THE COMPOSITION OF CRINOID SKELETONS.

By F. W. Clarke and W. C. Wheeler.

INTRODUCTION.

That many rocks, now raised far above sea level, were once marine sediments and that living organisms contributed to their formation are among the commonplaces of geology. It is also known that radiolarians, diatoms, and sponges form siliceous deposits; that calcareous rocks are derived in part from corals and mollusks; and that crustacean and vertebrate remains are largely phosphatic. These facts are established in a broad, general way, but they need to be studied in greater detail, so that the function of each class of organisms may be more exactly known. An investigation of this kind is reported in the following pages. The special problem covered by it was suggested by Mr. Austin H. Clark, of the United States National Museum, who furnished the specimens for analysis.

EXISTING CRINOIDS.

In 1906 H. W. Nichols[1] published a number of analyses of marine invertebrates, and in one of them, a crinoid, *Metacrinus rotundus*, from Japan, he found 11.72 per cent of magnesium carbonate. This analysis attracted Mr. Clark's attention, 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 22 specimens of recent crinoids, representing 19 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; 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; 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; 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; 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.

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

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

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; 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; 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; 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; 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.

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; temperature, —1.85° C. Salinity of water, 3.3 per cent.

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

In the following table the actual analyses are given. The symbol "R_2O_3" represents the sum of ferric oxide and alumina, and "Loss on ignition" covers carbon dioxide, water, and organic matter, the last being often very high. At the foot of each column the CO_2 calculated to satisfy the bases is given. The deficiencies in summation are mainly due to inclosed or adherent salt, an inevitable impurity, as was proved in the analyses of two samples, Nos. 15 and 17.[1] Analysis No. 1 is the mean of two concordant analyses of separate samples.

Analyses of crinoids.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	1.64	0.04	1.11	0.37	0.16	0.12	0.04	0.07	0.40	0.15	0.17
R_2O_3	1.07	.39	1.01	.71	.62	.63	.79	.09	.50	.19	.19
MgO	3.08	3.60	3.12	3.76	4.77	4.94	4.64	4.44	4.48	5.13	4.17
CaO	40.65	40.37	34.20	38.50	38.12	41.34	40.75	45.86	41.79	42.77	38.91
P_2O_5	.11	.21	Trace?	.40	Trace.	.43	.33	Trace.	Trace.	.11	.17
Loss on ignition	51.45	53.75	60.04	55.25	54.61	51.36	51.80	48.32	51.44	50.28	54.61
	98.00	98.36	99.48	98.99	98.28	98.82	98.35	98.78	98.61	98.63	98.22
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

	12	13	14	15	16	17	18	19	20	21
SiO_2	3.17	0.40	0.04	0.03	0.09	0.04	0.15	0.02	0.02	0.23
R_2O_3	.31	.31	.25	.07	.19	.20	.26	.35	.45	.37
MgO	2.49	4.56	4.75	5.08	4.70	5.09	5.04	4.51	3.02	3.27
CaO	26.12	47.08	41.78	45.67	42.77	45.42	43.41	39.57	40.68	42.49
P_2O_5	.23	Trace.	Trace.	Trace.	Trace?	Trace.	Trace.	.10	Trace.	Trace.
Loss on ignition	65.25	47.17	50.33	47.54	50.59	48.58	50.00	53.64	54.53	52.22
	97.57	99.52	97.15	98.39	98.34	99.33	98.86	98.19	98.70	98.58
CO_2 needed	22.73	41.93	38.00	40.40	38.71	41.29	39.65	36.05	35.18	37.08

In order to make these analyses more instructive it is necessary to recalculate them into such form as to show the composition of the true crinoid skeleton—that is, to eliminate the highly variable organic matter of the original specimens. On doing this and recalculating to 100 per cent, we find that they assume the following form:

[1] No. 15 contains 1.27 per cent of water-soluble salts and No. 17 contains 0.21 per cent. These raise the summations to 99.66 and 99.54 per cent, respectively.

Revised analyses of crinoids.

	1	2	3	4	5	6	7	8	9	10	11
SiO_2	2.01	0.05	1.57	0.48	0.21	0.14	0.05	0.08	0.47	0.24	0.21
R_2O_3	1.31	.48	1.41	.91	.78	.74	.95	.10	.59	.22	.24
$MgCO_3$	7.91	9.44	9.25	10.15	12.69	12.20	11.68	10.16	11.08	12.34	11.13
$CaCO_3$	88.48	89.45	87.77	87.34	86.32	85.81	86.46	89.66	87.86	86.93	87.94
$Ca_3P_2O_8$	.29	.58	Trace?	1.12	Trace.	1.11	.86	Trace.	Trace.	.27	.48
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

	12	13	14	15	16	17	18	19	20	21
SiO_2	5.73	0.42	0.05	0.03	0.10	0.04	0.17	0.02	0.02	0.28
R_2O_3	.56	.33	.30	.08	.21	.21	.29	.43	.57	.44
$MgCO_3$	9.36	10.09	11.69	11.69	11.42	11.62	11.96	11.77	7.86	8.23
$CaCO_3$	83.47	89.16	87.96	88.20	88.27	88.13	87.58	87.51	91.55	91.05
$Ca_3P_2O_8$	.88	Trace.	Trace.	Trace.	Trace?	Trace.	Trace.	.27	Trace.	Trace.
	100.00	100.00	100.00	100.00	100.00	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:

22. *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.

23. *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. 22, 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. 23, 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—

No. 22, 7.28 per cent.

No. 23, 10.34 per cent.

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 $MgCO_3$, with the accessory data as to latitude and locality conveniently abbreviated. In this table the two analyses of Endoxocrinus are averaged together, and so also are the two of Isocrinus.

Magnesium carbonate in crinoid skeletons.

No.	Locality.	Latitude.	Depth (meters).	Temperature (°C.).	Per cent $MgCO_3$.
22	Northern Japan	43° N.	315	1.5	7.28
20	Antarctic	67° S.	375	−1.8	7.86
1	British Columbia	52° 39′ N.	2,858	1.8	7.91
21	Antarctic	67° S.	375	−1.8	8.23
3	Northern Japan	44° N.	(?)	1.6	9.25
12	Massachusetts	39° 56′ N.	329	7.8	9.36
2	Washington	47° 29′ N.	1,145	3.3	9.44
13	Gulf of Mexico	28° 38′ N.	255	(?)	10.09
4	Southern Japan	34° N.	1,123	3.4	10.15
8	Philippines	9° 37′ N.	612	10.2	10.16
23	Southern Japan	30° 58′ N.	278	13.3	10.34
9	Philippines	9° 15′ N.	502	12	11.08
11	Australia	33° 15′ S.	(?)	(?)	11.13
15, 16	Cuba	24° N.	(?)	(?)	11.56
7	Philippines	8° N.	104	(?)	11.68
14	Cuba	23° 10′ N.	59	26.2	11.69
19	Brazil	25° 54′ S.	(?)	(?)	11.77
17, 18	Cuba	24° N.	(?)	(?)	11.79
6	Philippines	8° N.	104	(?)	12.20
10	.....do	5° 12′ N.	32	(?)	12.34
5	.....do	6° N.	36	(?)	12.69

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 $MgCO_3$ 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, has stated to us that they are exceptionally well suited to a study of the kind recorded here, "for the skeleton is always entirely internal and protected from the surrounding water by living tissue; so that whatever alteration it may undergo after its original deposition can not be influenced by the water in which it lives." He has also pointed out that the crinoids from warm regions have the most compact skeletons; the compactness being in general proportional to the temperature and also 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.

Only one other group of marine organisms, so far as is now definitely known, is conspicuous for its relative richness in magnesium carbonate, namely, the calcareous algæ, as shown in an investigation by Högbom.[1] In 11 analyses of algæ belonging to the genus Lithothamnium he found magnesium carbonate in proportions varying from 3.76 to 13.19 per cent. No temperature relation, however, appeared in his series of analyses. The highest figure was obtained in a specimen from the Arctic Ocean, the next highest in one from Bermuda, and the lowest in one from the Java Sea. Three analyses of fossil algæ gave even lower magnesia than was found in the living forms. The average proportion was near that found among the crinoids. It is highly desirable that both groups of organisms should be studied more completely and with every precaution against error. Crinoids from European, especially Mediterranean waters, from the coasts of Africa and South America, and from the Indian Ocean might be analyzed to much advantage. One caution, however, is needed: only alcoholic material should be used. Specimens preserved in formalin, which tends to become acid, are of doubtful value in a research of this kind. All the crinoids studied in the present investigation had been preserved in alcohol.

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 on page 37, and the analyses which follow were made in the same way as those of the modern species.

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

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
R_2O_3	2.64	.28	2.59	.43	2.18	.64	.87	1.73	.31	1.95
FeO	1.36	None.	....	None.	1.32	None.	1.19	.27	None.	.88
MnO	.13	None.	....	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	None.	Trace.	.09	Trace.	Trace.	Trace.	Trace.	None.	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

Revised analyses of fossil crinoids.

	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
R_2O_3	2.66	.28	2.64	.44	2.22	.64	.88	1.74	.30	1.97
$FeCO_3$	2.21	None.	....	None.	2.16	None.	1.94	.43	None.	1.42
$MnCO_3$	.21	None.	....	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
$Ca_3P_2O_8$	None.	Trace.	.20	Trace.	Trace.	Trace.	Trace.	None.	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 falling off 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 again 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 falling off 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.

[1] Loc. cit.