland channel; Faroe Bank, 750 metres (see Fig. 281).

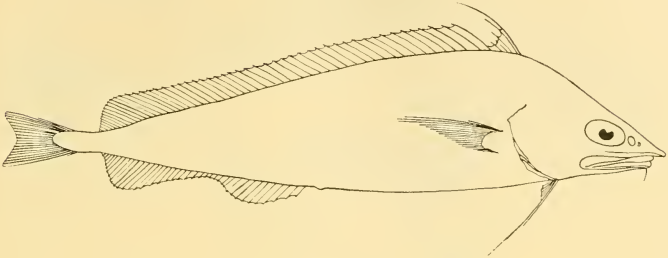


FIG. 279.
Antimora viola, G. and B. (After Günther.)

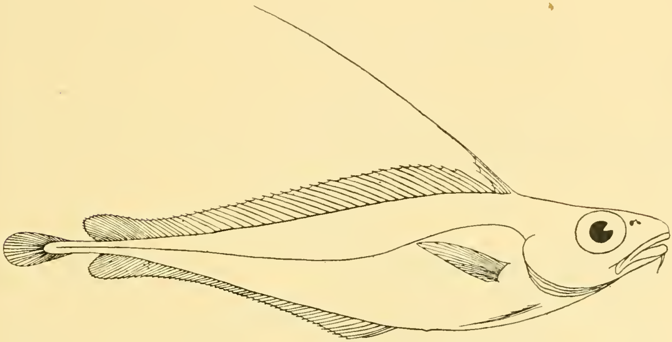


FIG. 280.
Lepidion eques, Günth. (After Günther.)

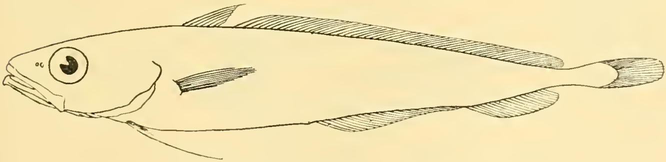


FIG. 281.
Halargyreus affinis, Coll. (After Collett.)

Sub-Order—ACANTHOPTERYGII

Division—PERCIFORMES

BERYCIDÆ

Hoplostethus mediterraneum, Cuv. and Val., 1910, Stations 4, 21 (see Fig. 282).

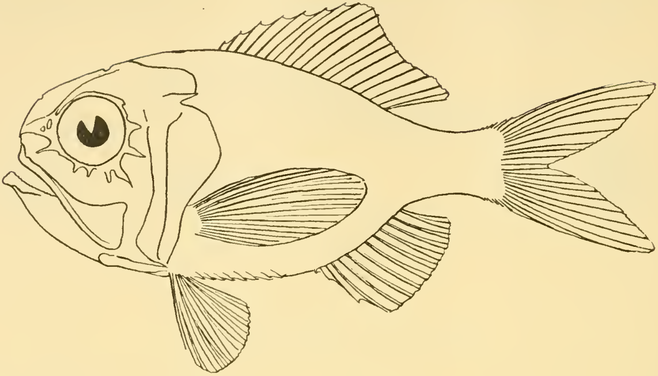


FIG. 282.
Hoplostethus mediterraneum, Cuv. and Val. (After Goode and Bean.

ACROPOMATIDÆ

Epigonus telescopus, Risso, 1902, Faroe Bank, 750 metres.

SERRANIDÆ

Serranus cabrilla, Cuv. and Val., 1910, Station 37 (see Fig. 283).

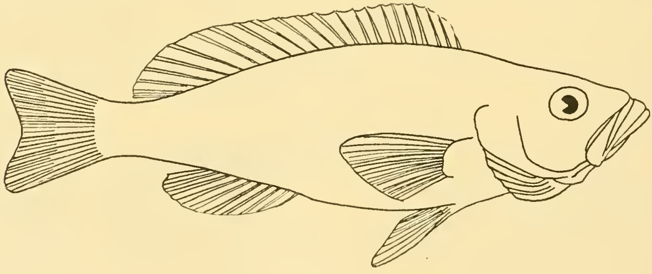


FIG. 283.
Serranus cabrilla, Cuv. and Val. Nat. size, 21 cm.

SCIÆNIDÆ

Sciæna aquila, Risso, 1910, Station 36 (see Fig. 284).
Umbrina ronchus, Val., 1910, Station 36.

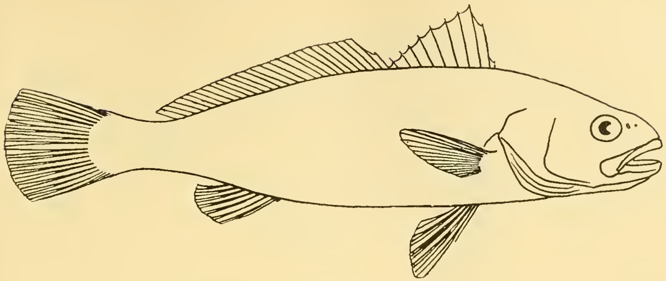


FIG. 284.
Sciæna aquila, Risso. (After Smitt.)

PRISTIPOMATIDÆ

Pristipoma bennettii, Lowe, 1910, Station 36.
Diagramma mediterraneum, Guichenot, 1910, Canary Islands.

SPARIDÆ (Sea-Breams)

Dentex vulgaris, Cuv. and Val., 1910, Canary Islands (see Fig. 285).
Dentex macrophthalmus, Cuv. and Val., 1910, Stations 20, 38, 39.
Dentex maroccanus, Cuv. and Val., 1910, Stations 20, 37 (see Fig. 48, *a*).

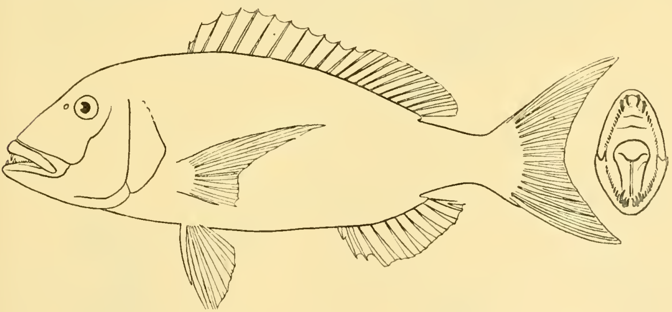


FIG. 285.
Dentex vulgaris, Cuv. and Val. (After Cuvier and Valenciennes.) (The teeth, after Day.)

Cantharus lineatus, Montagu (White), 1910, Canary Islands, Station 37.
Box vulgaris, Cuv. and Val., 1910, Station 36.
Sargus rondeletii, Cuv. and Val., 1910, Canary Islands.
Sargus annularis, Cuv. and Val., 1910, Station 36 (see Fig. 286).
Chrysophrys aurata, Cuv. and Val., 1910, Canary Islands.
Pagrus vulgaris, Cuv. and Val., 1910, Canary Islands, Stations 38, 39 (see Fig. 287).
Pagellus centrodontus, Cuv. and Val., 1910, Stations 13, 20 (see Fig. 288).
Pagellus acarne, Cuv. and Val., 1910, Station 20.

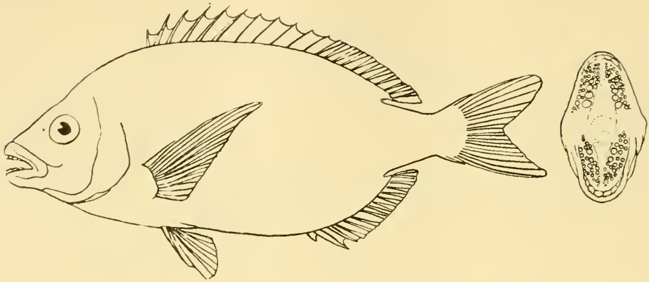


FIG. 286.
Sargus annularis, Cuv. and Val. (After Cuvier and Valenciennes.)

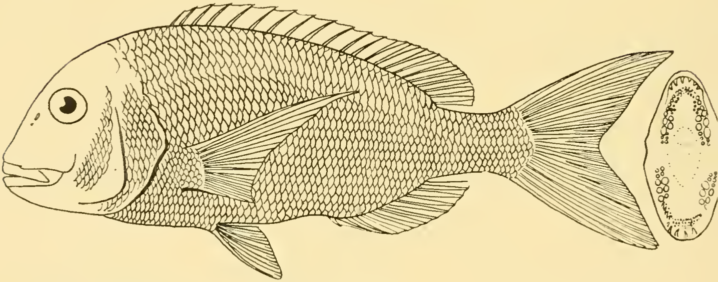


FIG. 287.
Pagrus vulgaris, Cuv. and Val. Nat. size, 50 cm.

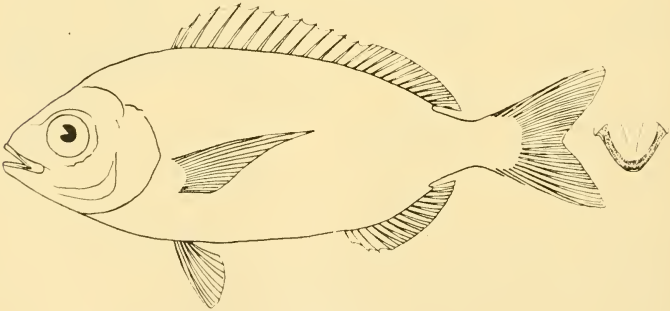


FIG. 288.
Pagellus centrodontus, Cuv. and Val. (After Smitt.)

MULLIDÆ

Mullus surmuletus, L. (red mullet), 1910, Stations 20, 37, 39 (see Fig. 289).