J.R. Pemberton

DEPARTMENT OF THE INTERIOR
FRANKLIN K. LANE, Secretary

UNITED STATES GEOLOGICAL SURVEY
GEORGE OTIS SMITH, Director

PROFESSIONAL PAPER 102

THE INORGANIC CONSTITUENTS OF MARINE INVERTEBRATES

BY

FRANK WIGGLESWORTH CLARKE

AND

WALTER CALHOUN WHEELER

WASHINGTON
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THE INORGANIC CONSTITUENTS OF MARINE INVERTEBRATES.

By Frank Wigglesworth Clarke and Walter Calhoun Wheeler.

INTRODUCTION.

That many important rocks were once marine sediments and that animals and plants shared in their formation is one of the commonplaces of geology. Coralline limestones, shell limestones, and crinoidal limestones are among the most familiar illustrations of this statement. That corals and shells furnish calcium carbonate to the sediments, that radiolarians and diatoms are siliceous, and that vertebrate animals, some crustaceans, and a few brachiopods are more or less phosphatic are also well-known facts, which, however, have been determined in a more or less desultory way. No systematic investigation to ascertain just what substances each class of organisms contributes to the sediments seems to have been made, and the present research is an attempt to cover the ground a little more thoroughly than it has been covered heretofore. Completeness is, of course, impossible, but something of a foundation for future work we have tried to lay.

Although many analyses of corals and molluscan shells are on record, some important groups of organisms have received only slight attention, and little has been done heretofore toward determining the composition of their tests or skeletons. The few published data, moreover, have been generally but not always incomplete in certain important particulars, especially with regard to the localities from which the specimens analyzed were obtained, the depth of water in which each creature lived, and the temperature of its habitat. Even in our own work some of these details are lacking, but their great significance when known is strikingly evident in the study of such groups of animals as the echinoderms and alcyonarians. Furthermore, some of the older analyses are unsatisfactory for other reasons, for many of them were made to determine single facts, such, for instance, as the proportion of magnesium carbonate alone; and in others such important constituents as organic matter were not taken into account, an omission that is especially serious, for it renders the accurate comparison of the analyses with others impossible. In the shells of mollusks the proportion of organic matter is small, but in the echinoderms, alcyonarians, and phosphatic brachiopods it is relatively large, ranging from 10 to even 40 per cent or more. This statement, however, must not be misconstrued; it refers, of course, only to the specimens, dried or alcoholic, which are actually analyzed. In order to compare the analyses, therefore, so as to determine the true composition of the inorganic shells or skeletons, the very variable amounts of organic matter must be rejected, and the remainders recalculated to 100 per cent. Relations then appear which are not recognizable when the crude unreduced analyses are compared. Any one of our tables of analyses will show this fact very clearly.

In a strict sense completeness can not be claimed even for our analyses. Minor constituents which have been detected in shells, corals, and seaweeds, such as lead, copper, and manganese, have been ignored. They occur only in traces and have little or no significance with respect to the larger problem before us. What organisms tend to form limestones and what ones are notably magnesian, phosphatic, or siliceous are the questions which we are attempting to answer. In most of the analyses lime, magnesia, phosphoric oxide, sulphur trioxide, silica, and loss on ignition were determined. Alumina and oxide of iron were also considered and weighed together. The loss on ignition covered carbon dioxide, organic matter, and water. The carbon dioxide was calculated to satisfy the bases, and the amount thus determined, subtracted from the total loss on ignition, gave a fair but rough estimate of organic matter plus water. From the crude analyses thus obtained the reduced or rational analyses, recalculated to 100 per cent, were computed. These rational analyses are comparable, and give, closely enough, the essential composition of the material which goes to build up the limestones. More refined work would add little toward the solution of our main problem and would require much tedious labor. In the following pages the detailed analyses are given, group by group, together with some of the older published data. After the evidence has been presented a general discussion of its significance will be in order. The analyses, except a few that are specified, were made by Mr. Wheeler.

FORAMINIFERA.

The Foraminifera, because of their enormous abundance, are of great importance in the formation of marine sediments. The globigerina ooze, for example, covers 49,520,000 square miles of the ocean floor, at a depth of 1,996 fathoms, or 3,653 meters. The analyses of it published in the report of the *Challenger* expedition on deep-sea deposits show that it consists mainly of calcium carbonate, with very little magnesia. Foraminifera are also abundant on "coral reefs," and great masses of limestone are composed largely of their remains.

These organisms, however, are so small, rarely larger than the head of a pin, that it is not easy to obtain enough material of any one species for chemical analysis. The difficulty, fortunately, is not insuperable, and with the help of others we have been so fortunate as to obtain representative samples of seven species, as follows:

1. *Pulvinulina menardii* D'Orbigny. *Albatross* station 2573; latitude, 40° 34′ 18″ N.; longitude, 66° 09′ W.; in line from Long Island Sound to Cape Sable; depth of water, 3,188 meters; bottom temperature, 3° C.
2. *Sphærodina dehiscens* Parker and Jones. East Coast of Mindanao, Philippine Islands; latitude, 8° 51′ 45″ N., longitude, 126° 26′ 52″ E.; depth of water, 804 meters.
3. *Tinoporus baculatus* Carpenter. Murray Islands, Torres Strait, Australia.
4. *Orbitolites marginalis* Lamarck. South of Tortugas, Fla., at depth of 29.3 meters.
5. *Orbiculina adunca* Fichtel and Moll. Key West, Fla.
6. *Polytrema mineaccum* Linné. Bahamas.
7. *Quinqueloculina auberiana* D'Orbigny. Same locality as No. 4; analysis by A. A. Chambers.

Analyses of Foraminifera.

	1	2	3	4	5	6	7
SiO_2	14.70	8.55	0.03	0.03	0.11	0.02	0.54
$(Al,Fe)_2O_3$	3.81	4.76	.18	.13	.09		
MgO	1.68	.82	5.03	4.93	4.64	5.09	4.32
CaO	41.36	45.48	47.35	48.92	48.79	47.35	49.02
P_2O_5	(?)	(?)	.00	Trace.	Trace.	(?)	
Ignition	38.12	39.01	46.57	45.20	45.56	46.24	45.54
	99.67	98.62	99.16	99.48	99.19	98.70	99.42
CO_2 needed	34.41	36.63	42.74	43.90	43.43	42.80	43.27
Organic matter, etc	3.71	2.38	3.73	1.30	2.13	3.44	2.27

Rejecting organic matter and water and recalculating to 100 per cent, the analyses assume the following rational form:

Reduced analyses.

	1	2	3	4	5	6	7
SiO_2	15.33	8.89	0.03	0.31	0.11	0.02	0.56
$(Al,Fe)_2O_3$	3.98	4.94	.19	.13	.09		
$MgCO_3$	3.67	1.79	11.08	10.55	10.04	11.22	9.33
$CaCO_3$	77.02	84.38	88.70	89.01	89.76	88.76	90.11
$Ca_3P_2O_8$	(?)	(?)	.00	Trace.	Trace.	(?)	(?)
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

In Nos. 1 and 2 the high percentages of silica and sesquioxides are evidently due to impurities. If they are rejected, the percentages of magnesium carbonate become 5.19 and 2.09, respectively. These two Foraminifera are from deep and presumably cold water. The others are from shallow water in warm regions. A similar difference in the magnesian content of the organisms with regard to temperature appears, with much regularity, in several other series of our analyses, notably in the series of crinoids and alcyonarians.

The only published analyses of Foraminifera that we have been able to find elsewhere appear in H. B. Brady's volume[1] on the material collected by the *Challenger* expedition. Four of these analyses relate to *Orbitolites complanata* var. *laciniata*, collected either at Fiji, or at Tongatabu, Friendly Islands. These analyses are as follows:

1, 2. Two different samples; analyses by C. R. A. Wright and J. T. Dunn.
3. Sample washed with boiling water.
4. Same as No. 3, unwashed; analyses 3 and 4 by J. Gibson.

Analyses of orbitolites.

	1	2	3	4
SiO_2	0.58	0.3	0.14	0.11
Al_2O_3 [a]		2.7		
$(Al,Fe)_2O_3$	.68			
$MgCO_3$	12.52	8.8	9.55	10.50
$CaCO_3$	86.46	88.2	88.74	87.91
	100.24	100.0	98.43	98.52

[a] Including "phosphates of lime and magnesia."

Other analyses, presented by Wright and Dunn, are of *Amphistegina lessonii*, from Cape Verde Islands, and *Operculina complanata*, from near Amboyna, in the Malay Archipelago. The analyses are obscurely stated but give from 4.8 to 4.9 per cent of magnesium carbonate. In a Tertiary fossil, *Nubecularia novorossica*, 26 per cent of magnesium carbonate was found, an amount which probably represents a concentration by leaching. There are also analyses of several siliceous Foraminifera containing from 76.1 to 94.7 per cent of silica. Their tests appear to have been built up of sand grains and are of little or no significance in relation to the main problem of the present investigation. Their remains are not true additions to the sediments.

SPONGES.

The sponges are a rather unsatisfactory group of organisms for chemical analysis, on account of their very porous structure. They are liable to contain inclosed impurities, such as sand or mud, which are difficult to remove entirely. Some sponges are siliceous, some calcareous, and others composed almost wholly of organic matter, the proteid spongin. The ideal method of procedure for our purposes would obviously be to separate the clean siliceous or calcareous spicules and to analyze them alone, but to do that a large amount of material would have to be gone over, and more time would be consumed than we could give to this part of our investigation. As the sponges are of minor importance in relation to the marine sediments, we have followed our usual course, and so have obtained results which are of some significance, even if they are not all that might be desired. Twenty sponges have been examined, more or less completely, as follows:

1. *Euplectella speciosa* Quoy and Gaimard ("Venus's flower basket"). Philippine Islands.
2. *Bathydorus uncifer* F. E. Schulze. Galapagos Islands, *Albatross* station 2818; latitude, 0° 29′ S.; longitude, 89° 54′ 30″ W.; depth of water, 617.4 meters; bottom temperature, 9.9° C.
3. *Halichondria panicea* Johnston. Alaska.
4. *Suberites suberea* Johnston. Unga Island and Popoff Strait, Alaska.
5. *Tethya gravata* Hyatt. Buzzards Bay, Mass.
6. *Pheronema grayi* Kent. Off southwest coast of Ireland, at depth of 1,098 meters.

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[1] *Challenger* Report, vol. 9, pp. XVII–XXI, 1884.

7. *Geodia mesotriæna* var. *pachana* Lendenfeld. Off southern California, *Albatross* station 2909; latitude, 32° 22′ N.; longitude, 120° 08′ 30″ W.; depth, 377 meters; bottom temperature, 7.3° C.
8. *Phakellia grandis* Verrill. East part of Browns Bank, nearly east of Cape Cod, between latitudes 40° 30′ and 42° 08′ N. and longitudes 66° to 69° W.; depth, 549 meters.
9. *Chondrocladia alaskensis* Lambe. On beach at Unalaska, Alaska.
10. *Gelliodes grandis* Verrill. Gulf of Maine.
11. *Esperiopsis quatsinoensis* Lambe. Auttu Island, Alaska.
12. *Chalina arbuscula* Verrill. Outer Island, Conn.
13. *Spinosella sororia* var. *crispa* Duchassaing and Michelotti. Harrington Sound, Bermuda.
14. *Euspongia officinalis tubulifera* var. *turrita* Hyatt. Harrington Sound, Bermuda.
15. *Hircinia campana* var. *turrita* Hyatt. Bermuda.
16. *Euspongia officinalis* var. *rotunda* Hyatt. Nassau, Bahama Islands.
17. *Hippospongia equina* var. *meandriformis* Duchassaing and Michelotti. Nassau, Bahamas.
18. *Hippospongia agaricina* var. *dura* Hyatt. Off Duck Key, Florida, at depth of 4.6 meters.
19. *Hippospongia caniculata* var. *gossypina* Duchassaing and Michelotti. Off Rock Island, Florida, at depth of 7.3 meters.
20. *Aplysina hirsuta* Hyatt. Off St. Thomas, Danish West Indies; depth of water, 37 to 42 meters.

The analyses, made by our usual methods, are as follows:

Analyses of sponges.

	1	2	3	4	5	6	7	8
SiO_2	88.56	76.33	74.52	72.92	68.46	65.19	64.96	60.70
$(Al,Fe)_2O_3$	.32	1.05	6.19	1.22	3.71	3.05	.21	2.30
MgO	.00	.48	1.43	.55	.61	Trace.	.38	.23
CaO	.22	2.78	2.33	.33	.89	3.26	.29	.51
P_2O_5	.00	.00	.17	.49	.48	Trace.	Trace.	.46
SO_3	.00	Trace.	.08	.39	.40	.02	.21	(?)
Ignition	10.26	18.60	12.11	22.21	23.02	27.05	31.73	35.84
	99.36	99.24	96.83	98.11	97.57	98.57	97.78	100.04

	9	10	11	12	13	14	15
SiO_2	53.96	52.24	51.94	31.93	3.08	1.31	0.57
$(Al,Fe)_2O_3$	1.64	3.86	1.38	1.44	.77	.96	2.29
MgO	.58	.86	.75	.97	.26	.43	1.60
CaO	1.28	.77	1.77	.97	2.80	7.58	20.01
P_2O_5	.31	.61	.46	.50	.69	.77	.68
SO_3	(?)	.81	(?)	.82	(?)	(?)	(?)
Ignition	41.97	34.64	42.29	61.25	91.32	89.75	75.68
	99.74	93.79	98.59	97.88	98.92	100.80	100.83

Sponges Nos. 16–20 were composed mainly of organic matter, and only loss on ignition was determined. The figures showing this loss are as follows:

	Per cent.
16. *Euspongia officinalis*	96.94
17. *Hippospongia equina*	96.98
18. *Hippospongia agaricina*	95.55
19. *Hippospongia caniculata*	94.72
20. *Aplysina hirsuta*	93.84

In these sponges the inorganic matter is so small that it may only represent impurities, an analysis of which would be meaningless. *Euspongia* and *Hippospongia* are the ordinary bath sponges of commerce.

In several of the analyses, notably in Nos. 3, 5, 7, 10, and 12, the summation is very low, on account of the presence of soluble salts (sea salt), which were not determined. Analyses 1 to 12 represent siliceous sponges, and in Nos. 2 and 6 the siliceous spicules are very conspicuous. No. 1, *Euplectella*, the beautiful "Venus's flower basket," may be taken as the type of these sponges, and its analysis shows that its skeleton is nearly pure opaline silica. Several analyses of siliceous sponge spicules by other chemists lead to similar conclusions. In spicules from unnamed species J. Thoulet[1] found from 12.88 to 13.18 per cent of water, F. E. Schulze[2] cites an analysis by Maly of spicules from *Poliopogon amadou* which contained 7.16 per cent, and in seven species of siliceous sponges W. J. Sollas[3] found water varying from 6.1 to 7.34 per cent. In all these sponges the spicules or skeletons are composed of amorphous opaline silica. The other constituents shown in our analyses, except organic matter, which is included in the loss on ignition, are probably but not certainly impurities. To this statement one exception may be made. The phosphoric oxide is perhaps a part of the organisms, which contain it not as such but as phosphorus in some organic compound. This, however, is by no means certain. That all the sponges analyzed contain phosphorus in some form, although in small amounts, is clear.

Analysis No. 13, of *Spinosella*, is very high in organic matter, and its precise character is doubtful, at least so far as the chemical evidence goes. Nos. 14 and 15, however, of *Euspongia* and *Hircinia* represent calcareous sponges. Reducing the analyses to standard form, rejecting organic matter, and recalculating to 100 per cent, we have the following figures for their inorganic portions:

Reduced analyses of calcareous sponges.

SiO_2	7.81	1.36
$(Al,Fe)_2O_3$	5.72	5.45
$MgCO_3$	5.37	8.00
$CaCO_3$	71.14	81.64
$Ca_3P_2O_8$	9.96	3.55
$CaSO_4$	(?)	(?)
	100.00	100.00

We can not assign much weight to these reductions, because of the apparent impurities in the specimens analyzed. The presence of magnesia, however, in these sponges is somewhat confirmed by an analysis by O. Bütschli[4] of spicules from a Mediterranean sponge, *Leucandra aspera*. His figures are as follows:

$CaCO_3$	86.76
$MgCO_3$	6.84
Fe_2O_3	.26
$CaSO_4.2H_2O$	1.97
H_2O	3.14
Organic matter	.42
	99.39

If we reject water and organic matter and recalculate to 100 per cent the percentage of magnesium carbonate rises to 7.17. It seems probable, then, that the calcareous sponges are distinctly magnesian, although more analyses are needed to establish the fact.[5]

MADREPORARIAN CORALS.

Madreporarian or stony corals have been repeatedly analyzed and with generally concordant results. Twenty-eight of these corals were studied in the course of this investigation, and with the results two old analyses made in the laboratory of the United States Geological Survey may properly be included. The order of arrangement here is regional, for reasons which will appear later, in our study of the alcyonarians. The list of corals analyzed is as follows:

1. *Balanophyllia floridana* Pourtalès. South of Key West, Fla.; depth of water, 165 meters.
2. *Paracyathus defilipii* Duchassaing and Michelotti. South of Key West; depth, 165 meters.
3. *Dendrophyllia cornucopia* Pourtalès. *Fish Hawk* station 7286. Gulf Stream, off Key West; latitude, 24° 18′ 00″ N.; longitude, 81° 47′ 45″ W.; depth, 243 meters; bottom temperature, 11.9° C.

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[1] Compt. Rend., vol. 98, p. 1000, 1884.

[2] *Challenger* Report, vol. 21, p. 28, 1887.

[3] *Challenger* Report, vol. 25, p. xlviii, 1888.

[4] K. Gesell. Wiss. Göttingen Abh., No. 3, 1908.

[5] On manganese and iron in sponges, see Cotte, J., Soc. biologie Compt. rend., vol. 55, p. 139, 1903. Traces of manganese were noted in our own analyses.

4. *Siderastrea radians* Pallas. Shoal water, Ragged Keys, Fla.
5. *Porites furcata* Lamarck. Shoal water, Ragged Keys, Fla.
6. *Favia fragum* Esper. Shoal water, Tortugas, Fla.
7. *Eusmilia aspera* Dana. Shoal water, Tortugas, Fla.
8. *Oculina diffusa* Lamarck. Shoal water, Tortugas, Fla.
9. *Cladocora arbuscula* Lesueur. Tortugas, Fla.; depth, 27.5 meters.
10. *Agaricia purpurea* Lesueur. Reef, Loggerhead Key, Tortugas, Fla.
11. *Orbicella annularis* Ellis and Solander. Reef, Loggerhead Key, Fla.
12. *Dasmosmilia lymani* Pourtalès. *Albatross* station 2087; latitude, 40° 06′ 50″ N.; longitude 70° 34′ 15″ W.; depth, 119 meters; bottom temperature, 10° C.
13. *Flabellum alabastrum* Moseley. *Albatross* station 2677; latitude, 32° 39′ N.; longitude, 76° 50′ 30″ W.; between the Bahamas and Cape Fear; depth, 875 meters; bottom temperature, 4.5° C.
14. *Madrepora prolifera* Linné. *Albatross* stations 2662–2672, between the Bahamas and Cape Fear; depth, 512–894 meters; bottom temperature, 6°–7° C.
15. *Dendrophyllia profunda* Pourtalès. Locality, etc., as under No. 14.
16. *Madracis decactis* Lyman. Shoal water, Bermuda.
17. *Deltocyathus italicus* Michelotti. *Albatross* station 2750; latitude, 18° 30′ N.; longitude, 63° 31′ W.; depth, 908 meters; bottom temperature, 7° C.
18. *Acropora cervicornis* Lamarck. Shoal water, South Bight, Bahamas.
19. *Orbicella cavernosa* Linné. Reef, Light House Point, Andros Island, Bahamas.
20. *Mæandra clivosa* Ellis and Solander. Locality as under No. 19.
21. *Mæandra labyrinthiformis* Linné. Reef, Golding Cay, Andros Island, Bahamas.
22. *Mussa* aff. *M. dipsacea* Dana. Reef, Golding Cay.
23. *Porites clavaria* Lamarck. Reef, Golding Cay.
24. *Porites astreoides* Lamarck. Reef, Golding Cay.
25. *Flabellum pavonium* var. *paripavoninum* Alcock. *Albatross* station 4080; north coast of Maui, Hawaiian Islands; depth, 326 to 369 meters; bottom temperature, 13.5° C.
26. *Madracis kauaiensis* Vaughan. *Albatross* station 3982; vicinity of Kauai, Hawaiian Islands; depth, 426–435 meters; bottom temperature, 9.1° C.
27. *Flabellum* sp. *Albatross* station 5273; latitude, 14° 03′ N.; longitude, 120° 27′ 45″ E.; China Sea, near southern Luzon; depth, 102.5 meters.
28. *Desmophyllum ingens* Moseley. *Albatross* station 2785; latitude, 48° 09′ S.; longitude, 74° 36′ W.; off coast of Chile; depth, 822 meters; bottom temperature, 8.3° C.

The actual analyses appear in the following tables. Sulphates were rarely determined, but they are unimportant.

Analyses of corals.

	1	2	3	4	5	6	7
SiO_2	0.09	0.42	0.09	0.12	0.11	0.28	0.00
$(Al,Fe)_2O_3$	.69	.35	.11	.11	.10	.12	.04
MgO	.49	.39	.19	.21	.36	.18	.21
CaO	51.46	52.03	51.71	51.23	51.61	53.69	53.25
SO_3	(?)	.00	(?)	(?)	(?)	(?)	(?)
P_2O_5	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
Ignition	47.32	44.62	46.23	47.21	46.76	44.44	44.90
	100.05	97.81	98.33	98.88	98.94	98.71	98.40
CO_2 needed	39.97	41.31	40.84	41.48	40.95	42.38	42.08
Organic matter, etc	7.35	3.31	5.39	5.73	5.81	2.06	2.82

	8	9	10	11	12	13	14
SiO_2	0.07	0.30	0.04	0.00	0.20	0.09	0.19
$(Al,Fe)_2O_3$	.05	.08	.00	.03	.27	.11	.07
MgO	.19	.05	.28	.27	.29	.17	.06
CaO	53.90	53.31	53.87	53.58	53.79	53.54	53.48
SO_3	(?)	(?)	(?)	(?)	.10	(?)	.12
P_2O_5	Trace.	Trace.	.00	.00	Trace.	Trace.	Trace.
Ignition	44.57	44.83	44.62	44.76	44.47	44.80	44.50
	98.78	98.57	98.81	98.64	99.12	98.71	98.42
CO_2 needed	42.56	41.94	42.64	42.40	42.52	42.26	42.03
Organic matter, etc	2.01	2.89	1.98	2.36	1.95	2.54	2.47

Analyses of corals—Continued.

	15	16	17	18	19	20	21
SiO_2	0.33	0.04	0.21	0.00	0.09	0.02	0.00
$(Al,Fe)_2O_3$	.07	.13	.25	.06	.00	.04	.04
MgO	.05	.34	.25	.20	.35	.34	.26
CaO	53.83	52.78	53.38	52.47	53.07	53.70	53.71
SO_3	(?)	(?)	(?)	(?)	(?)	(?)	(?)
P_2O_5	Trace.	Trace.	Trace.	Trace.	.00	.00	Trace.
Ignition	44.49	45.33	44.49	45.77	45.23	45.33	45.10
	98.77	98.62	98.58	98.50	98.74	99.43	99.11
CO_2 needed	42.35	41.84	42.41	41.45	42.09	42.56	42.49
Organic matter, etc	2.14	3.49	2.28	4.32	3.14	2.77	2.61

	22	23	24	25	26	27	28
SiO_2	0.14	0.04	0.02	0.40	0.06	0.07	0.13
$(Al,Fe)_2O_3$	.05	.09	.02	.53	.11	.15	.06
MgO	.04	.17	.18	.20	.15	.17	.27
CaO	53.34	52.12	53.84	53.22	53.25	52.94	53.69
SO_3	(?)	(?)	(?)	(?)	(?)	(?)	(?)
P_2O_5	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
Ignition	44.81	45.84	44.98	44.31	44.80	45.28	44.64
	98.38	98.26	99.04	98.66	98.37	98.61	98.79
CO_2 needed	41.95	41.14	42.50	42.04	42.81	41.79	42.48
Organic matter, etc	2.86	3.70	2.48	2.27	1.99	3.49	2.16

The two other analyses of corals, which were made some years ago in the Survey laboratory, do not appear in the foregoing table because they are stated in somewhat different form. They are, however, included in the following table of reduced analyses, in which the figures are recalculated to 100 per cent and as definite salts, with organic matter and water rejected. The two in question are as follows:

29. *Siderastrea* sp. Bermuda; analysis by L. G. Eakins.
30. Coral, species undetermined. Panama; analysis by W. T. Schaller.

Reduced analyses.

	1	2	3	4	5	6
SiO_2	0.10	0.44	0.10	0.13	0.12	0.29
$(Al,Fe)_2O_3$	.74	.37	.12	.12	.11	.12
$MgCO_3$	1.11	.87	.43	.48	.82	.39
$CaCO_3$	98.05	98.32	99.35	99.27	99.95	99.20
$CaSO_4$	(?)	.00	(?)	(?)	(?)	(?)
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00

	7	8	9	10	11	12
SiO_2	0.00	0.07	0.31	0.04	0.00	0.21
$(Al,Fe)_2O_3$	.04	.05	.08	.00	.03	.28
$MgCO_3$	.46	.41	.11	.61	.59	.63
$CaCO_3$	99.50	99.47	99.50	99.35	99.38	98.71
$CaSO_4$	(?)	(?)	(?)	(?)	(?)	.17
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	.00	.00	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00

Reduced analyses—Continued.

	13	14	15	16	17	18
SiO_2	0.09	0.20	0.34	0.04	0.22	0.00
$(Al,Fe)_2O_3$	.12	.07	.07	.14	.26	.06
$MgCO_3$	.37	.14	.12	.76	.54	.45
$CaCO_3$	99.42	99.38	99.47	99.06	98.98	99.49
$CaSO_4$	(?)	.21	(?)	(?)	(?)	(?)
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00

	19	20	21	22	23	24
SiO_2	0.10	0.02	0.00	0.15	0.04	0.02
$(Al,Fe)_2O_3$	.00	.04	.04	.05	.10	.02
$MgCO_3$	.77	.73	.57	.09	.37	.40
$CaCO_3$	99.13	99.21	99.39	99.71	99.49	99.56
$CaSO_4$	(?)	(?)	(?)	(?)	(?)	(?)
$Ca_3P_2O_8$	.00	.00	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00

	25	26	27	28	29	30
SiO_2	0.41	0.06	0.07	0.14	0.23	1.25
$(Al,Fe)_2O_3$	.55	.11	.15	.06	Trace.	.59
$MgCO_3$	.43	.33	.37	.59	.42	.59
$CaCO_3$	98.61	99.50	99.41	99.21	99.35	97.57
$CaSO_4$	(?)	(?)	(?)	(?)	(?)	(?)
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	(?)	(?)
	100.00	100.00	100.00	100.00	100.00	100.00

These analyses are remarkably concordant and show that the stony corals contain little besides calcium carbonate. Silica and sesquioxides are probably extraneous; magnesia is altogether subordinate, although fairly regular in its amount; phosphates occur only in traces. The older analyses all tell the same story, except that in six analyses by S. P. Sharples[1] of corals from the Gulf Stream from 0.27 to 0.84 per cent of calcium phosphate was determined. In five analyses of Brazilian corals, L. R. Lenox[2] found from 0.42 to 0.54 per cent of magnesium carbonate, quantities like those appearing in our tables. In short, the uniformity of the data is so marked that it is unnecessary to reproduce all the published analyses here.[3]

ALCYONARIAN CORALS.

The alcyonarians, which include the red corals, the gorgonias, or sea fans, and other similar, generally branching forms, differ from the madrepores in being notably magnesian. To this rule one exception is known, the genus *Heliopora,* which stands quite alone and resembles the ordinary corals not only in structure but also in chemical composition.[4] With this exception, the alcyonaria are chemically similar to the crinoids, but some genera are much richer in phosphates. In some respects the alcyonarians are difficult to deal with analytically, for many of them have a horny axis, composed chiefly of organic matter, surrounded by a cortex or envelope

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[1] Am. Jour. Sci., 3d ser., vol. 1, p. 168, 1871.

[2] Mus. Comp. Zool. Bull., vol. 44, p. 264, 1904. In a memoir by J. C. Branner on sandstone reefs.

[3] See also B. Silliman, jr., Am. Jour. Sci., 2d ser., vol. 1, p. 189, 1846, for 31 analyses of corals from the South Pacific and the Indian Ocean; G. Forchhammer, Neues Jahrb., 1852, p. 854, on magnesia in shells and corals; H. W. Nichols, Field Columbian Mus., Pub. 111, p. 31, 1906; also four determinations of magnesia. In *Cœlaria dædalea* from Abyssinia he found 0.35 per cent of $MgCO_3$. A. G. Högbom, Neues Jahrb., 1894, Band 1, p. 262, in two Bermuda corals found 0.36 and 0.62 per cent of $MgCO_3$.

[4] See H. W. Moseley, Philos. Trans., vol. 166, p. 91, 1876, on the structural relations of *Heliopora.*

which is largely calcareous. These two portions of the structure are so unlike in composition that imperfections in a sample taken for analysis may lead to very uncertain conclusions.

The list of alcyonarians analyzed is as follows:

1. *Heliopora cerulea* Pallas; blue coral. Southern Philippines. The blue color consists of organic matter.[1]
2. *Tubipora purpurea* Lamarck. Singapore, Straits Settlements; latitude, 1° 20′ N.; longitude, 103° 50′ E.
3. *Corallium elatior* Ridley; a red coral. Murotsu, Tosa (Shikoku), Japan; latitude, about 33° N.
4. *Primnoa reseda* Verrill. East of Nova Scotia; depth of water, 366 meters; latitude, 42° 16′ N.; longitude, 63° 15′ W.
5. *Lepidisis caryophyllia* Verrill. Off Nantucket Shoals, *Albatross* station 2037; latitude, 38° 53′ 00″ N.; longitude, 69° 23′ 30″ W.; depth, 3,168 meters; bottom temperature, 3.3° C.
6. *Pennatula aculeata* Dana. St. Peters Bank and Banquereau; *Albatross* station 2470; latitude, 44° 47′ N.; longitude, 56° 33′ 45″ W.; depth, 410 meters; bottom temperature, 4.5° C.
7. *Paramuricea borealis* Verrill. Southwest edge of the Grand Banks; depth, 641 to 732 meters.
8. *Paragorgia arborea* Milne-Edwards and Haime. La Have Ridge, off Nova Scotia.
9. *Alcyonium carneum* L. Agassiz. Southwest of Stellwagen Bank, off Race Point Light, Cape Cod, Mass.; depth, 57 meters; bottom temperature, 3.9° C.
10. *Gorgonia suffruticosa* Dana. Fiji Islands. Cortex and axis together.
11. *Gorgonia acerosa* Pallas. East end of Long Cay, Nassau, Bahamas; latitude, 25° 5′ 6″ N. Cortex and axis.
12. *Gorgonia acerosa.* Cæsars Creek, southern Florida; latitude, 23° 30′ N., approximately. Cortex alone.
13. *Muricea humilis* Milne-Edwards. Parahyba do Norte, Brazil; latitude, 7° to 8° S.
14. *Muricea echinata* Valenciennes. Cape San Lucas, Lower California; latitude, 22° 52′ N.
15. *Plexaurella grandiflora* Verrill. Mar Grande, Bahia, Brazil.
16. *Ctenocella pectinata* Valenciennes. Torres Straits, Australia; latitude, about 10° S.
17. *Xiphogorgia anceps* Pallas. Cæsars Creek, southern Florida; latitude 23° 30′ N., approximately.
18. *Rhipidogorgia flabellum* Linné. Bermuda; latitude, about 32° N.
19. *Rhipidogorgia flabellum.* East side of Andros Island, Bahamas; latitude, about 25° N.
20. *Leptogorgia pulchra* Verrill. La Paz, Gulf of California; latitude, 24° 16′ N.
21. *Leptogorgia rigida* Verrill. Cape San Lucas, Lower California; latitude, 22° 52′ N.
22. *Phyllogorgia quercifolia* Dana. Fernando de Noronha, Brazil; latitude, 3° 50′ S.; longitude, 32° 25′ W.

Analyses of alcyonarians.

	1	2	3	4	5	6	7	8
SiO_2	0.14	1.36	0.00	0.09	0.11	1.21	0.26	0.13
$(Al,Fe)_2O_3$	.07	.55	.14	.64	.05	.72	.18	.02
MgO	.16	5.67	5.44	2.15	3.16	2.62	2.27	3.71
CaO	54.42	46.60	48.65	37.76	49.87	35.67	29.92	43.47
SO_3	.29	.68	.77	.71	.37	.35	1.64	1.10
P_2O_5	Trace.	Trace.	.18	.28	Trace.	1.02	.39	.22
Ignition	44.33	44.75	46.01	57.58	45.70	59.26	77.32	50.48
	99.41	99.61	101.19	99.21	99.26	100.85	100.98	99.13
CO_2 needed	42.78	42.48	42.87	31.38	42.43	29.76	24.74	37.44
Organic matter, etc	1.55	2.27	3.14	26.20	3.27	29.50	41.58	13.04

	9	10	11	12	13	14	15
SiO_2	6.84	0.26	0.13	0.03	0.44	0.09	0.38
$(Al,Fe)_2O_3$	2.20	.13	.13	.13	.06	.05	.13
MgO	1.66	3.03	3.54	3.51	5.25	4.58	5.61
CaO	14.04	22.32	28.73	26.48	42.14	38.04	40.94
SO_3	.31	1.51	.68	1.33	.89	1.35	Trace.
P_2O_5	2.32	.10	.99	.73	.24	.30	Trace.
Ignition	72.24	71.46	62.34	63.49	51.59	54.09	52.49
	99.61	100.81	96.54	95.70	100.61	98.50	99.55
CO_2 needed	10.34	19.94	25.17	23.26	38.13	33.91	38.34
Organic matter, etc	61.70	51.52	37.17	40.23	13.43	20.18	14.15

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[1] See Moseley, H. W., op. cit., and Bourne, G. C., Philos. Trans., vol. 186, p. 455, 1895.

The low summation of Nos. 11 and 12 is due to inclosed or adherent sea salts. In No. 12 the amount of water-soluble matter was determined and proved to be 4.71 per cent, of which 0.55 per cent was SO_3. Applying these corrections to the analysis the summation becomes 99.96.

	16	17	18	19	20	21	22
SiO_2	0.17	0.08	0.12	0.16	0.06	0.21	0.26
$(Al,Fe)_2O_3$	.10	.04	.16	.06	.02	.16	.19
MgO	5.90	3.52	3.42	4.22	4.60	5.14	5.59
CaO	37.05	27.19	27.41	32.23	33.59	36.15	34.62
SO_3	.79	1.28	.80	1.17	1.21	.93	.93
P_2O_5	.32	.51	.28	.86	2.67	2.78	2.97
Ignition	56.15	65.56	65.67	62.10	55.89	55.39	55.28
	100.48	98.18	97.86	100.80	98.04	100.76	99.84
CO_2 needed	34.87	24.07	25.60	28.51	28.31	30.96	34.14
Organic matter, etc	21.28	41.49	40.07	33.59	27.58	24.43	21.14

The reduced or rational analyses are as follows:

Reduced analyses.

	1	2	3	4	5	6	7	8
SiO_2	0.15	1.40	0.00	0.13	0.11	1.70	0.44	0.15
$(Al,Fe)_2O_3$	.07	.57	.15	.88	.05	1.01	.30	.03
$MgCO_3$	.35	12.23	11.56	6.18	6.92	7.71	8.03	9.05
$CaCO_3$	98.93	84.61	86.57	90.39	92.24	85.62	85.11	88.04
$CaSO_4$	.50	1.19	1.32	1.59	.68	.84	4.69	2.17
$Ca_3P_2O_8$	Trace.	Trace.	.40	.83	Trace.	3.12	1.43	.56
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

	9	10	11	12	13	14	15
SiO_2	18.05	0.55	0.22	0.04	0.50	0.11	0.45
$(Al,Fe)_2O_3$	5.80	.28	.22	.24	.07	.06	.15
$MgCO_3$	9.21	13.43	12.52	13.29	12.64	12.28	13.79
$CaCO_3$	52.23	79.84	81.45	79.48	84.47	83.79	85.61
$CaSO_4$	1.36	5.43	1.95	4.08	1.73	2.93	Trace.
$Ca_3P_2O_8$	13.35	.47	3.64	2.87	.54	.83	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

	16	17	18	19	20	21	22
SiO_2	0.21	0.14	0.21	0.24	0.09	0.28	0.34
$(Al,Fe)_2O_3$	.13	.07	.28	.07	.03	.21	.26
$MgCO_3$	15.65	13.04	12.64	13.19	13.71	14.13	15.73
$CaCO_3$	81.44	80.96	83.38	80.75	74.99	75.36	72.99
$CaSO_4$	1.69	3.83	2.40	2.95	2.91	2.07	2.11
$Ca_3P_2O_8$	.88	1.96	1.09	2.80	8.27	7.95	8.57
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Analysis No. 1, that of *Heliopora,* might be an analysis of an ordinary coral, being nearly nonmagnesian and hence different from all the others. The material of No. 9, *Alcyonium carneum,* was obviously very impure, containing much admixture of sand or mud. That the species is remarkably rich in calcium phosphate, however, seems to be clear. It needs further investigation upon better material.

In two of the *Gorgonias* the black wiry axis was separately analyzed, although the amount of material was very small. The axis of a *Rhipidogorgia* sp. from Bermuda was also studied and to better advantage. The three analyses are as follows:

	Gorgonia acerosa.	Gorgonia suffruticosa.	Rhipidogorgia?.
SiO_2	0.04	0.39	0.07
$(Al,Fe)_2O_3$	.10	.06	Trace.
MgO	.71	.80	1.03
CaO	.53	1.10	.50
P_2O_5	.31	Trace.	.15
SO_3	.94	1.65	1.90
Ignition	96.45	94.39	95.83
	99.08	98.39	99.48

The axes, evidently, are composed largely of organic matter, and the inorganic portions differ in composition from the more abundant calcareous envelopes. In two of them magnesia is in excess of lime, and in all three the sulphates are conspicuous. To determine the exact chemical nature of these axes would require much material and a longer investigation than we are justified in attempting.

A specimen of *Leptogorgia flammea* Verrill, from the Cape of Good Hope, was also examined, but it was not sufficiently perfect. Much of the cortex had been broken away, leaving an excess of the axis. The partial results obtained, however, showed an exceedingly high proportion of phosphates, and a complete study of the species is much to be desired. Indeed, the genus *Leptogorgia* well deserves an exhaustive investigation, but perhaps more on biological than on geological grounds. The fact that it contributes both magnesium carbonate and calcium phosphate to the marine sediments seems to be established.

Several other analyses of alcyonarians, partial or complete, are on record, and three of them deserve reproduction here. The data are as follows:

1. *Pleurocorallium johnsoni* Gray. From latitude 25° 45′ N., longitude 20° 12′ W., about 160 miles southwest of the Canary Islands; depth of water, 2,791 meters. At that depth the temperature must have been very low, probably not much above 0° C. Analysis by Anderson in *Challenger* Report, Deep-sea Deposits, p. 465, 1891.
2. *Alcyonium palmatum.* Probably Mediterranean.
3. *Corallium rubrum;* the precious red coral. Mediterranean.

Analyses 2 and 3 by O. Bütschli in K. Gesell. Wiss. Göttingen Abh., No. 3, 1908.

Older analyses of alcyonarians.

	1	2	3
$CaCO_3$	93.39	86.25	86.78
$MgCO_3$	6.00	9.38	8.97
"Phosphate"		1.00	.70
$Ca_3P_2O_8$	.10		
Fe_2O_3			
$CaSO_4.2H_2O$		1.15	1.55
SiO_2 or sand	Trace.	1.36	
H_2O	.30	.82	1.46
Organic matter		.37	.06
Insoluble	.05		
	99.84	100.33	99.32

The reduced analyses, rejecting obvious impurities, are as follows:

Reduced analyses.

	1	2	3
SiO_2	Trace.		
Fe_2O_3	(?)		
$MgCO_3$	6. 03	9. 63	9. 18
$CaCO_3$	93. 87	88. 42	88. 84
$CaSO_4$		. 93	1. 26
$Ca_3P_2O_8$	. 10	1. 02	. 72
	100. 00	100. 00	100. 00

That these analyses fit well into our own series is evident.

In a worked specimen of *Corallium rubrum*, H. W. Nichols found 9.32 per cent of magnesium carbonate, not far from Bütschli's figure. In *Eunicea tourneforti* and *Plexaurella dichotoma*, both from the Bahamas, he found, respectively, 2.78 and 2.11 per cent. These percentages, however, are based on crude material; that is, without rejection of organic matter and water. They are, therefore, unavailable for comparison with our reduced analyses. Three similar analyses by G. Forchhammer[1] are also recorded, of *Tubipora musica*, *Corallium nobile* (= *C. rubrum*), and *Isis hippuris*, which gave, respectively, 3.83, 2.73, and 6.36 per cent of magnesium carbonate. These data lack sufficiently explicit details to admit of comparison with ours. Why his figure for the red coral is so low is not clear. The material taken for analysis must have been quite different from that used by Nichols or Bütschli. A still earlier analysis of red coral by Witting[2] gave 3.50 per cent of magnesium carbonate. The specimen analyzed, however, contained about 12 per cent of impurities.

If, now, we arrange the alcyonarians in the order of ascending magnesium carbonate, a remarkable relation connecting composition with temperature appears. *Heliopora*, being anomalous, is not included in the table. *Alcyonium carneum* is also excluded on account of its impurities. The three analyses by Anderson and Bütschli are, however, inserted. Localities and latitudes are abbreviated. The percentages of magnesium carbonate are from the reduced analyses, and those of calcium phosphate are also given.

Magnesium carbonate and calcium phosphate in alcyonarians.

Species.	Locality.	Latitude.	$Ca_3P_2O_8$.	$MgCO_3$.
Pleurocorallium johnsoni	Atlantic	25° 45′ N	0. 10	6. 03
Primnoa reseda	Nova Scotia	42° 16′ N	. 83	6. 18
Lepidisis caryophyllia	Off Nantucket	38° 33′ N	Trace.	6. 92
Pennatula aculeata	Atlantic	44° 47′ N	3. 12	7. 71
Paramuricea borealis	Grand Banks		1. 43	8. 03
Paragorgia arborea	Nova Scotia		. 56	9. 05
Corallium rubrum	Mediterranean		. 72	9. 18
Alcyonium palmatum	Mediterranean?		1. 02	9. 63
Corallium elatior	Japan	33° N	. 40	11. 56
Tubipora purpurea	Singapore	1° 20′ N	Trace.	12. 23
Muricea echinata	Cape San Lucas	22° 52′ N	. 83	12. 28
Gorgonia acerosa	Bahamas	25° 5′ N	3. 64	12. 52
Muricea humilis	Brazil	7°–8° S	. 59	12. 64
Rhipidogorgia flabellum	Bermuda	32° N	1. 09	12. 64
Xiphogorgia anceps	Florida	23° 30′ N	1. 96	13. 04
Rhipidogorgia flabellum	Bermuda	25° N	2. 80	13. 19
Gorgonia acerosa	Florida	23° 30′ N	2. 87	13. 29
Gorgonia suffruticosa	Fiji		. 47	13. 43
Leptogorgia pulchra	Lower California	24° 16′ N	8. 27	13. 71
Plexaurella grandiflora	Brazil		Trace.	13. 79
Leptogorgia rigida	Cape San Lucas	22° 52′ N	7. 95	14. 13
Ctenocella pectinata	Torres Strait	10° S	. 88	15. 65
Phyllogorgia quercifolia	Brazil	3° 50′ N	8. 57	15. 73

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[1] Neues Jahrb., 1852, p. 854.

[2] Annales Chemie Pharmacie, vol. 1, p. 119, 1832.

Although records of temperature and depths are available for only a few of these alcyonarians, the suggested relation is clearly evident. The organisms from cold, northern waters or from very deep waters are low in magnesia, and those from warm regions are high. The same relation appears in our analyses of echinoderms and is unmistakable. It is not rigorously exact, but some apparent irregularities are due to impurities, such as sand and mud, which appear in the analyses as silica and sesquioxides. If these were rejected the percentage of magnesia would be raised. Variations are also to be expected because of cold or warm currents and different depths of water. Very deep water, even under the Equator, is always cold, whereas shallow bays farther north may be relatively warm. Possibly, also, the alcyonarians may form two or more distinct series that are not perfectly comparable in chemical composition. *Corallium* and *Tubipora*, for example, are compact forms, with little organic matter and lower magnesia than the genera with horny, organic axes, such as those whose names appear at the end of the table. It is also noteworthy that the highest proportions of calcium phosphate are commonly associated with a high content of magnesia.

HYDROIDS.

In the course of this investigation six analyses have been made of coralline hydroids belonging to the genera *Millepora* and *Distichopora*. The species and localities are as follows:

1. *Millepora alcicornis* Linné. Shoal water, Tortugas, Fla.
2. *Millepora alcicornis*. Bermuda.
3. *Millepora braziliensis* Verrill. Candeas, Pernambuco, Brazil.
4. *Distichopora nitida* Verrill. Micronesia, exact locality unknown.
5. *Distichopora coccinea* Gray. South Sea Islands, exact locality unknown.
6. *Distichopora sulcata* Pourtalès. Off Habana, Cuba; depth of water, 143 to 179 meters.

Analyses of millepores, etc.

	1	2	3	4	5	6
SiO_2	0.23	0.02	0.09	0.10	0.09	0.07
$(Al,Fe)_2O_3$	.10	.07	.06	.20	.07	.05
MgO	.43	.10	.59	.11	.12	.12
CaO	52.50	53.14	53.36	53.07	53.43	53.90
SO_3	.27	.04	1.03	.69	.65	.61
P_2O_4	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
Ignition	44.77	45.16	44.87	44.89	45.05	45.37
	98.30	98.53	100.00	99.06	99.41	100.12
CO_2 needed	41.57	41.85	42.01	41.44	41.76	42.15
Organic matter, etc	3.20	3.31	2.86	3.45	3.29	3.22

Reduced analyses.

	1	2	3	4	5	6
SiO_2	0.24	0.02	0.09	0.11	0.09	0.07
$(Al,Fe)_2O_3$	.11	.07	.06	.21	.07	.05
$MgCO_3$	.95	.22	1.28	.24	.26	.26
$CaCO_3$	98.22	99.63	96.77	98.22	98.43	98.56
$CaSO_4$	.48	.06	1.80	1.22	1.15	1.06
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00

A few partial analyses and one fairly complete analysis of millepores have already been published, which in all important particulars agree with ours. The coralline structures consist essentially of calcium carbonate, with minor impurities, and resemble chemically the true corals. In two millepores from Bermuda A. G. Högbom[1] found respectively 95.86 and 94.39 per cent of calcium carbonate, with 0.41 and 0.97 of magnesium carbonate. In *Millepora alcicornis* from the Gulf Stream S. P. Sharples[2] found 97.45 per cent of calcium carbonate, 0.27 of calcium phosphate, 2.54 of organic matter and water, and only traces of iron and magnesia. B. Silliman, jr.,[3] in one analysis of the same species reported no magnesia, which evidently was not sought for. A single analysis of *M. braziliensis* by L. R. Lenox[4] gave the following composition:

$CaCO_3$	93.80
$MgCO_3$	2.14
$CaSO_4$	2.08
SiO_2	.03
$(Al,Fe)_2O_3$	.07
	98.12

It is interesting to note that the Brazilian species is the richest of all in magnesia, although it is poor in comparison with the echinoderms and alcyonarians. As reef builders the millepores contribute little to the coral rock but carbonate of lime.

In an analysis of *Millepora cervicornis*, by A. Damour,[5] 8.51 per cent of magnesium carbonate is reported. The name, however, belongs to a fossil species, and the specimen analyzed was at least partly fossilized. Its locality is given as Bréhat, Manche, France.

ANNELIDS.

The curious tubes formed by marine worms probably contribute little to the sediments. They are, however, of some interest in an investigation of this kind, and for that reason six analyses of them have been made, as follows:

1. *Filograna implexa* Berkeley (*Serpula complexa*). Scarborough, England.
2. *Protula tabularia* (Montagu) (*Serpula tabularia*). Locality unknown, probably British.
3. *Hydroides dianthus* Verrill. Vineyard Sound, Mass.
4. *Leodice polybranchia* Verrill. Off Marthas Vineyard, Mass.

5, 6. *Hyalinœcia artifex* Verrill. Off Marthas Vineyard, Mass., *Fish Hawk* station 1025; depth of water, 384 meters; bottom temperature, 7° C. Two analyses, of different samples; the tubes of this annelid, on ignition, gave an inorganic residue which fused to a white, porcelain-like mass.

Analyses of worm tubes.

	1	2	3	4	5	6
Insoluble in HCl	29.82	......	......	......	......	......
SiO_2	1.12	0.75	15.45	28.05	0.20	0.24
$(Al,Fe)_2O_3$	.75	.41	1.30	2.33	.07	.01
MgO	.00	.14	3.58	4.40	8.57	8.17
CaO	35.98	50.89	39.11	5.12	5.35	5.24
SO_3	Trace.	.07	Trace.	6.06	3.47	4.33
P_2O_5	.29	Trace.	.22	6.43	20.72	20.32
Ignition	31.23	45.99	38.82	46.91	61.83	61.41
	99.19	98.25	98.48	99.30	100.21	99.72
CO_2 needed	28.00	39.95	34.46	......	......	......
Organic matter, etç	3.23	6.04	4.36	......	......	......

Tests for fluorine failed to show its presence in any of these tubes.

These analyses fall into two distinct groups, one low in sulphates and phosphates, the other unusually high. The first three are easily reducible to standard form if we reject the insoluble matter, the silica, and the sesquioxides, which represent inclusions of sand or mud. The reduced analyses then assume the following form:

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[1] Neues Jahrb., 1894, Band 1, p. 262.

[2] Am. Jour. Sci., 3d ser., vol. 1, p. 168, 1871.

[3] Am. Jour. Sci. 2d ser., vol. 1, p. 189, 1846.

[4] Mus. Comp. Zool. Bull., vol. 44, p. 264, 1904.

[5] Compt. Rend., vol. 32, p. 253, 1851.

Reduced analyses of worm tubes.

	1	2	3
$MgCO_3$	0.00	0.32	9.72
$CaCO_3$	99.01	99.55	89.66
$CaSO_4$	Trace.	.13	Trace.
$Ca_3P_2O_8$	.99	Trace.	.62
	100.00	100.00	100.00

Two of these analyses resemble those of corals and mollusks; the third is more like one of an alcyonarian or an echinoderm. In all three the organic matter is very low. Three other partial analyses by Forchhammer [1] are on record, which may be compared with these; although only magnesium carbonate was determined. These are—

	Per cent $MgCO_3$.
Serpula sp. Mediterranean	7.644
Serpula triquetra. North Sea	4.455
Serpula filograna [2]	1.349

The tubes of *Serpula* are evidently quite variable in composition, at least as regards their magnesian content.

The tubes formed by *Leodice* and *Hyalinœcia,* being highly phosphatic, are difficult to interpret chemically. The bases are insufficient to satisfy the acids if the phosphoric oxide is assumed to represent the normal tribasic salts. Phosphorus may be present as part of the organic matter, and so, too, may a portion of the sulphur. Metaphosphates, pyrophosphates, and acid orthophosphates are also possibly present, and between these alternatives it is not easy to decide. Acid salts are, however, improbable, for when boiled in water the tubes give faintly alkaline reactions. We prefer, therefore, to leave the reduction of analyses 4, 5, and 6 in abeyance until more evidence can be obtained. In this direction an analysis of *Onuphis tubicola* Müller, by Schmiedeberg,[3] is suggestive. To the organic matter of the tube of *Onuphis,* "onuphin," he assigns the formula $C_{24}H_{43}NO_{18}$, and the tube itself he regards as a complex compound of the composition

$$C_{24}H_{43}NO_{18}+CaHPO_4+4MgHPO_4+22H_2O.$$

The analyses given by Schmiedeberg are as follows:

Analyses of Onuphis tubicola.

	Entire tube.	Calcined ash.	
Onuphin	38.48	P_2O_5	57.20
Water	24.07	CaO	12.48
P_2O_5	21.58	MgO	25.02
MgO	9.73	K	1.96
CaO	3.40	Na	.50
H (acid), etc	2.74	SO_3, SiO_2, CO_2, and loss	2.27
	100.00		99.43

In a general way this analysis of *Onuphis* resembles our analysis of *Hyalinœcia,* except that the magnesia is much higher and the sulphates, if present, are insignificant in amount. It will be noticed, moreover, that Schmiedeberg assumes the presence of acid phosphates in his interpretation of the data, which, as we have already stated, is improbable.

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[1] Neues Jahrb., 1852, p. 854.

[2] In a later memoir (Philos. Trans., vol. 155, p. 203, 1865) Forchhammer gives the percentage of $MgCO_3$ in *Serpula filograna* as 13.49 per cent Which figure is correct?

[3] Zool. Sta. Naples Mitt., vol. 3, p. 373, 1882.

None of the analyses of the phosphatic worm tubes can be regarded as wholly satisfactory, but it is clear that these structures add phosphorus to the sediments. If they decay in contact with calcareous sediments, the final product would probably be a tribasic phosphate, and that is as far as we now need to go.

ECHINODERMS.

1. CRINOIDS.

In 1906 H. W. Nichols[1] published a number of partial analyses of marine invertebrates, and in a crinoid, *Metacrinus rotundus* from Japan, he found 11.72 per cent of magnesium carbonate. This analysis attracted the attention of Austin H. Clark, and at his request two other analyses of crinoids were made in the laboratory of the United States Geological Survey by Chase Palmer, who also found that they contained abundant magnesia. These analyses, which were published and discussed by Mr. Clark,[2] will be considered in detail later. They at once suggested that crinoids generally might be highly magnesian and so play an important part in the formation of magnesian limestones.

In order to settle this question Mr. Clark supplied us with 24 specimens of recent crinoids, representing 21 genera and covering a wide range of localities. These were analyzed by Mr. Wheeler, and the analyses confirmed the original supposition. All the specimens contained magnesium carbonate in notable proportions but varying in a most remarkable manner. The data obtained are in detail as follows, beginning with the list of the specimens studied:

1. *Ptilocrinus pinnatus* A. H. Clark. *Albatross* station 3342, off the Queen Charlotte Islands, British Columbia; latitude, 52° 39′ 30″ N.; longitude, 132° 38′ W.; depth of water, 2,858 meters; bottom temperature, 1.83° C. Mean of two analyses.
2. *Florometra asperrima* Clark. *Albatross* station 3070, off the coast of Washington; latitude, 47° 29′ 30″ N.; longitude, 125° 43′ W.; depth, 1,145 meters; bottom temperature, 3.28° C.
3. *Psathyrometra fragilis* Clark. *Albatross* station 5032, Yezo Strait, Japan; latitude, 44° 05′ N.; longitude, 145° 30′ E.; depth, 540–959 meters; bottom temperature, 1.61° C.
4. *Pentametrocrinus japonicus* P. H. Carpenter. *Albatross* station 5083, 34.5 miles off Omai Saki Light, Japan; latitude, 34° 04′ 20″ N.; longitude, 137° 57′ 30″ E.; depth, 1,123 meters; bottom temperature, 3.39° C.
5. *Capillaster multiradiata* Linné. *Albatross* station 5137, Philippine Islands near Jolo, 1.3 miles from Jolo Light; latitude, 6° 04′ 25″ N.; longitude, 120° 58′ 30″ E.; depth, 36 meters; no temperature record.
6. *Pachylometra patula* Carpenter. *Albatross* station 5036, Philippine Islands, North Balabac Strait, 15.5 miles from Balabac Light; latitude, 8° 06′ 40″ N.; longitude, 117° 18′ 45″ E.; depth, 104 meters; no temperature record.
7. *Catoptometra ophiura* Clark. Same locality as No. 6.
8. *Hypalocrinus naresianus* Carpenter. *Albatross* station 5424, Philippine Islands, 3.4 miles off Cagayan Island, Jolo Sea; latitude, 9° 37′ 05″ N.; longitude, 121° 12′ 37″ E.; depth, 612 meters; bottom temperature, 10.22° C.
9. *Parametra granulata* Clark. *Albatross* station 5536, Philippine Islands, between Negros and Siquijor, 11.8 miles from Apo Island; latitude, 9° 15′ 45″ N.; longitude, 123° 22′ E.; depth, 502 meters; bottom temperature, 11.95° C.
10. *Craspedometra anceps* Carpenter. *Albatross* station 5157, 3.3 miles from Tinakta Island, Tawi Tawi group, Sulu Archipelago; latitude, 5° 12′ 30″ N.; longitude, 119° 55′ 50″ E.; depth, 32 meters; no temperature record.
11. *Ptilometra mülleri* Clark. Sydney Harbor, New South Wales, Australia; latitude, 33° 15′ S.; longitude, 151° 12′ E., approximately.
12. *Hathrometra dentata* Say. *Fish Hawk* station 1033, off Marthas Vineyard, Mass.; latitude, 39° 56′ N.; longitude, 69° 24′ W.; depth, 329 meters; bottom temperature, about 7.8° C.
13. *Bythocrinus robustus* Clark. *Albatross* station 2401, Gulf of Mexico, southeast of Pensacola; latitude, 28° 38′ 30″ N.; longitude, 85° 52′ 30″ W.; depth, 255 meters; no temperature record.
14. *Crinometra concinna* Clark. *Albatross* station 2324, north of Cuba; latitude, 23° 10′ 35″ N.; longitude, 82° 20′ 24″ W.; depth, 59 meters; bottom temperature, 26.17° C.
15. *Isocrinus decorus* Wyville Thomson, stem. Off Habana, Cuba; latitude, 24° N.; longitude, 82° W.; approximately.
16. Same as No. 15, arms.
17. *Endoxocrinus parræ* Gervais, stem. Off Habana, Cuba.
18. Same as No. 17, arms.
19. *Tropiometra picta* Gay. Rio de Janeiro, Brazil; latitude, 25° 54′ S.; longitude, 44° W., approximately.
20. *Promachocrinus kerguelensis* Carpenter. Shores of the Antarctic Continent in the vicinity of Gaussberg; latitude, 67° S.; longitude, 90° E., approximately; depth, 350–400 meters; bottom temperature, −1.85° C.; salinity of water, 3.3 per cent.

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[1] Field Columbian Mus. Pub. 111, p. 31.

[2] U. S. Nat. Mus. Proc., vol. 39, p. 487, 1911.

21. *Anthometra adriani* Bell. Same locality as No. 20. Nos. 20 and 21 were collected by the German South Polar Expedition.

22. *Zygometra microdiscus* Bell. Aru Islands, near the western point of New Guinea; latitude, 5°–6° S.

23. *Chlorometra rugosa* A. H. Clark. Near Rotti, Lesser Sunda Islands; latitude, 10° 39′ S.; longitude, 123° 40′ E.; depth, 520 meters.

The actual analyses are as follows. Sulphates were not determined because the material was insufficient.

Analyses of crinoid skeletons.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
SiO_2	1.64	0.04	1.11	0.37	0.16	0.12	0.04	0.07	0.40	0.15	0.17	3.17	0.40	0.04	0.03	0.09	0.04	0.15	0.02	0.02	0.23	0.04	0.05
$(Al,Fe)_2O_3$	1.07	.34	1.01	.71	.62	.63	.79	.09	.50	.19	.19	.31	.31	.25	.07	.19	.20	.26	.35	.45	.37	.48	.23
MgO	3.08	3.60	3.12	3.76	4.77	4.94	4.64	4.44	4.48	5.13	4.17	2.49	4.56	4.75	5.08	4.70	5.09	5.04	4.51	3.02	3.27	4.92	3.99
CaO	40.65	40.37	34.20	38.50	38.12	41.34	40.75	45.86	41.79	42.77	38.91	26.12	47.08	41.78	45.67	42.77	45.42	43.41	39.57	40.68	42.49	37.19	42.72
P_2O_5	.11	.21	Trace?	.40	Trace.	.43	.33	Trace.	Trace.	.11	.17	.23	Trace.	Trace.	Trace.	Trace?	Trace.	Trace.	.10	Trace.	Trace.	.17	Trace.
Ignition	51.45	53.75	60.04	55.25	54.61	51.36	51.80	48.32	51.44	50.28	54.61	65.25	47.17	50.33	47.54	50.59	48.58	50.00	53.64	54.53	52.22	55.05	51.69
	98.00	98.36	99.48	98.99	98.28	98.82	98.35	98.78	98.61	98.63	98.22	97.57	99.52	97.15	98.39	98.34	99.33	98.86	98.19	98.70	98.58	97.85	98.68
CO_2 needed	35.23	35.48	31.37	34.01	35.19	37.51	36.81	41.27	37.77	39.17	34.90	22.73	41.93	38.00	40.40	38.71	41.29	39.65	36.05	35.18	37.08	34.47	37.95
Organic matter, etc	16.22	18.27	28.67	21.24	19.42	13.85	14.99	7.05	13.67	11.11	19.71	42.52	5.24	12.33	7.14	11.88	7.29	10.35	17.59	19.35	15.14	20.58	13.74

The summation in most of these analyses is low. The deficiency is due mainly to inclosed or adherent sea salts, an inevitable impurity, as was proved in the analyses of two separate samples. In No. 15, 1.27 per cent of water-soluble salts was found, and in No. 17, 0.21 per cent. These additions raise the summations to 99.66 and 99.54 per cent, respectively.

The reduced analyses are as follows, rejecting organic matter and water and recalculating to 100 per cent:

Reduced analyses.

	1	2	3	4	5	6
SiO_2	2.01	0.05	1.57	0.48	0.21	0.14
$(Al,Fe)_2O_3$	1.31	.48	1.41	.91	.78	.74
$MgCO_3$	7.91	9.44	9.25	10.15	12.69	12.20
$CaCO_3$	88.48	89.45	87.77	87.34	86.32	85.81
$Ca_3P_2O_8$	.29	.58	Trace?	1.12	Trace.	1.11
	100.00	100.00	100.00	100.00	100.00	100.00

	7	8	9	10	11	12
SiO_2	0.05	0.08	0.47	0.24	0.21	5.73
$(Al,Fe)_2O_3$	.95	.10	.59	.22	.24	.56
$MgCO_3$	11.68	10.16	11.08	12.34	11.13	9.36
$CaCO_3$	86.46	89.66	87.86	86.93	87.94	83.47
$Ca_3P_2O_8$	.86	Trace.	Trace.	.27	.48	.88
	100.00	100.00	100.00	100.00	100.00	100.00

	13	14	15	16	17	18
SiO_2	0.42	0.05	0.03	0.10	0.04	0.17
$(Al,Fe)_2O_3$	.33	.30	.08	.21	.21	.29
$MgCO_3$	10.09	11.69	11.69	11.42	11.62	11.96
$CaCO_3$	87.16	87.96	88.20	88.27	88.13	87.58
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00

	19	20	21	22	23
SiO_2	0.02	0.02	0.28	0.05	0.06
$(Al,Fe)_2O_3$	.43	.57	.44	.62	.27
$MgCO_3$	11.17	7.86	8.23	13.37	9.87
$CaCO_3$	87.51	91.55	91.05	85.48	89.80
$Ca_3P_2O_8$	.27	Trace.	Trace.	.48	Trace.
	100.00	100.00	100.00	100.00	100.00

With these analyses the two made by Mr. Palmer may be advantageously compared, although they were not quite so elaborate. The data are as follows:

24. *Heliometra glacialis* var. *maxima.* Iwanai Bay, northeastern part of the Sea of Japan, latitude, 43° 01′ 40″ N.; depth, 315 meters; temperature, surface, 20.5° C., bottom, 1.5° C.

25. *Metacrinus rotundus.* Eastern Sea, off Kagoshima Gulf, southern Japan, latitude, 30° 58′ 30″ N.; depth, 278 meters; temperature, surface, 27.8° C., bottom, 13.3° C.

In No. 24, which contained much organic matter, Mr. Palmer found 2.68 per cent MgO (=5.61 $MgCO_3$) and 40.03 CaO (=71.48 $CaCO_3$). In No. 25, with no organic matter, he found 4.89 MgO (=10.29 $MgCO_3$) and 49.95 CaO (=89.19 $CaCO_3$). Assuming that the crinoid skeletons consist essentially of carbonates, and recalculating to 100 per cent, we have as the content of magnesium carbonate in these crinoids—

	Per cent.
24. *Heliometra glacialis* var. *maxima*	7.28
25. *Metacrinus rotundus*	10.34

These figures fit in well with the others and even by themselves suggest a relation between temperature and the magnesia content of crinoids. In the following table the entire series is arranged in the order of ascending magnesium carbonate, with the accessory data as to latitude and locality abbreviated. In this table the two analyses of *Endoxocrinus* are averaged together, and so also are the two of *Isocrinus.*

Percentage of magnesium carbonate in crinoids.

Genus.	Locality.	Latitude.	Depth.	Temperature.	$MgCO_3$.
			Meters.	*°C.*	*Per cent.*
Heliometra	Northern Japan	43° N	315	1.5	7.28
Promachocrinus	Antarctic	67° S	375	−1.8	7.86
Ptilocrinus	British Columbia	52° 39′ N	2,858	1.8	7.91
Anthometra	Antarctic	67° S	375	−1.8	8.23
Psathyrometra	Northern Japan	44° N	(?)	1.6	9.25
Hathrometra	Massachusetts	39° 56′ N	329	7.8	9.36
Florometra	Washington	47° 29′ N	1,145	3.3	9.44
Chlorometra	Rotti Island	10° 39′ S	520	(?)	9.87
Bythocrinus	Gulf of Mexico	28° 38′ N	255	(?)	10.09
Pentametrocrinus	Southern Japan	34° N	1,123	3.4	10.15
Hypalocrinus	Philippine Islands	9° 37′ N	612	10.2	10.16
Metacrinus	Southern Japan	30° 58′ N	278	13.3	10.34
Parametra	Philippine Islands	9° 15′ N	502	12	11.08
Ptilometra	Australia	33° 15′ S	(?)	(?)	11.13
Isocrinus	Cuba	24° N	(?)	(?)	11.56
Catoptometra	Philippine Islands	8° N	104	(?)	11.68
Crinometra	Cuba	23° 10′ N	59	26.2	11.69
Tropiometra	Brazil	25° 54′ S	(?)	(?)	11.77
Endoxocrinus	Cuba	24° N	(?)	(?)	11.79
Pachylometra	Philippine Islands	8° N	1,044	(?)	12.20
Craspedometra	Philippine Islands	5° 12′ N	32	(?)	12.34
Capillaster	Philippine Islands	6° N	36	(?)	12.69
Zygometra	Aru Islands	5°–6° S	(?)	(?)	13.37

The percentage of magnesium carbonate in *Chlorometra* is low for the latitude of the locality, but that is doubtless due to the depth of the water (520 meters) in which the crinoid lived. The probable temperature at that depth was between 7° and 10° C.

From the foregoing table it is perfectly clear that the proportion of magnesium carbonate in crinoids is in some way dependent on temperature. Temperature, however, is not entirely dependent on latitude. Depth of water has also a distinct influence. The crinoids from relatively shallow depths in the Tropics are highest in their magnesian content; those from the Antarctic and the far north are lowest. The proportion given for No. 12, from the coast of Massachusetts, is probably too low, for the specimen as analyzed contained over 6 per cent of silica and sesquioxides—evident impurities, due to adherent mud from which the delicate structure could not be wholly freed. If these are rejected, the magnesium carbonate is raised from 9.36 to 10 per cent, which gives the crinoid a better and more probable rating.

So far as we are aware such a peculiar relation between temperature and composition as is here recorded has not been previously observed. To recognize it is one thing; to account for it is not so easy. At first we supposed that it might possibly be due to a difference in the form of the more abundant carbonate—the less stable aragonite in the warm-water forms and calcite in the crinoids from colder regions. But tests by Meigen's reaction proved that the organisms were all calcitic, and so this supposition had to be abandoned.

Mr. A. H. Clark, who is an authority on the crinoids, informs us that the crinoids from warm regions have the most compact skeletons, the compactness being in general proportional to the temperature and to some extent dependent upon the size of the individual. *Heliometra,* for example, is the largest of the crinoids, its skeleton is one of the least compact, and its magnesian content is lowest among all the species examined. Structure as well as temperature seems to be correlated with the proportion of magnesia in the crinoids, but the chemical explanation of the facts is yet to be found. It may have connection with the gaseous content of sea water, carbon dioxide, for example, being more soluble in warm than in cold waters, but this is only a suggestion, which may or may not be fruitful. The same regularity of temperature also appears in our analyses of alcyonarians.

FOSSIL CRINOIDS.

In order to make this investigation more systematic it seemed desirable to analyze a number of fossil crinoids, so as to determine whether any definite and regular changes could be traced in passing from the recent to the ancient organisms. For the material studied we are indebted to the kindness of Mr. Frank Springer, who selected the material with great care so as to cover a range of horizons from the Lower Ordovician up to the Eocene. The 10 crinoids chosen are described in the list below, and the analyses which follow were made in the same way as those of the modern species.

1. *Pentacrinus decadactylus* D'Orbigny, stem. Eocene, Vincenza, Italy.
2. *Millericrinus mespiliformis* Goldfuss, stem. Upper Jurassic, Kelheim, Bavaria.
3. *Pentacrinus basaltiformis* Miller, stem. Middle Lias (Lower Jurassic) Breitenbach, Wurttemberg, Germany.
4. *Encrinus liliiformis* Lamarck, stem. Triassic, Braunschweig, Germany.
5. *Graphiocrinus magnificus* Miller and Gurley, complete crown. Pennsylvanian (upper Carboniferous), Kansas City, Mo.
6. *Dorycrinus unicornis* Owen and Shumard, calyx and stem. Lower part of Burlington limestone, Mississippian (lower Carboniferous), Burlington, Iowa.
7. *Megistocrinus nodosus* Barris, plates. Middle Devonian, Alpena, Mich.
8. *Eucalyptocrinus crassus*, plates. Silurian, western Tennessee.
9. Crinoid sp.?, stem. Trenton limestone, Middle Ordovician, Kirkfield, Canada.
10. *Diabolocrinus vesperalis* White, plates and stem. Lower Ordovician, Tennessee.

Analyses of fossil crinoids.

	1	2	3	4	5	6	7	8	9	10
SiO_2	0.99	2.84	1.55	0.24	3.07	6.92	10.39	29.11	2.56	4.07
$(Al,Fe)_2O_3$	2.64	.28	2.59	.43	2.18	.64	.87	1.73	.31	1.95
FeO	1.36	.00	....	.00	1.32	.00	1.19	.27	.00	.88
MnO	.13	.00	....	Trace.	.15	Trace.	.16	.04	Trace.	.04
MgO	.78	.38	.84	9.44	.78	.38	1.21	.58	.91	.79
CaO	51.22	53.68	51.78	43.40	50.10	51.20	46.57	37.43	53.87	50.42
P_2O_5	.00	Trace.	.09	Trace.	Trace.	Trace.	Trace.	.00	Trace.	Trace.
Loss on ignition	42.80	42.93	43.21	45.95	41.71	41.00	39.20	30.71	42.45	41.53
	99 92	100.11	100.06	99.46	99.32	100.14	99.59	99.87	100.10	99.68

Reduced analyses.

	1	2	3	4	5	6	7	8	9	10
SiO_2	1.00	2.85	1.57	0.24	3.11	6.94	10.48	29.30	2.55	4.10
$(Al,Fe)_2O_3$	2.66	.28	2.64	.44	2.22	.64	.88	1.74	.30	1.97
$FeCO_3$	2.21	.00	....	.00	2.16	.00	1.94	.43	.00	1.42
$MnCO_3$	.21	.00	....	Trace.	.24	Trace.	.26	.06	Trace.	.06
$MgCO_3$	1.66	.80	1.79	20.23	1.66	.80	2.56	1.23	1.90	1.67
$CaCO_3$	92.26	96.07	93.80	79.09	90.61	91.62	83.88	67.24	95.25	90.78
$Ca_3P_2O_8$	.00	Trace.	.20	Trace.	Trace.	Trace.	Trace.	.00	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

In some respects these analyses are unsatisfactory, for they show no regularities of any kind. In only one of them, No. 4, is there exhibited a concentration of magnesium carbonate; in the others the percentage of this constituent is very low. The reason for this decrease of magnesia is by no means clear. It is conceivable that the ancient crinoids may have been deficient in magnesia, but it is more probable that the loss is due to alteration, perhaps to the infiltration of calcium carbonate. Such a change would obviously lower the apparent proportion of magnesium carbonate. Several of the crinoids contain noteworthy quantities of ferrous carbonate and manganese—constituents which did not appear in the analyses of the modern species. In No. 8 there is a very strong silicification, 29.11 per cent; but the matrix of the specimen contained only 7.55 per cent of silica. Here the infiltration of the impurity seems to be very clear. Some of the deficiencies in magnesia may have been caused by solution and leaching, but calcium carbonate should then have been removed to a greater extent. In short, the fossil crinoids differ widely in composition from the still living species, and in a very irregular manner, and it is worth noting that in three analyses of fossil algæ reported by Högbom[1] a similar decrease of magnesia appears. It would be easy to speculate on the significance of these differences, but the conclusions so reached would not be entitled to much weight. That the recent crinoids are distinctly magnesian and that the proportion of magnesia is dependent in some way on temperature are the two positive results of this investigation.

2. SEA URCHINS.

Nine sea urchins, selected for us by Mr. Austin H. Clark, were analyzed. The species chosen were as follows:

1. *Strongylocentrotus dröbachiensis* O. F. Müller. Upernivik, Greenland, latitude 72° 48′ N.
2. *Strongylocentrotus fragilis* Jackson. *Albatross* station 2946, off southern California; latitude, 33° 58′ 00″ N.; longitude, 119° 30′ 45″ W.; depth of water, 274.5 meters; bottom temperature, 13.6° C.
3. *Echinarachnius parma* Lamarck. Coast of New England.
4. *Encope californica* Verrill. Galapagos Islands, on or near the Equator.
5. *Lytechinus anamesus* H. L. Clark. *Albatross* station 2938, off Wilmington, Cal.; latitude, 33° 35′ 15″ N.; longitude, 118° 08′ 30″ W.; depth, 86 meters; bottom temperature, 15° C.
6. *Loxechinus albus* Molina. Port Otway, Patagonia; latitude, about 46° or 47° S.
7. *Tetrapygus niger* Molina. Coast of Peru.
8. *Tretocidaris affinis* Philippi. *Albatross* stations 2316 and 2317, off Key West, Fla.; latitude, 24° 25′ N.; longitude, 81° 47′ W.; depth, 85 meters; bottom temperature, 24° C.
9. *Heterocentrotus mammillatus* Linné. Low or Paumotu Archipelago, southern Pacific Ocean; latitude, between 14° and 24° S.

The following analyses differ from those previously published[2] in being more complete and in the correction of certain errors of calculation:

Analyses of sea urchins.

	1	2	3	4	5	6	7
SiO_2	0.12	0.26	0.14	3.86	8.52	0.05	0.31
$(Al,Fe)_2O_3$	.34	.65	.27	5.03	3.01	.17	.30
MgO	2.58	2.68	2.97	4.75	3.04	3.07	2.82
CaO	47.34	41.08	49.17	43.42	37.92	45.87	48.86
SO_3	.20	1.15	.26	.28	.37	.35	1.43
P_2O_5	Trace.	.39	.05	Trace.	.19	Trace.	Trace.
Ignition	48.53	52.21	45.74	43.01	45.38	49.47	44.98
	99.11	99.42	98.60	99.35	98.43	98.98	98.70
CO_2 needed	39.92	34.20	41.71	38.99	32.28	39.34	40.69
Organic matter, etc	8.61	18.01	4.03	4.02	13.10	10.13	4.29

Rejecting the very variable organic matter, etc., the reduced analyses assume the following form:

Reduced analyses.

	1	2	3	4	5	6	7
SiO_2	0.13	0.32	0.15	3.99	9.93	0.05	0.33
$(Al,Fe)_2O_3$	.37	.81	.29	5.20	3.51	.18	.32
$MgCO_3$	5.99	6.95	6.59	10.38	7.44	7.38	6.27
$CaCO_3$	93.13	88.44	92.39	79.94	77.91	91.73	90.52
$CaSO_4$	.38	2.42	.46	.49	.73	.66	2.56
$Ca_3P_2O_8$	Trace.	1.06	.12	Trace.	.48	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

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[1] Neues Jahrb., 1894, Band 1, p. 252.

[2] Clarke, F. W., and Wheeler, W. C., The inorganic constituents of echinoderms: U. S. Geol. Survey Prof. Paper 90, pp. 191–192, 1915.

Sea urchins Nos. 8 and 9, *Tretocidaris* and *Heterocentrotus*, must be considered separately from the others. No. 9, a giant form, was the subject of four analyses, the shell or test, the dental pyramid, the small white spines on the border of the peristome, and the large purplish-red spine. The large red spine analyzed was 15 centimeters long and weighed 13 grams.

Analyses of Heterocentrotus mammillatus.

	Shell.	Dental pyramid.	White spines.	Red spines.
SiO_2	0.02	0.02	0.05	0.05
$(Al,Fe)_2O_3$	.13	.08	.13	.26
MgO	5.21	5.50	3.74	4.47
CaO	43.60	46.02	48.26	47.72
SO_3	.61	.58	.29	.78
P_2O_5	Trace.	Trace.	Trace.	Trace.
Ignition	49.62	47.00	46.46	45.99
	99.19	99.20	98.93	99.27
CO_2 needed	39.66	42.89	41.77	41.49
Organic matter, etc	9.96	4.11	4.69	4.50

Reduced analyses.

	Shell.	Dental pyramid.	White spines.	Red spines.
SiO_2	0.02	0.02	0.05	0.05
$(Al,Fe)_2O_3$	.14	.09	.14	.28
$MgCO_3$	12.26	12.27	8.32	9.86
$CaCO_3$	86.42	86.57	90.97	88.43
$CaSO_4$	1.16	1.05	.52	1.38
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00

From these analyses we see that the inorganic constituents of *Heterocentrotus* are not uniformly distributed. The shell and teeth are alike and are rich in magnesium carbonate; the coarser spines are much less magnesian. The composition of the entire skeleton, if it can be called so, would probably be somewhere near that of the red spines alone, only a little higher in magnesia.

A similar example is offered by No. 8, *Tretocidaris*. In the specimen analyzed the shell and spines were taken separately, but the spines were dead when the urchin was collected. The analyses are as follows:

Analyses of Tretocidaris affinis.

Actual analyses.			Reduced analyses.		
	Shell.	Spines.		Shell.	Spines.
SiO_2	0.11	0.53	SiO_2	0.12	0.56
$(Al,Fe)_2O_3$	.15	.14	$(Al,Fe)_2O_3$	.16	.15
MgO	4.02	2.07	$MgCO_3$	9.30	4.63
CaO	45.80	49.79	$CaCO_3$	89.35	94.66
SO_3	.57	(?)	$CaSO_4$	1.07	(?)
P_2O_5	Trace.	Trace.	$Ca_3P_2O_8$	Trace.	Trace.
Ignition	48.32	46.28			
	98.97	98.81		100.00	100.00
CO_2 needed	40.09	41.40			
Organic matter, etc	8.23	4.88			

Here again the spines are lower in their content of magnesia than the shell.

In two of the analyses, Nos. 4 and 5, large percentages of silica and sesquioxides appear. These are due to inclosed or adherent sand and mud, which were visible in the specimens but not readily removable. On rejecting these impurities and recalculating to 100 per cent, the percentages of magnesium carbonate became 11.43 and 8.59, respectively. Similar corrections to the other analyses are negligible. After making these corrections and assuming the percentages found for the shell rather than the spines in Nos. 8 and 9, the next table has been constructed. If, however, the composition of the entire *Heterocentrotus* should be taken, it would change places with *Encope*.

Percentage of magnesium carbonate in sea urchins.

	Locality.	Latitude.	Depth.	Temperature.	$MgCO_3$.
			Meters.	°*C*	*Per cent.*
Strongylocentrotus dröbachiensis	Greenland	72° 48′ W.	(?)	(?)	5.99
Tetrapygus	Peru	(?)	(?)	(?)	6.27
Echinarachnius	New England	42° 45′ N.	(?)	(?)	6.59
Strongylocentrotus fragilis	California	33° 58′ N.	2,745	13.6	6.95
Loxechinus	Patagonia	46° 47′ S.	(?)	(?)	7.38
Lytechinus	California	33° 35′ N.	85	15	8.59
Tretocidaris	Key West	24° 25′ N.	85	24	9.30
Encope	Paumotu	14° 24′ S.	(?)	(?)	11.43
Heterocentrotus	Galapagos	Equator	(?)	(?)	12.26

These figures, like those for the crinoids, seem to show a regular variation in temperature, at least so far as temperatures have been determined or can be inferred. The sea urchins from cold regions are relatively low in magnesia; those from the Tropics are high. There is, however, one apparent exception—the urchin from Peru. This abnormality is probably due to the cold Humboldt current which flows northward from the Antarctic Ocean. A larger series of analyses of sea urchins, with more details as to depth of water and temperatures, is much to be desired.

Two published analyses of sea urchins are worth reproducing. They are:

1. *Echinus* (*Strongylocentrotus?*) *dröbachiensis.* North Sea; analysis by L. Schmelck. Norske Nordhavs Exped., No. 28, p. 129, 1901.
2. *Echinus esculentus.* Locality not stated, probably Mediterranean; analysis by O. Bütschli. K. Gesell. Wiss. Göttingen Abh., No. 3, 1908.

Older analyses of sea urchins.

Actual analyses.			Reduced analyses.		
	1	2		1	2
SiO_2	Trace.	0.04	SiO_2	Trace.	0.04
Al_2O_3	Trace.	....	Al_2O_3	Trace.	....
Fe_2O_3	0.30	....	Fe_2O_3	0.36	....
$CaCO_3$	77.75	86.40	$MgCO_3$	6.36	8.84
$MgCO_3$	5.30	8.53	$CaCO_3$	93.28	89.64
P_2O_5	Trace.	....	$CaSO_4$	Trace.	1.40
Phosphate	....	.08	$Ca_3P_2O_8$	Trace.	.08
$CaSO_4$	Trace.	....			
$CaSO_4.2H_2O$	....	1.70		100.00	100.00
H_2O	....	2.45			
Organic matter	16.33	.03			
	99.68	99.23			

Although different in minor details these analyses are fairly comparable with ours. The urchin analyzed by Schmelck was from the far north, and its composition is very near that of our specimen from Greenland. Bütschli's sea urchin is doubtless from warmer water and shows the higher figure for magnesium carbonate.

3. STARFISHES AND BRITTLE STARS.

Eleven starfishes, including brittle stars, were analyzed, as follows:

1. *Asterias vulgaris* Packard. Eastport, Maine; latitude, 44° 55′ N.; longitude, 67° 00′ W.
2. *Asterias tanneri* Verrill. *Albatross* station 2309; latitude, 35° 43′ 30″ N.; longitude, 74° 52′ W.; depth, 102 meters; bottom temperature not given.
3. *Asterina miniata* Brandt. Pacific Grove, Cal.; latitude, 36° 36′ N.; longitude, 121° 55′ W.
4. *Leptasterias compta* Stimpson. *Albatross* station 2250; latitude, 40° 17′ 15″ N.; longitude, 69° 51′ 45″ W.; depth, 86 meters; bottom temperature, 10.8° C.
5. *Benthopecten spinosus* Verrill. *Albatross* station 2568; latitude, 39° 15′ 00″ N.; longitude, 68° 08′ 00″ W.; depth, 3,249 meters; bottom temperature, 2.7° C.
6. *Luidia clathrata* Say. Near Charleston, S. C.; latitude, 32° 47′ N.; longitude, 79° 57′ W.; depth, between 2 and 22 meters.
7. *Acanthaster planci* Linné. Palmyra Island, in the Pacific Ocean, west of south from Hawaii; latitude, 5° 49′ N.
8. *Gorgonocephalus arcticus* Gray. Off Cape Cod, Mass.; about latitude 42° N.
9. *Gorgonocephalus caryi* Lyman. Alaska.
10. *Ophioglypha sarsii* Lütken. *Albatross* station 2176; latitude, 39° 32′ 30″ N.; longitude, 72° 21′ 30″ W.; depth, 553 meters; bottom temperature, 5° C.
11. *Ophioderma cinereum* Müller and Troschel. Ensenada Honda, Culebra Island, east of Porto Rico; latitude, 18° 20′ N., approximately.

The last locality is in or on the edge of the equatorial current. The *Albatross* stations were all fixed on cruises between Cape Hatteras and Nantucket. The analyses are as follows:

Analyses of starfishes.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	0.45	0.79	0.03	1.21	2.06	0.27	0.19	1.77	1.08	0.98	0.21
$(Al,Fe)_2O_3$	.21	.55	.20	.48	.79	.36	.14	.62	.72	.53	.09
MgO	2.59	3.83	3.98	3.05	3.93	4.89	4.36	3.36	2.82	3.99	5.80
CaO	35.71	38.51	36.85	30.35	40.54	41.30	33.18	36.13	29.80	42.14	41.32
SO_3	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)	.69	(?)	.16
P_2O_5	.07	.24	.14	.13	.11	.14	.07	.22	.32	.29	.07
Ignition	60.18	54.89	57.64	63.91	51.66	52.03	62.07	55.72	63.37	50.95	51.58
	99.21	98.81	98.84	99.13	99.09	98.99	100.01	97.82	98.80	98.88	99.23
CO_2 needed	30.84	34.30	33.05	27.08	35.94	37.70	30.81	31.65	25.85	37.29	38.69
Organic matter, etc.	29.34	20.59	24.59	36.83	15.72	14.33	31.26	24.07	37.52	13.66	12.89

Reduced analyses.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	0.64	1.01	0.03	1.94	2.47	0.32	0.27	2.39	1.76	1.15	0.24
$(Al,Fe)_2O_3$	.30	.70	.27	.77	.94	.42	.20	.84	1.17	.62	.11
$MgCO_3$	7.79	10.28	11.24	10.27	9.88	12.13	13.33	9.53	9.66	9.84	14.08
$CaCO_3$	91.06	87.44	88.06	86.57	86.42	86.77	85.99	86.60	84.36	87.65	85.09
$CaSO_4$	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)	1.91	(?)	.30
$Ca_3P_2O_8$	.21	.57	.40	.45	.29	.36	.21	.64	1.14	.74	.18
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

In the following table the analyses are arranged in the order of ascending magnesium carbonate, like those of the sea urchins and crinoids:

Percentage of magnesium carbonate in starfishes.

Species.	Locality.	Latitude.	Depth.	Temperature.	$MgCO_3$.
			Meters.	°*C.*	*Per cent.*
Asterias vulgaris	Eastport	44° 55′ N.	(?)	(?)	7.79
Gorgonocephalus arcticus	Cape Cod	42° ± N.	(?)	(?)	9.53
Gorgonocephalus caryi	Alaska	(?)	(?)	(?)	9.66
Ophioglypha sarsii	Station 2176	39° 32′ N.	553	5	9.84
Benthopecten spinosus	Station 2568	39° 15′ N.	3,249	2.7	9.88
Leptasterias compta	Station 2250	40° 17′ N.	86	10.8	10.27
Asterias tanneri	Station 2309	35° 43′ N.	102	(?)	10.88
Asterina miniata	California	36° 38′ N.	(?)	(?)	11.24
Luidia clathrata	Charleston	32° 47′ N.	(?)	(?)	12.13
Acanthaster planci	Palmyra Island	5° 49′ N.	(?)	(?)	13.33
Ophioderma cinereum	Culebra	18° 20′ N.	(?)	(?)	14.08

Here again we meet the same coordination of temperature with content of magnesium carbonate that was noted among the other echinoderms. The starfishes from cold regions run lowest in magnesium carbonate; those from warm regions run higher. Whether, however, this coordination is general or not is still an open question, for several analyses by L. Schmelck of forms from the North Sea are not easy to explain. Schmelck's data are as follows:[1]

1. *Astrophyton;* an ophiuran. Station 37; latitude, 78° 48′ N.; longitude, 8° 57′ E.; depth of water 199 meters; bottom temperature, 1.1° C.
2. *Arcaster tenuispinus.* Station 10; latitude, 61° 41′ N.; longitude, 3° 19′ E.; depth, 402 meters; bottom temperature, 6° C.
3. *Arcaster tenuispinus.* Station 25; latitude, 63° 10′ N.; longitude, 5° 25′ E.; depth, 179 meters; bottom temperature, 6.9° C.
4. *Astropecten andromeda.* Station 10; details under No. 2.

Schmelck's analyses of starfishes.

	1	2	3	4
SiO	Trace.	Trace.	Trace.	7.09
Al_2O_3	Trace.	Trace.	Trace.	.65
Fe_2O_3	0.31	0.31	0.60	.37
$MgCO_3$	7.60	9.36	9.24	8.55
$CaCO_3$	74.82	74.11	78.92	64.48
$CaSO_4$	.71	(?)	1.00	.83
P_2O_5	Trace.	Trace.	Trace.	Trace.
Organic matter	17.57	16.23	10.24	13.83
	101.01	100.00	100.00	95.80

Schmelck's analyses reduced.

	1	2	3	4
SiO_2	Trace.	Trace.	Trace.	8.66
Al_2O_3	Trace.	Trace.	Trace.	.79
Fe_2O_3	0.37	0.36	0.66	.45
$MgCO_3$	9.11	11.18	10.29	10.42
$CaCO_3$	89.67	88.46	87.92	78.67
$CaSO_4$	.85	(?)	1.13	1.01
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00

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[1] Norske Nordhavs Exped. No. 28, p. 129, 1901.

Nos. 2 and 4 of this group of analyses represent the same locality and temperature. If the excessive and surely extraneous silica in No. 4 is rejected and the analyses are recalculated to 100 per cent the figure for magnesium carbonate becomes 11.41, nearly that for No. 2. All the percentages given for magnesium carbonate are higher than the temperatures would lead us to expect, but they still fall far below the three highest in our table. A general tendency to regularity as regards temperature is evident, but it is perhaps not invariable. More data relative to starfishes are much to be desired.

4. HOLOTHURIANS.

Although the holothurians are of slight importance as contributors to the marine sediments, it seemed desirable to compare a few of them with the other echinoderms. Four holothurians were therefore analyzed, but their organic matter was so vastly in excess of their hard parts that the analyses, with one exception, are far from satisfactory. However, the data, which are not without some significance, are as follows:

1. *Holothuria floridana* Pourtalès. Fajardo, Porto Rico.
2. *Cucumaria frondosa* (Gunnerus). A northern cold-water species, precise locality unknown.
3. *Trochostoma intermedium* Ludwig. Off Cersos Island, Cal. Weight of sample, 0.2204 gram.
4. *Trochostoma intermedium*. *Albatross* station 3307, in Bering Sea; latitude, 56° 12′ N.; longitude, 172° 55′ W.; depth of water, 130 meters; bottom temperature, 3.3° C. Weight of sample, 0.1175 gram.

Analyses of holothurians.

	1	2	3	4
SiO_2	0. 08	0. 27	5. 56	6. 93
$(Al,Fe)_2O_3$	. 18	. 25	8. 40	6. 31
MgO	3. 48	. 41	1. 81	1. 36
CaO	25. 19	1. 10	4. 91	1. 44
P_2O_5	Trace.	. 85	3. 15	1. 86
SO_3	. 74	1. 29	(?)	(?)
Ignition	69. 93	95. 71	76. 71	82. 21
	99. 60	99. 88	100. 54	100. 11
CO_2 needed	23. 21	(?)	(?)	(?)
Organic matter, etc	46. 72	(?)	(?)	(?)

In No. 2, 0.31 per cent of matter soluble in water was found, which raises the summation to 100.19.

Of these analyses only the first is reducible with any certainty to standard form. The percentage composition of the inorganic portion of the specimen then becomes—

SiO_2	0. 15
$(Al,Fe)_2O_3$	. 34
$MgCO_3$	13. 84
$CaCO_3$	83. 29
$CaSO_4$	2. 38
$Ca_3P_2O_8$	Trace.
	100. 00

This is very near the analysis of the starfish from Culebra Island, which is not far from the locality of this holothurian. The coincidence is very striking.

In the specimen represented by analysis 2 the proportion of inorganic matter was so small that good results could hardly be obtained. The other two analyses were also made with altogether inadequate material. These analyses, however, show that the small inorganic portions of the holothurians are relatively rich in phosphatic matter and in magnesia. The difficulties of discussing them intelligently are like those of discussing the worm tubes and the axes of alcyonarians. In *Trochostoma* there are brown spots, which were already known to be phosphatic, although quantitative analyses of them seem to be lacking. The true character of such bodies can be determined only by an elaborate investigation upon abundant material, a task which lies outside of our main problem.

Two analyses of holothurians are already on record, as follows:

1. *Stichopus regalis.* Locality not stated; analysis by O. Bütschli, K. Gesell. Wiss. Göttingen Abh., No. 3, 1908.
2. Ash of the epidermis ("lederhaut") of a large holothurian, species and locality not stated; analysis by Hilger. Pflüger's Archiv. f. Physiologie, vol. 10, p. 212, 1875.

Old analyses of holothurians.

	1	2		1	2
Na_2SO_4		4.47	$FeCO_3$		1.02
NaCl		.83	H_2O	3.67	
$CaCO_3$	81.54	78.96	Sand	3.23	
$MgCO_3$	8.10	12.10	SiO_2		.57
$CaSO_4$		1.04	Organic	1.03	
$CaSO_4.2H_2O$	2.09				
$Ca_3P_2O_8$		.96		99.66	99.95

These analyses, together with ours of *Holothuria*, show that the hard parts of these animals, like those of the other echinoderms, are distinctly magnesian. Although definite data are wanting, it seems probable that Hilger's specimen came from warmer water than that analyzed by Bütschli. The sodium salts are of course extraneous.

5. SUMMARY.

From the evidence now available it seems almost certain that the inorganic constituents of any echinoderm will have the composition of a moderately magnesian limestone. There may be exceptions, but none has yet been found. The four tables—for crinoids, sea urchins, starfishes, and holothurians—all tell the same story, and with remarkable unanimity. Furthermore, the proportion of magnesium carbonate appears to be a function of temperature, the organisms from warm waters being richer in it than those from cold waters. The exceptions to this rule are few and may be only apparent, for cold or warm currents and varying depths of water account for nearly all irregularities. Schmelck's analyses of starfishes from the North Sea are the only ones so far which are troublesome to explain.

The sea urchins seem to be a little poorer in magnesia than either of the other groups, but the analyses are fewer and therefore less conclusive. Silica and sesquioxides are probably altogether extraneous, although it is possible that small quantities of them may really belong to the organisms. In phosphate of lime the starfishes are richest, and all the specimens analyzed contain it in small amounts. Whether it is an essential constituent or not is uncertain. As shown by Meigen's reaction, all the echinoderms studied are calcitic, and no evidence of aragonite in them was found.

The temperature relations shown by the analyses offer an interesting biological problem, with which we can not undertake to cope. It is not due to differences of composition in the solid matter of sea water, for that is practically uniform the world over. In all the great oceans, and even in minor bodies of water like the Mediterranean, the Baltic, and the Black seas, the proportion of magnesia to lime is very nearly if not actually constant. In gaseous contents and especially in carbon dioxide the waters vary; the gases being more soluble in cold than in warm water. Whether this fact has any relation to the phenomenon under discussion we can not attempt to say. We can only report the facts and leave their biological discussion to others.

BRYOZOA.

Nine Bryozoa have been analyzed in the course of this research, as follows:

1. *Schizoporella unicornis* Johnston. Vineyard Sound, Mass.; depth of water, 15.5 meters; bottom temperature, 20.5° C.
2. *Schizoporella unicornis* Johnston. Between Johns Pass and Pass a Grille, Fla.
3. *Microporella grisea* Lamouroux. Australia.
4. *Cellepora incrassata* Lamarck. Northeast part of the Grand Banks.
5. *Flustra membranacea truncata* Smith. St. Paul Island, Pribilof group, Alaska; latitude, 57° N.; longitude, 170° W. Only 0.1165 gram available for analysis.
6. *Lepralia pallasiana* Möller. Off Gloucester, Mass. A thin coating on a granite pebble; weight of organism, 0.4078 gram.
7. *Catenicella margaritacea* Busk. Australia.
8. *Bugula turrita* Desor. Georges Bank, off coast of Massachusetts; *Albatross* station 2578; latitude, 41° 20′ 30″ N., longitude, 68° 34′ 30″ W.; depth of water, 67.7 meters; bottom temperature, 12.3° C.
9. *Bugula neritina* Linné. Florida.

The actual analyses are as follows:

Analyses of Bryozoa.

	1	2	3	4	5	6	7	8	9
SiO_2	1.65	2.49	0.17	0.19	3.00	4.78	0.95	8.77	6.31
$(Al,Fe)_2O_3$	.29	.37	.11	.19		.13	.41	1.18	.75
MgO	.28	2.04	.49	2.74	2.06	2.32	3.50	2.55	2.57
CaO	50.90	48.17	50.83	49.36	30.81	43.08	40.83	20.45	19.69
P_2O_5	Trace.	Trace.	.10	Trace.	.09	.11	.16	.38	.60
SO_3	.73	.77	.79	.98	(?)	(?)	1.00	1.47	2.43
Ignition	45.64	45.70	46.80	46.03	61.45	....	52.66	61.51	59.47
	99.49	99.54	99.29	99.49	97.41	50.42	99.51	96.31	91.82
CO_2 needed	39.92	40.16	39.94	41.26	26.39	36.29	35.23	17.69	16.41
Organic matter, etc	5.72	5.54	6.86	5.06	35.06	13.29	17.43	43.82	43.06

Reduced analyses.

	1	2	3	4	5	6	7	8	9
SiO_2	1.77	2.66	0.18	0.20	4.82	5.52	1.15	16.71	12.94
$(Al,Fe)_2O_3$	.31	.39	.12	.20		.15	.50	2.25	1.54
$MgCO_3$	.63	4.58	1.11	6.07	6.94	5.62	8.96	10.19	11.08
$CaCO_3$	95.97	90.97	96.90	91.77	87.92	88.44	86.89	64.51	63.29
$Ca_3P_2O_8$	Trace.	Trace.	.24	Trace.	.32	.27	.43	1.58	2.68
$CaSO_4$	1.32	1.40	1.45	1.76	(?)	($)	2.07	4.76	8.47
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Bryozoa Nos. 1 to 5 were massive coralline forms and were easily handled. No. 6, *Lepralia*, was an incrustation upon a pebble, from which it could not well be separated mechanically. The entire specimen was therefore weighed, the bryozoan was then dissolved by hydrochloric acid, and the pebble was weighed again. The solution only was available for analysis, and the usual loss on ignition could not be determined but was necessarily taken by difference. Such an analysis is obviously unsatisfactory but not entirely worthless. Bryozoa Nos. 7 to 9 were delicate mossy or fernlike organisms, and the poor summations of the last two indicate the presence of undetermined saline matter. The high silica in them is evidently due to inclosed sand. If silica and sesquioxides are rejected and the remainders recalculated to 100 per cent the percentages of magnesium carbonate become 12.51 and 12.95, respectively. The magnesia, however, shows no such regularity as regards temperature as appears in our series of alcyonarians and echinoderms. The difference between the magnesian content of the two specimens of *Schizoporella* is very striking. What this difference may signify is yet to be determined.

Several other analyses of Bryozoa, complete or partial, are recorded in the literature. Two of them, fairly complete, were made by A. Schwager for J. Walther.[1] They are as follows, both specimens being from the Bay of Naples:

1. *Eschara foliacea.*
2. *Lepralia* sp.

Schwager's analyses of Bryozoa.

	Actual analyses.			Reduced analyses.	
	1	2		1	2
SiO_2	0.29	2.39	SiO_2	0.31	2.58
$(Al,Fe)_2O_3$	.32	1.47	$(Al,Fe)_2O_3$	.34	1.58
MgO	1.20	2.22	$MgCO_3$	2.71	5.02
CaO	50.12	47.18	$CaCO_3$	96.64	90.82
CO_2	41.06	39.51			
Organic matter+H_2O	6.88	7.53		100.00	100.00
	99.87	100.00			

The reduced analyses were computed by us from Schwager's data.

In *Flustra foliacea* from California H. W. Nichols[2] found 1.23 per cent of magnesium carbonate, and in a bryozoan from Bermuda 5.35 per cent. Several similar determinations by G. Forchhammer[3] on other Bryozoa gave less than 0.6 per cent. The other constituents of the organisms were not determined, and the figures given for magnesium carbonate therefore have little present value.

From the evidence now at hand no broad general conclusions can be drawn. That the magnesian content of the Bryozoa varies widely, however, is clear, being lowest in the compact coralline forms and highest in the fernlike varieties. Even this conclusion needs to be verified by a much larger series of analyses.

BRACHIOPODS.

A few analyses of brachiopod shells already on record show that they fall into two chemically distinct groups—one calcareous, the other highly phosphatic. This conclusion is supported and emphasized by the new data obtained by us, which also bring out some minor peculiarities that seem not to have been previously observed. For our material we are indebted to Dr. W. H. Dall, who selected typical specimens from among the duplicates in the United States National Museum. First in order come five brachiopods representing as many genera in the calcareous group. The analyses are as follows:

1. *Terebratula cubensis* Pourtalès. Coast of Florida.
2. *Terebratulina septentrionalis* Gray. Eastport, Maine.
3. *Laqueus californicus* Koch. Esteros Bay, Cal.
4. *Rhynchonella psittacea* Gmelin. Shetland Islands.
5. *Crania anomala* Muller. Coast of Norway.

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[1] Deutsch. geol. Gesell. Zeitschr., p. 338, 1885.

[2] Field Columbian Mus. Pub. 111, p. 31, 1906.

[3] Neues Jahrb., p. 854, 1852.

Analyses of calcareous brachiopods.

	1	2	3	4	5
SiO_2	0.06	0.50	0.18	0.14	0.21
$(Al,Fe)_2O_3$	.04	.14	.47	.23	.26
MgO	.44	.62	.32	.23	3.90
CaO	54.96	51.79	54.48	53.76	48.67
SO_3	.21	.66	.21	.31	.97
P_2O_5	Trace.	Trace.	Trace.	.17	.25
Loss on ignition	44.35	45.28	44.46	44.81	45.38
	100.06	98.99	100.12	99.65	99.64
CO_2 needed	43.42	40.55	42.91	42.16	40.88
Organic matter, etc	.93	4.73	1.55	2.65	3.52

Rejecting organic matter and recalculating to 100 per cent, the analyses assume the following rational form:

Reduced analyses.

	1	2	3	4	5
SiO_2	0.06	0.52	0.18	0.15	0.22
$(Al,Fe)_2O_3$	.04	.15	.48	.23	.27
$MgCO_3$	.93	1.37	.68	.49	8.63
$CaCO_3$	98.61	96.78	98.30	98.20	88.59
$CaSO_4$	.36	1.18	.36	.55	1.72
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	.38	.57
	100.00	100.00	100.00	100.00	100.00

For comparison the following analyses of calcareous brachiopods, made elsewhere, are significant:

6. *Terebratula* sp. Collected by Pourtalès between Florida and Cuba; S. P. Sharples, analyst.[1]
7. *Terebratulina caput serpentis.* Locality not given; F. Kunckell, analyst.[2]
8. *Crania anomala* Müller. Locality not given; Kunckell, analyst.
9. *Waldheimia cranium* Müller. Locality not given; Kunckell, analyst.
10. *Waldheimia cranium.* Collected by the Norwegian North Sea Expedition, station 255; latitude, 68° 12′ N.; longitude, 15° 40′ E.; depth, 624 meters; bottom temperature, 6.5° C.
11. *Waldheimia cranium.* Lofoten Islands. Analyses 10 and 11 by L. Schmelck.[3]

Older analyses of calcareous brachiopods.

	6	7	8	9	10	11
SiO_2	......	......	......	......	0.60	(?)
Fe_2O_3	Trace.	......	......	......	.40	0.15
$MgCO_3$	Trace.	1.05	3.4	......	1.20	1.40
$CaCO_3$	98.39	94.6	87.8	96.2	96.20	95.98
$CaSO_4$	......	2.4	2.15	.9	.85	(?)
$Ca_3P_2O_8$	.61	......	.28	.18	......	......
SrO	......	......	......	......	......	Trace.
CaO	......	......	......	.3	......	......
MgO	......	......	1.8	.6	......	......
P_2O_5	......	......	......	......	Trace.	.12
Organic matter	1.00	2.55	4.3	2.0	1.24	1.99
	100.00	100.00	99.73	100.18	100.49	99.64

With these analyses ours agree in a broad, general way, although the older ones vary much as regards completeness. Kunckell's analyses, showing free lime and magnesia, are

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[1] Am. Jour. Sci., 3d ser., vol. 1, p. 168, 1871.

[2] Jour. prakt. Chemie, 2d ser., vol. 59, p. 102, 1899.

[3] Norske Nordhavs Exped., No. 28, p. 129, 1901.

suspicious, but only in this detail; otherwise they have confirmatory value. All the analyses show that brachiopods of this group have shells in which calcium carbonate is the principal constituent and that the proportion of organic matter is low. The only aberrant one is *Crania*, which is noteworthy on account of its high percentage of magnesia. In this respect, Kunckell's analysis, if recalculated to a common basis, agrees approximately with ours. *Rhynchonella* is also interesting for the reason that an analysis by Hilger of shells supposed to belong to this genus indicates that they are phosphatic and practically identical in composition with those of *Lingula*. The authenticity of Hilger's material is questionable, and his analysis will not be reproduced here.

Four analyses of shells of phosphatic brachiopods have been made by us. As these shells contain a large amount of organic matter, which possibly varies with the age or maturity of the animal, we prefer to report our results, as others before us have done, in proximate rather than ultimate form. The analyses are as follows:

1. *Lingula anatina* Gmelin. Coast of Higo Province, Japan. Organic matter, rejected, 40 per cent.
2. *Lingula anatina*. Iloilo, Philippine Islands. Organic matter, rejected, 39.5 per cent.
3. *Discinisca lamellosa* Broderip. Coast of Peru. Organic matter, rejected, 25 per cent.
4. *Glottidia* (formerly *Lingula*) *pyramidata* Stimpson, coast of North Carolina. Organic matter, about 37 per cent; analysis incomplete for lack of sufficient material.

Analyses of phosphatic brachiopods.

	1	2	2	4
SiO_2	0. 91	0. 50	0. 85	0. 49
$(Al,Fe)_2O_3$	. 54	. 29	. 58	1. 16
$MgCO_3$	2. 70	. 79	6. 68	1. 71
$CaCO_3$	1. 18	4. 25	8. 35	(?)
$CaSO_4$	2. 93	4. 18	8. 37	(?)
$Ca_3P_2O_8$	91. 74	89. 99	75. 17	74. 73
	100. 00	100. 00	100. 00	....

These analyses are noteworthy on account of the unusual proportion of calcium sulphate reported in them. *Discinisca* is especially remarkable in this respect and also in its percentage of magnesium carbonate. Small amounts of sulphates have been found in many mollusks and corals as well as in the calcareous brachiopods but in nothing like the proportion given here. A new analysis of *Discinisca* made upon fresh material is much to be desired.

In the older analyses of this group the sulphate seems to have been ignored, or at least to have escaped attention. The figures are as follows:

5. *Lingula ovalis*. Hawaiian Islands; T. S. Hunt, analyst.[1]
6, 7. *Lingula ovalis*. Locality not given; A. Hilger, analyst.[2]
8. *Lingula anatina*. S. Clöez, analyst;[3] recalculated to 100 per cent after rejecting 42.6 per cent of organic matter.

Older analyses of phosphatic brachiopods.

	5	6	7	8
SiO_2	....	0. 18	0. 17	Trace.
$MgCO_3$	....	2. 94	3. 13	....
$CaCO_3$	11. 75	10. 76	10. 86	12. 19
$Ca_3P_2O_8$	85. 79	84. 94	85. 24	77. 17
$Mg_3P_2O_8$	....	....	....	7. 03
$FePO_4$	....	. 77	. 76	3. 61
MgO?	2. 80	....	....	....
	100. 34	99. 59	100. 00	100. 00

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[1] Logan, W. E., and Hunt, T. S., Am. Jour. Sci., 2d ser., vol. 17, p. 237, 1854.

[2] Jour. prakt. Chemie, vol. 102, p. 418, 1867.

[3] Jahresb. Chemie, 1859, p. 642; from L'Institut, 1859, p. 240.

The relatively high figures for calcium carbonate shown in this table are doubtless due to the neglect to determine sulphate. The analysis by Clöez differs from the others principally in form—that is, in its mode of calculation. If the phosphoric oxide in it is assigned entirely to the lime, then the proportion of calcium phosphate becomes 88.6 per cent, which is well in line with the other figures. The amount of calcium carbonate would be correspondingly reduced.

The brachiopods, as stated at the beginning of this section, fall into two distinct groups; the shells of one consist mainly of calcium carbonate, with little organic matter, and those of the other predominatingly of calcium phosphate, with much organic matter. The two groups, although they may be alike structurally, are physiologically quite dissimilar, the chemical reactions involved in building the shells being of two different orders. Such a distinction ought to be significant to biologists and it is for them to determine what it means. Geologically, however, we can see that the phosphatic brachiopods have probably played some part in the formation of phosphatic sediments, a function which is shared by vertebrate animals and some crustaceans.

MOLLUSKS.

Numerous analyses of molluscan shells have been published, and they show remarkable uniformity of composition. It has nevertheless seemed desirable to make a liberal series of new analyses, which are best classified into groups. Sulphates were not determined, except in four analyses.

1. PELECYPODS.

The pelecypod shells analyzed are as follows:

1. *Astarte crenata* Gray. Off Marthas Vineyard, Mass.; depth of water, 668 meters; bottom temperature, 72° C.
2. *Callista convexa* Say. Vineyard Sound, Mass.
3. *Macoma sabulosa* Spengler. Massachusetts Bay; depth, 825 meters; bottom temperature, 5.5° C.
4. *Pecten dislocatus* Say. Charlotte Harbor, Fla.
5. *Pecten ventricosus* Sowerby. Head of Concepcion Bay, Lower California.
6. *Venericardia ventricosa* Gould. Off Point Concepcion, southern California; latitude, 34° 25′ N.; depth, 447 meters; bottom temperature, 7.3° C.
7. *Cardium substriatum* Conrad. Long Beach, Cal.
8. *Calyptogena pacifica* Dall. Clarence Strait, Alaska; latitude, 55° 46′ N.; depth, 589 meters; bottom temperature, 5.8° C.
9. *Nucula expanser* Hancock. North of Bering Strait.
10. *Acila mirabilis* Adams and Reeve. Japan Sea, off the coast of Chosen (Korea); depth, 128 meters; bottom temperature, 16° C.
11. *Placuna orbicularis* Retzius. Off Luzon, Philippine Islands.

Analyses of pelecypod shells.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	0.25	0.18	0.29	0.31	0.14	0.12	0.11	0.08	0.33	0.09	0.00
$(Al,Fe)_2O_3$	.08	.11	.22	.08	.15	.08	.09	.04	.46	.08	.08
MgO	.00	Trace.	.00	.46	.34	.00	Trace.	.00	Trace.	.00	.32
CaO	53.92	53.67	43.77	53.68	54.13	54.16	53.99	53.95	51.18	53.36	53.80
P_2O_5	Trace.	.03	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	.17	Trace.	Trace.
Ignition	44.79	44.77	44.62	44.34	44.36	44.65	44.85	44.93	46.67	45.59	44.10
	99.04	98.76	98.90	98.87	99.12	99.01	99.04	99.00	98.81	99.12	98.30
CO_2 needed	42.37	42.10	42.25	42.69	42.90	42.55	42.41	42.39	39.86	41.93	41.73
Organic matter, etc.	2.42	2.67	2.37	1.65	1.46	2.10	2.44	2.54	6.81	3.66	2.37

Reduced analyses.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	0.26	0.19	0.30	0.32	0.14	0.13	0.11	0.09	0.36	0.10	0.00
$(Al,Fe)_2O_3$	.09	.12	.23	.08	.15	.08	.09	.04	.50	.08	.08
$MgCO_3$	.00	Trace.	.00	1.00	.73	.00	Trace.	.00	Trace.	.00	.70
$CaCO_3$	99.65	99.62	99.47	98.60	98.98	99.79	99.80	99.87	98.74	99.82	99.22
$Ca_3P_2O_8$	Trace.	.07	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	.40	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100,00

2. SCAPHOPODS AND AMPHINEURANS.

Under this heading we have only two analyses to offer, as follows:

12. *Dentalium solidum* Verrill. Off Georges Bank, east of Cape Cod, Mass.; depth of water, 2,361 meters; bottom temperature, 4.5° C.

13. *Mopalia muscosa* Gould. Santa Barbara, Cal. A chiton.

Analyses of scaphopods and amphineurans.

Analyses.		
	12	13
SiO_2	0.39	0.59
$(Al,Fe)_2O_3$	.26	.21
MgO	.09	.25
CaO	53.89	53.42
SO_3	(?)	.20
P_2O_5	Trace.	Trace.
Ignition	44.48	44.74
	99.11	99.41
CO_2 needed	42.44	42.13
Organic matter, etc	2.04	2.61

Reduced analyses.		
	12	13
SiO_2	0.40	0.61
$(Al,Fe)_2O_3$	.27	.22
$MgCO_3$	.20	.45
$CaCO_3$	99.13	98.37
$CaSO_4$	(?)	.35
$Ca_3P_2O_8$	Trace.	Trace.
	100.00	100.00

3. GASTROPODS.

14. *Purpura lapillus* Linné. Eastport, Maine.

15. *Aporrhais occidentalis* Beck. Off Marthas Vineyard, Mass.; depth of water, 435.5 meters; bottom temperature, 5.5° C.

16. *Buccinum undatum* Linné. Narragansett Bay, R. I.; depth, 53.3 meters; bottom temperature, 9° C.

17. *Natica duplicata* Say. Cape Lookout, N. C.

18. *Olivia literata* Lamarck. Sarasota, Fla.

19. *Fasciolaria distans* Lamarck. Sarasota, Fla.

20. *Crepidula onyx* Sowerby. San Pedro, Cal.

21. *Antiplanes perversa* Gabb. Off Bodega Head, Cal.; latitude, 38° 23′ 35″ N.; depth, 112.5 meters; bottom temperature, 9° C.

22. *Nassa californiana* Conrad. Monterey Bay, Cal.; latitude, 36° 47′ 50″ N.; depth, 67.7 meters; bottom temperature, 11.3° C.

23. *Nassa tegula* Reeve. Musgrove Island, Magdalena Bay, Lower California.

24. *Nassa insculpta* Carpenter. Cortez Bank, Cal.; latitude, 32° 20′ 30″ N.; depth, 165 meters; bottom temperature, 9.5° C.

25. *Turritella gonostoma* Valenciennes. Mulege, Gulf of California.

26. *Volutometra alaskana* Dall. Off Unalaska, Alaska; latitude, 55° N.; depth, 143 meters; bottom temperature, 4.5° C.

27. *Pyrolofusus harpa* Mörch. Unalaska, Alaska.

28. *Plicifusus dirus* Reeve. Sitka Harbor, Alaska.

29. *Tachyrynchus erosa* Couthouy. Avatcha Bay, Kamchatka.

30. *Ranella pulchra* Gray. China Sea, north of Prabas Island; depth, 256 meters; bottom temperature, 14.2° C.

31. *Cerithium aluco* Linné. Reef opposite Cebu, Philippine Islands.

32. *Strombus canarium* Linné. Subig Bay, Luzon, Philippine Islands.

33. *Cavolina longirostris* Lesueur. Off Adyagan Island, Philippines; depth, 247 meters.

Analyses of gastropods.

	14	15	16	17	18	19	20	21	22	23
SiO_2	0.14	1.27	0.94	0.00	0.05	0.33	0.15	0.46	0.27	2.07
$(Al,Fe)_2O_3$	.15	.22	.41	.05	.04	.04	.11	.11	.12	.33
MgO	.19	Trace.	.12	Trace.	.00	.06	Trace.	Trace.	.17	.20
CaO	53.34	52.84	52.77	54.83	54.38	53.87	53.63	54.06	53.20	51.30
SO_3	(?)	.08	(?)	(?)	(?)	(?)	.00	(?)	(?)	(?)
P_2O_5	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	.08
Ignition	45.33	44.09	44.49	44.22	44.46	44.49	44.40	44.15	44.84	44.76
	99.15	98.50	98.73	99.10	98.93	98.79	98.29	98.78	98.60	98.74
CO_2 needed	42.12	41.52	41.59	43.08	42.73	42.39	42.14	42.48	41.99	40.37
Organic matter, etc	3.21	2.57	2.90	1.14	1.73	2.10	2.26	1.67	2.85	4.39

	24	25	26	27	28	29	30	31	32	33
SiO_2	0.47	0.25	0.07	0.08	0.16	0.23	2.20	0.00	0.08	0.71
$(Al,Fe)_2O_3$	.47	1.83	.17	.08	.22	.81	.61	.09	.20	.39
MgO	.77	.20	Trace.	Trace.	.11	.44	.23	Trace.	Trace.	.09
CaO	49.32	52.57	53.88	54.23	52.66	49.30	52.63	54.47	54.04	53.73
SO_3	(?)	.11	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)
P_2O_5	.04	Trace.	Trace.	Trace.	Trace.	.36	Trace.	Trace.	Trace.	.38
Ignition	48.00	43.51	44.60	44.42	45.83	47.60	43.31	44.37	44.31	43.82
	99.07	98.47	98.72	98.81	98.98	98.74	98.98	98.93	98.63	99.12
CO_2 needed	39.51	41.46	42.33	42.61	41.50	38.54	41.64	42.80	42.46	41.96
Organic matter, etc	8.49	2.05	2.27	1.81	4.33	9.06	1.67	1.57	1.85	1.86

Reduced analyses.

	14	15	16	17	18	19	20	21	22	23
SiO_2	0.15	1.32	0.98	0.00	0.05	0 34	0.16	0.48	0.28	2.19
$(Al,Fe)_2O_3$	.16	.23	.43	.05	.04	.04	.11	.11	.13	.35
$MgCO_3$	.41	Trace.	.26	Trace.	.00	.14	Trace.	Trace.	.37	.44
$CaCO_3$	99.28	98.30	98.33	99.95	99.91	99.48	99.73	99.41	99.22	96.84
$CaSO_4$	(?)	.15	(?)	(?)	(?)	(?)	.00	(?)	(?)	(?)
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	Trace.	.18
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

	24	25	26	27	28	29	30	31	32	33
SiO_2	0.52	0.26	0.07	0.08	0.17	0.26	2.26	0.00	0.09	0.73
$(Al,Fe)_2O_3$	.52	1.89	.18	.08	.23	.90	.63	.10	.21	.40
$MgCO_3$	1.78	.44	Trace.	Trace.	.24	1.02	.51	Trace.	Trace.	.20
$CaCO_3$	97.08	97.21	99.75	99.84	99.36	97.00	96.60	99.90	99.70	97.82
$CaSO_4$	(?)	.20	(?)	(?)	(?)	(?)	(?)	(?)	(?)	(?)
$Ca_3P_2O_8$	.10	Trace.	Trace.	Trace.	Trace.	.82	Trace.	Trace.	Trace.	.85
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

4. CEPHALOPODS.

34. *Nautilus pompilius* Linné. Mindanao, Philippine Islands.
35. *Argonauta argo* Linné; the paper nautilus. High seas, Pacific Ocean.
36. *Sepia* sp.; cuttle-fish bone. Port Tataan, Tawi Tawi group, Philippine Islands.

Analyses of cephalopods.

	34	35	36
SiO_2	0.18	0.08	0.00
$(Al,Fe)_2O_3$	.14	.12	.06
MgO	.07	2.58	.66
CaO	52.44	46.78	47.42
P_2O_5	Trace.	Trace.	Trace.
Ignition	46.65	49.16	51.63
	99.48	98.72	99.77
CO_2 needed	41.28	42.30	38.65
Organic matter, etc	5.37	6.86	2.98

Reduced analyses.

	34	35	36
SiO_2	0.19	0.09	0.00
$(Al,Fe)_2O_3$	.15	.13	.06
$MgCO_3$	.16	6.02	1.62
$CaCO_3$	99.50	93.76	98.32
$Ca_3P_2O_8$	Trace.	Trace.	Trace.
	100.00	100.00	100.00

For comparison a series of four analyses of cephalopod shells by O. Bütschli[1] is worth citing in full. They are as follows:

1. *Nautilus pompilius*. 2. *Argonauta argo*. 3. *Spirula peronii*. 4. *Sepia officinalis*.

Analyses of cephalopods by Bütschli.

	1	2	3	4
$CaCO_3$	94.75	85.07	90.43	87.36
$MgCO_3$	.16	5.08	.46	.21
Phosphate	....	3.06	3.20	2.26
$CaSO_4.2H_2O$	.20	1.75	.48	.78
H_2O	2.62	2.92	2.17	4.89
Organic matter	2.03	2.43	2.32	5.36
Sand	....	....	.33	....
	99.76	100.31	99.39	100.86

Exactly what is meant by "phosphate" is not clear. Assuming it to mean calcium phosphate and reducing the analyses to uniformity with ours, they take the following form:

Bütschli's analyses reduced.

	1	2	3	4
$CaCO_3$	99.66	89.93	95.75	96.58
$MgCO_3$	.17	5.37	.48	.23
CaP_2O_8	....	3.24	3.39	2.50
$CaSO_4$	.17	1.46	.38	.69
	100.00	100.00	100.00	100.00

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[1] K. Gesell. Wiss. Göttingen Abh., No. 3, 1908. Bütschli also gives analyses of three other mollusks, *Pinna japonica*, *Patella vulgata*, and *Purpura lapillus*, but they show no unusual features.

The unusual proportion of magnesium carbonate in *Argonauta* is confirmed by our analysis, but the high phosphate in three of Bütschli's analyses is unlike anything in our series. Possibly the calcium sulphate is really present in the hydrated form, that is, as gypsum, but that is uncertain. However, it is not necessary to make that assumption, and to do so would complicate the comparison of analyses.

From the evidence now at hand and from many older data it is clear that molluscan shells consist almost entirely of calcium carbonate with quite insignificant impurities. The only notable exception is *Argonauta*, which contains 6 per cent of magnesium carbonate, but the paper nautilus has no importance as a contributor to the marine sediments. The mollusks generally are of immense importance, a fact to which their fossil remains abundantly testify. In composition they resemble the corals and millepores, so much so that an analysis from one group might readily pass for an analysis from the other.[1]

CRUSTACEANS.

The 19 crustaceans analyzed in the course of this investigation fall into two distinct groups. First, the barnacles, which have shells composed mainly of calcium carbonate with very little organic matter. Second, a group of the more familiar crustaceans, such as crabs, shrimps, and lobsters. These have shells containing notable amounts of calcium phosphate and much organic matter. The analyses of the first group cover the following species:

1. *Lepas anatifera* Linné. Florida.
2. *Lepas anserifera* Linné. Woods Hole, Mass.
3. *Mitella polymerus* Sowerby. Pacific Grove, Cal.; latitude, 36° 36′ N.; longitude, 121° 55′ W.
4. *Balanus hameri* Ascanius. Georges Bank, east of Cape Cod, Mass.
5. *Balanus amphitrite niveus* Darwin. Cape May, N. J.
6. *Balanus eburneus* Gould. Smiths Creek, Potomac River, Md.
7. *Scalpellum regium* Wyville Thomson and Hoek. *Albatross* station 3342; off Queen Charlotte Islands; latitude, 52° 39′ 30″ N.; longitude, 132° 38′ W.; depth of water, 2,906 meters; bottom temperature, 18° C.

The analyses are as follows:

Analyses of barnacles.

	1	2	3	4	5	6	7
SiO_2	0.04	0.04	0.08	0.03	1.99	0.39	0.73
$(Al,Fe)_2O_3$	.19	.56	.30	.14	.68	.22	
MgO	1.14	.86	.94	.35	.73	.76	1.03
CaO	52.33	52.53	50.83	53.57	50.09	53.23	52.65
P_2O_5	Trace.	.34	Trace.	.00	Trace.	Trace.	Trace.
Ignition	44.50	43.90	46.18	44.39	44.84	44.28	44.79
	98.20	98.23	98.33	98.48	98.33	98.88	99.20
CO_2 needed	42.37	41.82	40.97	42.47	40.16	42.67	42.48
Organic, etc	2.13	2.08	5.21	1.92	4.68	1.61	2.31

Reduced analyses.

	1	2	3	4	5	6	7
SiO_2	0.04	0.04	0.09	0.03	2.12	0.40	0.75
$(Al,Fe)_2O_3$	.20	.58	.33	.15	.72	.22	
$MgCO_3$	2.49	1.87	2.11	.75	1.63	1.65	2.23
$CaCO_3$	97.27	96.74	97.47	99.07	95.53	97.73	97.02
$Ca_3P_2O_8$	Trace.	.77	Trace.	.00	Trace.	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00

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[1] For additional data see L. Schmelck, Norske Nordhavs Exped., No. 28, p. 129, 1901. Fourteen analyses of molluscan shells are given, of the genera *Buccinum*, *Astarte*, *Neptunea*, and *Pecten*, all from the North Sea. The highest percentage of magnesium carbonate found was 0.78, the lowest 0.26. For ten complete analyses of oyster shells see Chatin, A., and Muntz, A., Compt. Rend., vol. 120, p. 531, 1895. For eleven analyses of land shells see an inaugural dissertation by A. Döring, Göttingen, 1872. Several determinations of magnesium carbonate, maximum 1 per cent, are given by G. Forchhammer in Neues Jahrb., 1852, p. 854.

Sulphates and soluble salts were not determined. Except for the slightly higher magnesia, these analyses closely resemble those of mollusks.

One analysis of a barnacle, *Balanus tintinnabulus*, by Bütschli,[1] is essentially similar to ours. His figures are—

$CaCO_3$	94.44
$MgCO_3$	1.20
$Ca_3P_2O_8$	.36
$CaSO_4.2H_2O$	2.06
	98.06

In all the analyses calcium carbonate is the main constituent, and there are only minor impurities. We have found no other analysis of a barnacle recorded.

In the second group of crustaceans the following species were analyzed:

1. *Tryphosa pinguis* Boeck; sand flea. Woods Hole, Mass.
2. *Pagurus rathbuni* Benedict; hermit crab. Bering Sea; *Albatross* station 3531; latitude, 50° 55′ N.; longitude, 174° 17′ W.; depth of water, 105 meters; bottom temperature, 1.7° C.
3. *Callinectes sapidus* M. J. Rathbun; blue crab. Ranges from Cape Cod to Florida.
4. *Homarus americanus* Milne Edwards; common lobster. Vineyard Sound, Mass.
5. *Pandalus platyceros* Brandt; shrimp. Off Monterey Bay, Cal.; *Albatross* station 3129; latitude, 36° 39′ 40″ N.; longitude, 122° 01′ W.; depth, 49.4 meters; bottom temperature, 6.5° C.
6. *Lithodes maia* Linné; spider crab. North Atlantic coast, precise locality of specimen unknown.
7. *Libinia emarginata* Leach; spider crab. Vineyard Sound, Mass.
8. *Munida iris* Milne Edwards; long-armed munida. Off Chesapeake Bay; *Albatross* station 2420; latitude, 37° 03′ 20″ N.; longitude, 74° 31′ 40″ W.; depth, 190.3 meters; bottom temperature, 8.7° C.
9. *Crago dalli* Rathbun; a shrimp. Off Cape Stroganoff, Alaska; *Albatross* station 3294; latitude, 57° 16′ 45″ N.; longitude, 159° 03′ 30″ W.; depth, 54.9 meters; bottom temperature, 5° C.
10. *Panulirus argus* Latreille; spiny lobster. West Indies.
11. *Chloridella empusa* Say; mantis shrimp. Ranges from Cape Cod to Florida.
12. *Penæus brasiliensis* Latreille; edible shrimp. Ranges from New York to Brazil.

Analyses of crustaceans.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	0.62	0.16	0.04	0.00	0.32	0.00	2.61	0.32	0.62	0.16	0.02
$(Al,Fe)_2O_3$	.37	.15	.04	.21	.26	.15	.78	.16	.20	.13	.17
MgO	1.27	1.55	2.06	2.35	1.44	1.90	2.81	2.58	1.01	3.15	2.60
CaO	28.63	29.11	33.42	31.35	18.56	24.15	32.79	31.28	9.95	25.36	15.38
P_2O_5	4.56	3.25	4.26	3.04	4.60	3.51	2.73	1.87	2.65	2.09	7.75
SO_3	.23	.75	.23	.45	.54	.63	.49	.47	.47	.41	1.07
Ignition	64.73	64.50	58.89	61.82	73.81	69.00	57.07	62.29	83.70	66.69	72.35
	100.41	99.47	98.94	99.22	99.53	99.34	99.28	98.97	98.60	97.99	99.34
CO_2 needed	19.53	21.14	24.43	24.08	11.58	17.46	26.05	25.41	6.20	21.23	7.15
Organic matter, etc.	45.20	43.36	34.46	37.74	62.23	51.54	31.02	36.88	77.50	45.46	65.20

In No. 12, the common edible shrimp of the Washington (D. C.) markets, the shell was so thin that the available material was too small for complete analysis. Only P_2O_5, 3.07 per cent, was determined.

Reduced analyses.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	1.12	0.28	0.06	0.00	0.87	0.00	3.82	0.52	2.94	0.31	0.06
$(Al,Fe)_2O_3$	.67	.27	.06	.34	.70	.31	1.14	.27	.95	.25	.50
$MgCO_3$	4.84	5.80	6.69	8.02	8.09	8.35	8.65	8.71	10.05	12.58	15.99
$CaCO_3$	74.64	78.03	78.14	79.50	60.94	73.07	76.44	82.64	54.83	76.87	28.56
$Ca_3P_2O_8$	18.02	13.55	14.45	10.91	26.94	16.03	8.73	6.57	27.44	8.68	49.56
$CaSO_4$	.71	2.07	.60	1.23	2.46	2.24	1.22	1.29	3.79	1.31	5.33
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

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[1] K. Gesell. Wiss. Göttingen Abh., No. 3, 1908.

The crustaceans of this second group are very different in composition from the barnacles. They are distinctly phosphatic, a fact which was already known, and they are also notably magnesian, a peculiarity which, with a single exception, to be noted later, seems to have escaped serious attention hitherto. The proportion of magnesium carbonate appears to be somewhat dependent on temperature, as was shown in our analyses of echinoderms and alcyonarians; but the evidence for such a variation is not conclusive. Analysis 2, of a crab from Bering Sea, is low in magnesia; analysis 10, of a West Indian specimen, is high. Analyses 5, 6, 7, and 8 are intermediate in their magnesian content, and so far as can be determined from the evidence before us, they represent specimens from waters of intermediate and similar temperatures. Unfortunately the records for some specimens are defective as to precise localities and temperatures. Furthermore, the large amounts of organic matter and water render the reduced analyses to some extent unsatisfactory. This is especially true of analysis No. 9, in which the inorganic portion amounted to only 21 per cent. In reducing such an analysis the unavoidable analytical errors are multiplied, and the percentages of magnesium carbonate, calcium carbonate, and calcium phosphate may be uncertain by as much as 1 per cent each. In no case is the order of magnitude seriously changed, but the accuracy of the figures is not what we should wish it to be. The variation in the percentages of magnesium carbonate is, however, suggestive, in spite of all real or apparent irregularities.

The older analyses of the shells of crustaceans are more or less unsatisfactory, but they all agree as to the phosphatic character of these organisms. C. Schmidt,[1] for example, gives three analyses, as follows:

1. *Astacus fluviatilis;* fresh-water crawfish. 53.27 per cent inorganic.
2. Lobster; probably either *Homarus vulgaris* or *Palinurus.* 77.06 per cent inorganic.
3. *Squilla mantis;* a shrimp. 37.17 per cent inorganic.

Schmidt's analyses of crustaceans.

	1	2	3
$Ca_3P_2O_8$	13.17	12.06	47.52
$CaCO_3$	86.83	87.94	52.08
	100.00	100.00	100.00

The figures given here are for the inorganic matter alone. Schmidt mentions magnesium phosphate as present but gives no determinations of it.

Two analyses of crustacean shells by E. Fremy[2] are also worth citing:

1. "Langouste"; *Palinurus vulgaris.*
2. "Ecrevisse"; probably the crawfish, *Astacus fluviatilis.*

Fremy's analyses of crustaceans.

	1	2
$Ca_3P_2O_8$	6.7	6.7
$CaCO_3$	49.0	56.8
Organic matter	44.3	36.5
	100.0	100.0

Here, again, the determination of magnesia has been neglected. If we reject the organic matter, the percentages of calcium phosphate in the inorganic part of the shells become 12.03 and 10.55, respectively.

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[1] Annalen Chemie Pharm., vol. 54, p. 303, 1845.

[2] Annales chimie et phys., 3d ser., vol. 43, p. 94, 1855. Fremy also gives many analyses of vertebrate bones, both recent and fossil.

Astacus fluviatilis seems to have received more attention from chemists than any other crustacean. H. Weiske[1] found in fresh shells 4.97 to 5.31 per cent of calcium phosphate and in old shells, partly cast off, 9.16 to 9.21 per cent. In "Krebsteine," the concretions found in the shells, the percentages ran from 10.73 to 11.28 per cent. The total inorganic matter varied between 61 and 67 per cent.

Astacus has also been studied by Agnes Kelly,[2] who also analyzed a myriapod, *Julus* (*Iulus*). Her figures are as follows:

Analyses by Agnes Kelly.

	Astacus.	Julus.
CaO	30.44	36.29
CO_2	21.23	21.60
P_2O_5	2.79	3.37
	54.52	56.26

In an analysis of *Astacus fluviatilis* by O. Bütschli[3] magnesia was actually determined. We append his analysis, together with our own reduction of it:

Bütschli's analysis of Astacus.

Actual analysis.		Reduced analysis.	
$CaCO_3$	47.51	$CaCO_3$	83.40
$MgCO_3$	1.38	$MgCO_3$	2.42
Phosphate	6.77	$Ca_3P_2O_8$?	11.88
$CaSO_4.2H_2O$	1.66	$CaSO_4$	2.30
H_2O	1.34		
Organic matter	40.60		100.00
	99.26		

In this analysis the low percentage of magnesia is very significant. *Astacus* is a fresh-water crustacean, whereas the analyses in our series are all of marine forms. In fresh water—the average river water—calcium is 6 times as abundant as magnesium, but in ocean water magnesium is 3½ times as abundant as calcium. This difference in the environment may possibly explain the difference between the fluviatile and the marine shells, 2.42 per cent of $MgCO_3$ in one and 4.84 per cent in the lowest of our determinations.

One more determination of phosphoric oxide in a crustacean remains to be noted. In the shell of a lobster, *Homarus vulgaris*, W. H. Hudleston[4] found 3.26 per cent of P_2O_5. This is equivalent to 7.12 per cent of $Ca_3P_2O_8$, or, if the organic matter was about the same in amount as in our analysis of the American lobster, 11.44 per cent in the inorganic portion alone. This is not far from the figure given in our reduced analysis No. 4, namely, 10.91 per cent.

Although the crustaceans are not of great importance as contributors to the marine sediments, they are more important than appears at a casual glance. A crab or lobster sheds its shell annually and grows a new one, so that an old individual has contributed many times. A single shell might count for little, but when multiplied by a dozen or more the contributions become significant. How significant they may be is for zoologists to determine.

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[1] Landwirthschaftliche Versuchsstationen, vol. 20, p. 45, 1877.

[2] Jenaisches Zeitschr., vol. 35, p. 429, 1901.

[3] K. Gesell. Wiss. Göttingen Abh., No. 3, 1908.

[4] Geol. Soc. Quart. Jour., vol. 31, p. 376, 1875.

CALCAREOUS ALGÆ.

The calcareous algæ are so important as reef builders that, although they are not marine invertebrates in the ordinary acceptance of the term, it seemed eminently proper to include them in this investigation. In many places they far outrank the corals in importance, and of late years much attention has been paid to them. To Dr. Marshall A. Howe, of the New York Botanical Garden, we are indebted for a fine series of algæ, and to him we express our thanks.

For the purposes of this research the calcareous algæ fall into two groups. One of these, of which *Lithothamnium* is the most familiar example, is highly magnesian; the other, represented by *Halimeda*, is almost free from magnesia. These groups are best considered separately, and under the first one we have the following species:

1. *Lithothamnium glaciale* Kjellman. Topsail, Conception Bay, Newfoundland; latitude, 48° N.; longitude, 53° W.
2. *Lithothamnium erubescens* Foslie. Haingsisi, near Timor, East Indian Archipelago.
3. *Archæolithothamnium episporum* Howe. Point Toro, near Colon, Isthmus of Panama.
4. *Lithophyllum craspedium* Foslie. Palmyra Island, in the Pacific Ocean, west of south from Hawaii; latitude, 5° 49′ N.
5. *Lithophyllum pallescens* Foslie. Bay of La Paz, Gulf of California; latitude, 24° 16′ N.
6. *Lithophyllum dædalium* Foslie and Howe. Salinas Bay, near Guanica, Porto Rico; latitude, about 18° N.
7. *Lithophyllum antillarum* Foslie and Howe. Culebra Island, Porto Rico; latitude, about 18° 20′ N.
8. *Lithophyllum oneodes* Heydrich. Coetivy Island, in the Indian Ocean, northeast of Madagascar; latitude, 7° 6′ S.; longitude, 56° 30′ E.
9. *Lithophyllum intermedium* Foslie. Fort Kingston, near Clarence, Jamaica.
10. *Lithophyllum pachydermum* Foslie. Dollar Harbor, South Cat Cay, Bahamas; latitude, about 25° N.
11. *Lithophyllum tamiense* Heydrich. New Guinea.
12. *Amphiroa fragilissima* Lamouroux. Lemon Bay, near Guanica, P. R.
13. *Phymatolithon compactum* Foslie. Torbay, Newfoundland.
14. *Goniolithon acropetum* Foslie and Howe. Culebra Island, P. R.
15. *Goniolithon strictum* Foslie. Bemini Harbor, Bahamas.
16. *Goniolithon strictum*. Soldiers Key, Fla.

The actual analyses are as follows:

Analyses of algæ.

	1	2	3	4	5	6	7	8
SiO_2	0.41	0.19	1.47	0.03	1.01	0.18	0.04	0.09
$(Al,Fe)_2O_3$	.23	.12	.89	.09	.22	.08	.10	.12
MgO	4.78	7.52	5.93	8.64	6.42	8.14	7.24	8.07
CaO	45.41	42.96	44.80	41.56	40.39	40.48	43.34	42.57
P_2O_5	Trace.	Trace.	Trace.	.03	.11	Trace.	Trace.	.08
SO_3	.14	.61	.53	.15	.71	.44	.57	.27
Ignition	48.00	47.89	45.69	48.37	49.94	49.99	48.11	47.96
	98.97	99.29	99.31	98.87	98.80	99.31	99.40	99.16
CO_2 needed	40.86	41.69	41.43	42.04	38.31	40.51	41.70	42.11
Organic matter, etc	7.14	6.20	4.26	6.33	11.63	9.48	6.41	5.85

	9	10	11	12	13	14	15	16
SiO_2	0.27	0.04	0.12	2.82	0.10	0.06	0.02	0.05
$(Al,Fe)_2O_3$	.21	.08	.16	1.31	.23	.04	.01	
MgO	7.25	6.47	8.81	6.71	4.02	8.27	10.39	10.93
CaO	42.55	42.60	41.07	34.82	38.19	40.60	38.54	38.03
P_2O_5	Trace.	.00	Trace.	Trace.	.10	.18	Trace.	Trace.
SO_3	.02	.59	.69	.56	.52	.62	.60	.61
Ignition	48.63	49.55	48.77	48.78	55.42	49.56	49.91	49.91
	98.93	99.33	99.62	95.00	98.58	99.33	99.47	99.53
CO_2 needed	41.89	40.24	41.58	34.43	35.05	40.50	41.38	41.56
Organic matter, etc	6.74	9.31	7.19	14.35	20.37	9.06	8.53	8.35

The low summation of No. 12, a very fragile form, is due to inclosed salts, mainly alkaline chlorides and sulphates. These were determined as 5.40 per cent, which brings the summation up to 100.40.

Reducing the analyses, as usual, to standard form, we have the following table:

Reduced analyses.

	1	2	3	4	5	6	7	8
SiO_2	0.45	0.20	1.55	0.03	1.16	0.20	0.04	0.10
$(Al,Fe)_2O_3$	.25	.13	.94	.10	.25	.09	.11	.13
$MgCO_3$	10.93	16.96	13.09	19.60	15.46	19.03	16.35	18.17
$CaCO_3$	88.11	81.59	83.47	79.92	81.48	79.85	82.46	80.93
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	.08	.26	Trace.	Trace.	.18
$CaSO_4$	.26	1.12	.95	.27	1.39	.83	1.04	.49
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

	9	10	11	12	13	14	15	16
SiO_2	0.30	0.04	0.13	3.50	0.13	0.07	0.02	0.06
$(Al,Fe)_2O_3$	.23	.09	.17	1.62	.30	.05	.01	
$MgCO_3$	16.59	15.08	20.02	17.47	10.93	19.24	24.00	25.17
$CaCO_3$	82.85	83.68	78.43	76.23	87.21	79.05	74.85	73.63
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.	.29	.43	Trace.	Trace.
$CaSO_4$	.03	1.11	1.25	1.18	1.14	1.16	1.12	1.14
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

In No. 12, *Amphiroa*, the high silica and sesquioxides are evidently impurities. If they are rejected, the percentage of magnesium carbonate rises to 18.41.

Of *Halimeda*, four species were analyzed, as follows:

17. *Halimeda opuntia* Lamouroux. Key West, Fla.
18. *Halimeda simulans* Howe. East of Guanica Harbor, Porto Rico.
19. *Halimeda tridens* Lamouroux. Cayo Maria Langa, Bay of Guayanilla, Porto Rico.
20. *Halimeda monile* Lamouroux. Same locality as No. 19.

Analyses of Halimeda.

	17	18	19	20
SiO_2	0.37	0.44	0.88	1.90
$(Al,Fe)_2O_3$	.20	.18	.58	1.10
MgO	.01	.19	.44	.45
CaO	50.32	50.20	45.32	48.21
P_2O_5	Trace.	Trace.	Trace.	Trace.
SO_3	.07	.23	.49	.02
Ignition	48.20	48.38	51.94	47.56
	99.17	99.62	99.65	99.24
CO_2 needed	39.47	39.53	35.83	38.35
Organic matter, etc	8.73	8.85	16.11	9.21

Reduced analyses.

	17	18	19	20
SiO_2	0.41	0.48	1.04	2.11
$(Al,Fe)_2O_3$	.22	.20	.68	1.22
$MgCO_3$	.02	.44	1.09	1.04
$CaCO_3$	99.21	98.45	96.21	95.58
$Ca_3P_2O_8$	Trace.	Trace.	Trace.	Trace.
$CaSO_4$	.14	.43	.98	.05
	100.00	100.00	100.00	100.00

After allowance is made for obvious impurities the essential identity of these four analyses becomes clear. The inorganic portion of *Halimeda* consists of calcium carbonate and an insignificant amount of magnesia. In the first group of algæ, Nos. 1 to 16, magnesium carbonate is conspicuous, more so than in any other class of organisms so far analyzed. In *Goniolithon strictum* especially it ranges from 24 to over 25 per cent, or more than half way to dolomite These algæ are probably the largest contributors of magnesia to the marine limestones.

It is also noteworthy that the two algæ of the first group, Nos. 1 and 13, are from the cold waters of Newfoundland, and that the others are from tropical or subtropical regions. Several, if not all of them, are shoal-water organisms and were collected on reefs, or rocks, or on sands near low-tide levels. It is desirable that Arctic species should be carefully studied—at least more carefully than hitherto. The older published data leave much to be desired, especially as to definiteness of species and localities.

Of the earlier analyses of calcareous algæ those by A. Damour[1] are the most complete and most nearly comparable with ours. Five species were analyzed, as follows:

1. *Lithophyllum* sp. Mediterranean Sea.
2. *Melobesia* sp. Coast of Algeria.
3. *Amphiroa tribulus*. Antilles.
4. *Halimeda opuntia*. Red Sea.
5. *Galaxaura fragilis*. Antilles.

Damour's "*Millepora cevricornis*," of which he gives an analysis, is not included here on account of its doubtful character. (See p. 18.)

Damour's analyses of algæ.

	1	2	3	4	5
$CaCO_3$	77.36	72.78	70.83	86.17	72.56
$MgCO_3$	11.32	12.32	16.99	.56	.86
Na_2O	.55	1.75	.89	1.13	.73
K_2O	.27	.65	.39	.54	1.02
Fe_2O_3	.08	.20	....	....	....
SO_3	.95	1.25	.93	(?)	(?)
P_2O_5	.32	.38	.27	(?)	(?)
Cl	.60	.34	.53	.84	1.17
$CaSO_4$	....	....	.20	.55	1.80
Organic matter	4.70	3.95	6.40	8.30	17.50
H_2O	1.46	1.40	1.38	.90	.95
SiO_2	....	....	....	....	2.20
Sand	1.36	4.28	....	....	....
	98.97	99.30	98.81	98.99	98.79

In these analyses Na_2O, K_2O, Cl, and SO_3 evidently represent sea salts. Rejecting them as impurities, together with the organic matter, water, and sand, and recalculating to 100 per cent, we have the following reduced analyses, which are similar to ours:

Damour's analyses reduced.

	1	2	3	4	5
SiO_2	....	....	....	....	2.84
Fe_2O_3	0.09	0.23	....	....	....
$MgCO_3$	12.76	14.44	19.29	0.64	1.11
$CaCO_3$	86.36	84.36	79.81	98.73	93.73
$Ca_3P_2O_8$	.79	.97	.67	(?)	(?)
$CaSO_4$	....	....	.23	.63	2.32
	100.00	100.00	100.00	100.00	100.00

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[1] Compt. Rend., vol. 32, p. 253, 1851.

Three of these algæ are highly magnesian; *Halimeda* and *Galaxaura* are not.

Two analyses of algæ by A. Schwager were published by J. Walther[1] in 1885. There is also one by C. W. Gümbel,[2] and these three may be combined in one table, as follows:

1. *Lithothamnium* sp. Bay of Naples; Schwager, analyst.
2. *Lithothamnium ramulosum.* Bay of Naples; Schwager, analyst.
3. *Lithothamnium nodosum.* Locality not stated; Gümbel, analyst.

Actual analyses of algæ.

	1	2	3
SiO_2	1.59	1.91	
Al_2O_3	3.36	3.61	2.55
Fe_2O_3	.28	.41	
MnO	Trace.	Trace.	
MgO	1.90	3.06	2.66
CaO	48.09	45.88	47.14
CO_2	39.87	39.41	40.06
P_2O_5			.06
Organic matter+H_2O	5.06	5.57	
Insoluble			4.96
H_2O and loss			2.57
	100.15	99.85	100.00

Reducing these to uniformity with our analyses we have the following table:

Reduced analyses.

	1	2	3
SiO_2	1.68	2.03	
$(Al,Fe)_2O_3$	3.83	4.26	2.76
$MgCO_3$	4.19	6.81	6.06
$CaCO_3$	90.30	86.90	91.04
$Ca_3P_2O_8$			.14
	100.00	100.00	100.00

In these analyses, all of *Lithothamnium*, the percentage of magnesium carbonate is remarkably low. Why this should be so is not clear, but it may be due to differences in the age of the plants; that is, young specimens may have secreted less magnesia proportionally to lime than older, more mature examples. This suggestion might well be tested by special analyses of properly selected material. Until that has been done the suggestion can carry little weight.

Eleven partial analyses of *Lithothamnium*, made by A. G. Högbom,[3] assisted by R. Mauzelius, N. Sahlbom, and J. Guinchard, are curiously irregular. The percentages of magnesium carbonate vary enormously, and with no apparent or even probable relation to temperatures. The data given are as follows:

	$CaCO_3$.	$MgCO_3$.
Lithothamnium sp. Java Sea	72.03	3.76
Lithothamnium sp. Galapagos Islands	83.60	6.53
Lithothamnium sp. Spitzbergen	84.83	8.67
Lithothamnium polymorphun. Kattegat	74.22	9.10
Lithothamnium sp. Honolulu	84.01	9.39
Lithothamnium ramulosum. Naples	63.00	9.46
Lithothamnium soriferum. Arctic Ocean	80.90	9.56
Lithothamnium sp. Bering Islands	74.24	4.94
Lithothamnium racemus. Naples	77.39	11.33
Lithothamnium sp. Bermuda	82.44	12.37
Lithothamnium glaciale. Arctic Ocean	83.10	13.19

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[1] Deutsch. geol. Gesell. Zeitschr., p. 338, 1885.

[2] K. bayer. Akad. Wiss. Abh., Math.-phys. Classe, vol. 2, p. 26.

[3] Neues Jahrb., 1894, Band 1, p. 262.

In this series the percentages of magnesium carbonate are much lower than those found by us, and there is uncertainty in six examples as to the exact species. Högbom, however, points out the importance of these algæ in respect to the formation of dolomite, which was the real subject of his investigation. In *Halimeda* sp., from Labuan, only a trace of magnesia was found.

In *Lithothamnium racemus,* from the Bahamas, H. W. Nichols[1] found 5.35 per cent of magnesium carbonate, but without rejection of organic matter, etc., undetermined. This percentage is remarkably low. A similar low figure for magnesium carbonate—5.85 per cent—was found by E. W. Skeats[2] in *Lithothamnium phillipi* var. *funafutiensis* Foslie. The specimen was taken on the atoll of Funafuti.

In a very fresh *Halimeda opuntia* Skeats found 0.60 per cent of $MgCO_3$ and 86.50 of $CaCO_3$, but in a mass of fronds dredged up from a depth between 50 and 60 fathoms the percentages were 4.0 $MgCO_3$ to 93.59 $CaCO_3$. The increase in magnesia may have been due to concentration by leaching. These data are given by J. W. Judd,[3] who also cites an analysis of dead *Halimeda* fronds made for him by C. G. Cullis, who found in them 1.39 per cent of $MgCO_3$ and 98.32 of $CaCO_3$. Judd also quotes an analysis of *Halimeda,* cited by Payen in his Flora, which contained 5.50 per cent of $MgCO_3$ and 90.16 of $CaCO_3$. The character of the specimen represented by the last analysis, whether fresh or old, is uncertain. The best analyses agree in assigning little magnesium to *Halimeda.*

In an important memoir on *Melobesia* Madame P. Lemoine[3] gives several analyses of calcareous algæ. The analyses, made for her by M. Charf, are not very complete, but they are, nevertheless, of distinct value. The data are as follows:

1. *Lithothamnium calcareum.* St.-Vaast-la-Hougue, Manche, France.
2. *Lithothamnium calcareum.* Isle Glenan, Finistere, France.
3. *Lithothamnium fornicatum.* Norway.
4. *Lithophyllum incrustans.* Gatteville, Manche, France.
5. *Lithophyllum incrustans.* Mazagan, Morocco.
6. *Lithophyllum tortuosum.* Genoa.
7. *Lithophyllum craspedium.* Tahiti.

To the analyses as reproduced in the following table we venture to add a line for reduced or corrected magnesium carbonate, computed on the basis of 100 per cent for the two carbonates alone.

Lemoine's analyses of algæ.

	1	2	3	4	5	6	7
Soluble in H_2O	2.3	3.0	1.2	1.7	3.8	5.7	3.2
Insoluble in HCl	.0	.0	.0	.0	.0	6.2	.0
$CaCO_3$	80.9	75.2	81.6	84.4	77.7	73.4	75.4
$MgCO_3$	11.8	10.7	9.3	10.8	9.8	9.3	15.9
Organic matter	5.0	11.1	7.9	3.1	8.7	5.4	5.5
	100.0	100.0	100.0	100.0	100.0	100.0	100.0
$MgCO_3$ corrected	12.7	12.5	10.2	11.3	11.2	11.2	17.4

In this series the highest magnesia is in the alga from Tahiti and the lowest in that from Norway. This tendency toward increased magnesia in algæ from warm regions, as compared with those from cold waters, was noticed by Madame Lemoine, but only incidentally. The subject was not given any detailed consideration by her.

Madame Lemoine also cites the older analyses of algæ, including three by J. Chalon, as follows:

1. *Lithothamnium calcareum.* Roscoff, Finistere, France.
2. *Lithophyllum incrustans.* Banyuls, France, on the Mediterranean.
3. *Lithophyllum tortuosum.* Naples.

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[1] Field Columbian Mus. Pub. 111, p. 31, 1906.

[2] The atoll of Funafuti, pp. 376, 377, London, The Royal Society, 1904.

[3] Idem.

[3] Inst. océanographique Monaco Annales, vol. 2, fasc. 2, 1911.

Chalon's analyses of algæ.

	1	2	3
$CaCO_3$	82.41	76.06	82.20
$MgCO_3$	11.80	14.38	11.57
Organic matter	4.30	7.38	5.26
Water	.86	1.72	.80
	99.37	99.54	99.83
$MgCO_3$ corrected	12.52	15.90	12.35

These recent analyses, from the memoir of Madame Lemoine, agree well with ours and, notwithstanding Högbom's divergent data, strengthen the suggestion that the proportion of magnesia in the algæ is influenced by temperature.

The material studied by us was carefully chosen by Dr. Howe, with direct reference to the purpose of our investigation. Every species was thoroughly identified, its locality was definitely stated, and the specimens were remarkably clean and free from misleading impurities. The results obtained by us are therefore as nearly trustworthy as it is practicable for us to make them. The significance of the algæ in reference to dolomite was already well established by previous workers, but our new data strengthen the conclusions which our predecessors had drawn.[1]

ADDENDA.

Since the foregoing pages were written three more calcareous algæ have been submitted for analysis by T. Wayland Vaughan. The species, with analyses by A. A. Chambers, are as follows:

1. *Goniolithon fratescens* Foslie. Cocos-Keeling Islands, in the Indian Ocean, latitude 12.5° S.; longitude 96.53° E.
2. *Goniolithon orthoblastum* (Heydrich) Howe. Murray Island, Torres Straits, Australia.
3. *Lithophyllum kaiseri* Heydrich. Cocos-Keeling Islands.

Analyses of algæ.

	1	3	3
SiO_2,Al_2O_3,Fe_2O_3	0.07	0.11	0.28
MgO	6.29	5.71	7.09
CaO	46.16	42.39	45.92
P_2O_5	Trace.	Trace.	Trace.
SO_3	.00	.00	.00
Ignition	46.70	50.97	45.72
	99.22	99.18	99.01
CO_2 needed	43.19	39.59	43.88
Organic matter, etc	3.51	11.38	1.84

Reduced analyses.

	1	2	3
SiO_2,Al_2O_3,Fe_2O_3	0.07	0.12	0.29
$MgCO_3$	13.80	13.66	15.33
$CaCO_3$	86.13	86.22	84.38
$Ca_3P_2O_8$	Trace.	Trace.	Trace.
$CaSO_4$	.00	.00	.00
	100.00	100.00	100.00

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[1] On the importance of algæ as reef builders see an interesting paper by Dr. Howe in Science, new ser., vol. 35, p. 837, 1912. He cites much other literature.

These algæ are much lower in magnesia than our specimens from similarly warm regions. The two species of *Goniolithon* contain little more than half as much magnesium carbonate as the species from Florida and the West Indies. For this difference we have no explanation to offer.

GENERAL DISCUSSION.

In the foregoing pages we have reported 250 new analyses of marine invertebrates and have cited many other analyses made elsewhere. These data shed much light upon the chemistry of the marine sediments, and they also suggest various problems, some of them biological, which are yet to be solved. The limitations of our research have been pointed out in the introduction to this memoir, and are taken for granted in the following general discussion of the results that we have obtained. First in order we may consider the distribution of the essential constituents of the invertebrate skeletons, taking each one separately.

Silica.—The skeletons of radiolarians and diatoms and the spicules of siliceous sponges consist almost entirely of opaline silica. The radiolarian and diatom oozes of the *Challenger* expedition show the importance of these organisms. In our own work we have studied only the sponges, and our results show nothing new. Our analysis of *Euplectella,* however, is probably more complete than any previous analysis of a siliceous sponge. We have found recorded in the literature only partial analyses of sponge spicules.

In nearly all our analyses, in every group of organisms, silica appears, generally in small but exceptionally in rather large proportions. Some of this may be essential, but in most cases it is an impurity. In fact, sand grains were distinctly visible in some of the specimens analyzed but were not readily removable.

Alumina and iron oxide.—In most of our analyses alumina and iron oxide were usually determined but they are to be regarded generally as impurities due to adherent silt or mud. Iron is doubtless a normal constituent in small amounts.

Lime.—The most important base in nearly all marine shells or skeletons, whether vertebrate or invertebrate, is lime. Only the siliceous organisms are free from it. Molluscan shells, the stony corals, the hard parts of millepores, some brachiopods, and the barnacles are composed almost entirely of calcium carbonate and contain only minor impurities. In the other series of marine invertebrates, with few exceptions, it is the dominant inorganic constituent. Calcium phosphate and sulphate were also determined in most of our analyses, but they will be considered in other paragraphs.

Magnesia.—One of the most interesting results of our investigation is the discovery that magnesium carbonate is much more widely distributed as an essential constituent of marine invertebrates than it has hitherto been supposed to be. In the Foraminifera, alcyonarians, echinoderms, crustaceans, and coralline algæ it is especially important, and some other organisms contain it in notable proportions. Its peculiar relations to temperature have been noted in several sections of this work and will be discussed more fully later.

Our determinations of magnesia, however, are subject to at least one small correction. Many of the specimens analyzed contained inclosed or adherent sea salts and in a few of them it could not be estimated. They rarely amounted to more than 2 per cent but in one analysis 5 per cent was found. Sea salts contain magnesium, and its equivalent in magnesium carbonate must therefore be deducted from the percentages of magnesium carbonate given in our reduced analyses. The maximum correction to be thus applied is about 0.4 per cent but 0.1 per cent would be the more common amount. In our work such a correction is negligible, for the proportion of magnesium carbonate in our important magnesian series ranges from 5 to 25 per cent. The small quantities of magnesia found in most mollusks and corals, however, may be due in part, if not entirely, to saline impurities.

Phosphorus.—In nearly all our analyses phosphoric oxide appears, but generally in trifling quantities. It is abundant, however, in the series of phosphatic brachiopods, the crustaceans, and the alcyonarians. Some worm tubes also are notably phosphatic. In reducing the analyses to standard form we have assumed that the phosphoric oxide is best represented in combination as tricalcium phosphate, although the assumption is not absolutely proved. It is a pure convention, adopted for the sake of uniformity and to simplify the comparison of analyses. It is of course possible that magnesium phosphates may exist in some of the organisms and that a part of the phosphorus may be contained in their organic matter. Magnesium phosphates, however, are very rare as minerals, whereas calcium phosphate is extremely common. The organic matter decomposes after the death of the animals and its phosphorus would doubtless appear in the sediments as a phosphate. In any case the dead organisms are likely to be buried among calcareous sediments, where calcium phosphate should be formed. Even the phosphatic worm tubes, in which the calcium is insufficient to form a tribasic salt, would probably follow this rule. Lime from the sediments would supply the deficiency.

Sulphur.—In many of our analyses sulphur was determined as sulphur trioxide and recalculated into the form of calcium sulphate. Part of the sulphur may really exist in organic combination, especially in the phosphatic brachiopods, and another part may be derived from sea salts, but this part is extraneous and should not be considered as contributory to the sediments. A correction for them would be like that which we have regarded as applicable to the magnesia and of the same order of magnitude. In the marine sediments generally calcium sulphate is of minor importance.

Other constituents.—Among the inorganic constituents of invertebrates there are other elements than those which we have determined. The most important one of these is fluorine, which is probably present in small amount in all living organisms. P. Carles,[1] for example, has detected fluorine in the shells of mollusks—as much as 0.012 per cent in oyster shells. In combination with calcium phosphate fluorine may form a compound analogous to or identical with apatite. Its presence in vertebrate bones is well known. Boron also is widely distributed in the animal kingdom. G. Bertrand and H. Agulhon [2] detected it in crustaceans, mollusks, and echinoderms, as well as in vertebrate animals. The presence of manganese has been reported in sponges and mollusks [3] and the element is probably of common occurrence in other organisms. Copper has long been recognized in oysters, and was found by L. B. Mendel and H. C. Bradley,[4] together with zinc, iron, magnesium, and phosphorus, in the liver of another mollusk, *Sycotypus*. M. Henze [5] also detected copper in the liver of cephalopods. In two corals G. Forchhammer [6] found traces of copper, silver, and lead. The blood of ascidians, according to Henze,[7] contains vanadium. In short, a systematic search for minor metallic constituents in marine invertebrates would probably show that they contain many other elements. This subject, however, lies outside the scope of our investigation, and these few citations are enough for present purposes.

For the intensive study of coral reefs the analyses furnished by us together with those cited from others are of great significance. The limestone immediately below the zone of living forms owes its composition to all the organisms that flourished on the reef. Algæ, corals, alcyonarians, Foraminifera, and other forms of less importance contribute their remains to the building of the limestone, which may vary in composition as the life upon it varies. Corals may predominate in one place, algæ in another. Each reef must therefore be studied on its individual merits if its chemical character is to be understood. Precipitated carbonates, whether of bacterial origin or not, must also be taken into account, and their quantity may be large. At Funafuti, where the limestone has been studied with unusual thoroughness, the order of importance of the leading organisms is estimated by A. E. Finckh,[8] as follows:

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[1] Compt. Rend., vol. 144, pp. 437, 1240, 1907.

[2] Idem, vol. 156, p. 732, 1913.

[3] See Cotte, J., Soc. de biologie, Compt. rend., vol. 55, p. 139, 1903; Bradley, H. C., Jour. Biol. Chemistry, vol. 3, p. 151, 1907; idem, vol. 8, p. 237, 1910.

[4] Am. Jour. Physiology, vol. 14, p. 313, 1905.

[5] Zeitschr. physiol. Chemie, vol. 33, p. 417, 1901.

[6] Philos. Trans., vol. 155, p. 203, 1865.

[7] Zeitschr. physiol. Chemie., vol. 72, p. 401, 1911; idem, vol. 86, p. 340, 1913.

[8] The atoll of Funafuti, pp. 125-150, London, The Royal Society, 1904.

1, *Lithothamnion;*[1] 2, *Halimeda;* 3, Foraminifera; 4, the corals, including *Heliopora* and other alcyonarians and the millepores. Here the corals are subordinate to the algæ, and even the Foraminifera outrank them. To call the Funafuti rock a coralline limestone would therefore be somewhat misleading.

Chemical analysis, however, is not the only factor of importance in determining the composition of a marine limestone. The crystalline character of the shells and skeletons, whether calcitic or aragonitic, must also be considered. For this purpose the well-known reaction with cobalt nitrate, the "Meigen reaction," is commonly employed, especially by W. Meigen himself, who has studied a considerable number of organisms, both recent and fossil, and some of his determinations[2] relate to genera examined by us. For these, excluding fossil forms, the data are as follows:

Calcite.	*Aragonite.*
Lithothamnium. Alga.	Halimeda. Alga.
Lithophyllum. Alga.	Galaxaura. Alga.
Polytrema. Foraminifer.	Millepora. Hydromedusa.
Corallium. Alcyonarian.	Distichopora. Hydromedusa.
Tubipora. Alcyonarian.	Heliopora. Alcyonarian.
Serpula. Annelid.	Spirula. Cephalopod.
Terebratula. Brachiopod.	Sepia. Cephalopod.
Argonauta. Cephalopod.	
Balanus. Crustacean.	

Of these genera, so far as they have been studied chemically, all in the aragonite column are almost completely nonmagnesian. The trifling amounts of magnesia which they contain may be due to impurity or to alteration. Two in the calcite column, *Terebratula* and *Balanus*, are also nonmagnesian, and the others are all rich in magnesium carbonate. Meigen also tested twenty zoantharian corals, all aragonitic and nonmagnesian, and a considerable number of mollusks. Some of the molluscan shells were aragonitic and some were calcitic, but all except *Argonauta* were nearly free from magnesia. One echinoderm in Meigen's list, of a genus not represented in our series of analyses, was calcitic, and so too were ours. All the echinoderms, so far as we know, are distinctly magnesian. In short, it seems probable, in the light of existing evidence, that all aragonitic organisms are essentially nonmagnesian; and that those characterized by the presence of much magnesia are calcitic. Many calcitic forms, however, are practically free from magnesia. The general relation thus brought out is very suggestive. Magnesium carbonate associates itself only with calcite, with which it is isomorphous, rather than with aragonite of different crystalline form, but why some organisms should secrete calcite and others aragonite in building their shells or skeletons is as yet unexplained, although the difference may be of physiologic origin, and may perhaps be correlated with differences of structure.

The considerations presented in the preceding pages bear directly upon the problem of the origin of marine dolomite. We now know what classes of organisms supply magnesia to the limestones and something also of what may be called their mineralogic nature. The dolomite ratio between the two carbonates is, however, never directly reached; there is always at first a large excess of calcium over magnesium, and a mixture is formed instead of the true double salt. To produce dolomite the original limestone must either be enriched by magnesia derived from sea water or else concentrated by leaching away of lime; furthermore, its two component carbonates must be somehow forced to combine. These processes may be operative simultaneously, but it is more probable that the change from magnesian limestone to dolomite is brought about by a series of steps, taken one at a time.

In this connection the report on Funafuti, already cited, is remarkably suggestive. On that atoll or island a committee of the Royal Society put down a boring 1,114 feet, in limestone all the way. The rock throughout contained organic remains and was studied both

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[1] The term *Lithothamnion* as used in the Funafuti report is general, and includes not only *Lithothamnium*, but also *Lithophyllum*, *Goniolithon*, and perhaps other genera. See Atoll of Funafuti, p. 332, London, The Royal Society, 1904.

[2] Naturf. Gesell. Freiburg Ber., vol. 13, p. 40, 1903.

microscopically and chemically. At a depth of 4 feet from the surface it contained 4.23 per cent of magnesium carbonate, and at 15 feet 16.4 per cent. To this point a concentration by leaching is indicated, even if not absolutely proved, and it is probable that the relatively soluble nonmagnesian aragonitic structures had been in part at least dissolved away. The unstable aragonite is more easily dissolved than calcite, a relation so well established that it does not need to be discussed here.[1] The fact that many sections of the core are described as "cavernous" in structure is additional evidence that solution had occurred. Solution is also aided by the carbonic acid generated during the decomposition of the organic matter of the organisms, and through its agency calcite would be dissolved also. Magnesium carbonate is much less readily removed.

At a depth of 25 feet the core contained 16 per cent of magnesium carbonate, but the specimen examined consisted largely of *Lithothamnion* remains, which accounts for its composition. On the other hand, the core at 40 feet carried only 5.85 per cent of magnesium carbonate and was in great part composed of *Heliopora* and *Millepora*, both originally nonmagnesian. The core sections evidently varied in composition according to the variations in the organisms from which they were formed. A sample taken only a few feet away from the boring might have had a different composition. Some fluctuations in the series of analyses may be accounted for in this way.

Below 40 feet the magnesian content of the rock diminished rapidly, falling at one point to 0.79 per cent of magnesium carbonate. Between 40 and 637 feet the composition of the rock was about that of an ordinary limestone, but at the latter depth crystals of dolomite began to appear.[2] At 640 feet the percentage of magnesium carbonate was 26.33, and it increased, with some fluctuations, to the final depth of 1,114 feet. At 950 feet it reached 43 per cent and at the lowest depth it was 41.05 per cent. From 640 feet downward the rock was essentially dolomite, although it contained an excess of calcite. Pure dolomite contains 45.65 per cent of magnesium carbonate, a figure that was very nearly approached.

The column of rock represented by the Funafuti boring thus appears to be divisible into three fairly definite zones. The surface layer is about 25 feet thick, and its composition is directly determined by the organisms living above it. In this zone the evidence of concentration by leaching is quite clear. From 25 feet down to 640 feet the rock is essentially a limestone, with very little magnesia. The lowest zone, from 640 feet downward, is dolomite, and the dividing line between this and the limestone above is very distinct. Within 3 feet the proportion of magnesium carbonate in the rock rises from 2.44 to 26.33 per cent.

To account for all the differences in the Funafuti column does not fall within the scope of this investigation, even if it were possible to explain them. Possibly the limestone of the middle zone was laid down during a period when nonmagnesian organisms were relatively much more abundant than they are now. This supposition, however, does not account for the sudden change from limestone to dolomite in passing from the second to the lowest zone.

In order to partly explain these changes we venture to offer some purely speculative suggestions, believing that speculation is legitimate if it tends to stimulate investigation or to provoke a closer scrutiny of existing evidence.

The lowest portion of the Funafuti rock is, of course, the oldest, and it contains fragments of *Lithothamnion* and other organisms which flourish abundantly only at moderate depths. Magnesia was then concentrated in the rock, in part directly from living forms and in part by leaching, as at present. The thickness of the rock shows that it must have been deposited during a long period of depression, which may have submerged the island to a depth at which few of the magnesian organisms, especially the algæ, could thrive. A prolonged rest, a period of equilibrium, then followed, during which very little rock was formed, and in this period much of the dolomitization took place.

The period of rest was succeeded by one of elevation, which brought the dolomitic rock again to the surface, when reef building began anew, but with relatively fewer magnesian

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[1] This leaching at Funafuti has already been pointed out by J. W. Judd in The atoll of Funafuti, p. 384.

[2] See the petrographic report by C. G. Cullis in The atoll of Funafuti, pp. 392–420.

organisms than formerly. Between 552 and 660 feet the nonmagnesian *Halimeda* is the main constituent of the cores. The new rock, then, was less magnesian than the older, and the sharp break between the two zones becomes intelligible. Magnesian organisms were not extinct, for their remains appear throughout the Funafuti cores, but they were much less abundant than at first. Whether this supposition is true or not might be determined by a quantitative study of the thin sections of the rock, which ought to be still in existence. The published records of them seem to be purely qualitative, except in so far as they indicate the frequency of occurrence of the different organisms. They do not show their relative quantities.[1] At present magnesian organisms predominate and their composition is reflected in the composition of the surface limestone.

Our assumptions regarding changes of sea level at Funafuti are not altogether imaginary. In their report upon the geology of the island T. W. E. David and G. Sweet[2] assert that—

> the surface geological evidence collected by us proves, in our opinion, that several oscillating vertical movements of the above have taken place in the immediate past at Funafuti, and we should not, therefore, be surprised if the evidence gained from the core shows that movements of the shore line in both directions have occurred at Funafuti at earlier epochs.

The chemical and algal evidence reinforce the physiographic evidence. On the formation of "coral reefs" during subsidence or elevation there is an abundant literature, which we can not attempt to summarize. We are dealing with a specific instance from a single point of view. The subject is one over which there has been much controversy. Our principal assumption, which may or may not be sustained, is that the dolomitic zone at Funafuti represents an old reef upon which the present reef is superimposed. A similar basing of new reefs upon older ones has already been pointed out by T. Wayland Vaughan.[3]

On many other islands in the South Pacific dolomitized limestones which were originally reefs are found at elevations hundreds of feet above sea level. A number of these rocks have been described by E. W. Skeats,[4] who made good series of chemical analyses of them and also discussed their origin. Organic and especially algal remains were common in the rocks and were clearly recognizable in spite of the fact that in many places they had been much altered by the process of dolomitization. In these islands an elevation of the land had clearly taken place. Similar limestones from the Fiji, Tonga, Paumotus, and Ladrone islands have been studied by R. L. Sherlock,[5] who found them to be composed in great part of algal and foraminiferal remains. Among 47 thin sections which he examined, "*Lithothamnion*" was found in 35, *Polytrema* in 21, echinoderm fragments in 17, and corals in 15. In short, all the evidence goes to prove the importance of the algæ as limestone builders and the subordinate character of the corals. This importance is now fully recognized by students of marine limestones and by paleontologists generally.

It is not our purpose to discuss the origin of dolomite in general, for probably the rock originates in more than one way.[6] At Funafuti, however, and at other similar localities marine organisms have much to do with its origin, and that phase of the dolomite problem may appropriately be considered here. The first step in the process, concentration by leaching, has already been described, but that is only a beginning. The living organisms, plant or animal, contain much less magnesia than is required to form dolomite, and its quantity must be increased from some outer source. That source, or at least the only source which we can discover, is found in ocean water, in which magnesium is much more abundant than calcium. This source has been recognized by many authorities, and it is generally assumed that an exchange may occur between the magnesium of the water and the calcium of the limestones, the one replacing the other. This assumption is due to J. D. Dana,[7] who sought to explain the dolomitization of a limestone on the island of Makatea.

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[1] The atoll of Funafuti, tables on pp. 336–361.

[2] Idem, p. 88.

[3] Papers from the Tortugas laboratory of the Carnegie Institution of Washington, vol. 5, p. 66, 1914.

[4] Idem, vol. 42, p. 51, 1903.

[5] Mus. Comp. Zool. Bull., vol. 38, p. 349, 1903.

[6] For a rather full summary of the subject see Clarke, F. W., The data of geochemistry, 3d ed., U. S. Geol. Survey Bull. 616, pp. 559–57 , 1916.

[7] Corals and coral islands, 3d ed., p. 393 [1890].

That an enrichment in magnesia from sea water is possible is shown by some experiments made by C. Klement,[1] who found that a concentrated solution of magnesium sulphate and sodium chloride, at 90° C., attacked aragonite and corals strongly, yielding a mixture of carbonates containing as high as 41.9 per cent of magnesium carbonate. Calcite, on the other hand, was but slightly altered. In the light afforded by these experiments the nonmagnesian aragonitic organisms assume new importance, and are perhaps more influential in the production of dolomite than the distinctly magnesian species. Their solubility is evident in the first stage of magnesian concentration; their alterability is effective in the second.

Klement's experiments, however, were performed with concentrated solutions and at a rather high temperature. Under natural conditions, with less concentration and at lower temperatures, the same reaction may take place very slowly but be equally complete in time. Years, or even decades, may be needed to effect such changes as were produced in the laboratory within 48 hours. In the study of geochemical processes the time factor must always be taken into account.

So far, according to Klement, a mixture of the two carbonates has been found. To convert them into the double carbonate, dolomite, another step must be taken, and here again time may be important. A porous rock has been produced, which is saturated with water and buried at a depth which subjects it to considerable pressure. If the two carbonates of calcium and magnesium were perfectly dry, pressure alone would probably not effect their union, but under the influence of moisture, with slight solution going on at the surfaces of the solid particles, there would be a degree of molecular mobility which might bring about combination. This is probable, although so far as we know it has not been actually proved. The establishment of the facts ought not to be beyond the range of experimental investigation. Views similar to ours relative to the formation of dolomite have already been advanced by Général E. Jourdy, who especially recognizes the importance of the algæ, of aragonite, and of time. Much remains to be done, however, before the problem of dolomitization can be completely solved.[2]

On the subject of phosphate rock we have little to say. We have shown that several groups of organisms are rich in phosphates, but the extent of their contributions to the sediments is uncertain. At best they can at first form beds of only moderately phosphatic limestone, which may perhaps be concentrated by the leaching away of the excess of carbonates. Vertebrate skeletons are also phosphatic and may possibly be more important additions to the sediments than invertebrate remains. In some localities limestones have been phosphatized by percolations from beds of guano,[3] but that process is not one which needs to be considered here. It has no relation to the present research.

In the course of our investigation we have made one very curious discovery, to which we have repeatedly called attention, namely, the fact that in certain groups of organisms the proportion of magnesium carbonate is dependent upon or determined by temperature. The crinoids and alcyonarians show this relation very clearly, and it is also suggested by our analyses of Foraminifera, crustaceans, and algæ. As a rule the organisms from warm waters are much richer in magnesia than those from cold waters, and the observed differences are often strikingly conspicuous. This rule, or rather tendency, we are inclined to believe is general, although we must admit that there are probably exceptions to it. Whether the increase in magnesia in passing from cold to warm regions is absolutely regular or not we do not venture to say, but apparent irregularities may be due to any one of several different causes. Slight analytical errors, uncertainty as to exact temperatures, impurities in the specimens analyzed, and differences in the concentration of sea water may all help to produce irregularities, which, however, are not likely to be large. The salinity of ocean water is very variable; it is 3.5 per cent in the great ocean, 4 per cent on the southern shores of the Mediterranean, and less than 1

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[1] Min. pet. Mitt., vol. 14, p. 526, 1894. See also Pfaff, F. W., Centralbl. Mineralogie, 1903, p. 659, and Neues Jahrb., Beilage Band 9, p. 485, 1894. Two separate papers.

[2] Soc. géol. France Bull., 4th ser., vol. 14, p. 279, 1914.

[3] In The data of geochemistry: U. S. Geol. Survey Bull. 616, pp. 519-528, 1916, a summary of our knowledge of phosphate rock may be found.

per cent in the Baltic, differences that are great enough to exert some influence upon the vital processes of marine animals. Although the ratio between calcium and magnesium is practically constant in all oceanic waters, a concentrated water would contain more magnesium, volume for volume, than a water that was more dilute. Whether an organism living in a concentrated water would assimilate more magnesia because of its enriched environment no one can say, but conceivably it might do so. The influence of temperature might in that way be slightly modified. This is only a suggestion, not a statement of established fact. That warmth favors the assimilation of magnesia by marine invertebrates seems to be reasonably certain, but why it should be so is not clear. The relation is definite but as yet unexplained. We hope it is not inexplicable.

Attempts will probably be made to use our data in studies of climatology, but are such attempts likely to be fruitful? The question is not easy to answer. At a first glance it would seem as if warm regions should be more favorable to the formation of magnesian limestones than cold regions, but the evidence is by no means conclusive. A dense population of cold-water organisms might add more magnesia to the sediments than a sparse population of warm-water forms. The massiveness of the animals must also be considered. The alcyonarian *Paragorgia arborea,* as its specific name indicates, grows to treelike dimensions, but its skeleton contains only about 9 per cent of magnesium carbonate. Tropical alcyonarians are much richer individually in magnesia, but they are not so large. One *Paragorgia* would therefore count for more than many smaller alcyonarians in the formation of magnesian limestone. If, however, the warm-water organisms are as abundant as the cold-water forms, and if their aggregate mass is as great, then the tropical limestones of marine origin should be more richly magnesian than those from higher latitudes. The determination of the facts we must leave to zoologists.

In conclusion we must express our thanks to the officers of the United States National Museum and the Geological Survey who have aided us by furnishing authentic material for our investigations. Messrs. Paul Bartsch, Austin H. Clark, William H. Dall, W. L. Schmitt, and T. Wayland Vaughan have all been most generous with their services. Dr. Marshall A. Howe, of the New York Botanical Garden, has also been most kind in supplying us with algæ. Without the help of these friends our research would have been impossible.