SOME SHOAL-WATER BOTTOM SAMPLES FROM MURRAY ISLAND, AUSTRALIA, AND COMPARISONS OF THEM WITH SAMPLES FROM FLORIDA AND THE BAHAMAS

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SALINITY OF OCEAN WATER AT FOWEY ROCKS, FLORIDA

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SOLUBILITY OF CALCITE IN SEA-WATER IN CONTACT WITH THE ATMOSPHERE, AND ITS VARIATION WITH TEMPERATURE

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SOME SHOAL-WATER BOTTOM SAMPLES FROM MURRAY ISLAND, AUSTRALIA, AND COMPARISONS OF THEM WITH SAMPLES FROM FLORIDA AND THE BAHAMAS.

INTRODUCTION.

In order to have this investigation considered in its proper relations to coral reefs and their associated phenomena, I will refer to page 54 of my paper on the corals from Murray, Cocos-Keeling, and Fanning Islands, where it is said that "a complex of geologic processes operating in the area must be studied, analyzed, and evaluated. Among these are the agencies other than corals whereby calcium carbonate may be taken from the sea-water, the probability of the solvent action of sea-water on calcium carbonate," etc. In a previous publication[1] I made the statement:

> "In order properly to evaluate corals as constructional agents, the subject needs to be studied from at least five different view points, viz: (1) In dealing with sediments uplifted above the sea, the quantity of material contributed by corals and that contributed by other agents must be estimated and the respective proportions determined; (2) in coral reef-areas, the proportion of the area covered by corals to that not covered by them should be estimated; (3) the relations of coral reefs to continuity and discontinuity of marginal submarine platforms must be ascertained; (4) marine bottom deposits must be analyzed according to the source of the material, and the percentage of the calcium carbonate contributed by the different agents estimated; (5) the rate of growth of corals needs to be known, especially for the light it may throw on the rate of reef formation."

In papers already published, I have devoted special attention to topics numbered 1, 2, 3, and 5, and have given some consideration to topic 4.[2]

The present paper is a preliminary contribution to the study of the marine bottom deposits in three coral-reef areas, viz: (1) Murray Island, Australia; (2) the Bahamas; (3) southern Florida. The Murray Island specimens were collected by Dr. A. G. Mayer. The samples from the Bahamas and Florida, here described, were collected mostly by me while working in association with Dr. Mayer, and have been selected, as representing certain important classes of deposits, from a lot of about 200 samples. I have previously discussed the calcium-carbonate sediments of these two areas in several of my papers on the geology of the areas (see bibliography on pp. 61, 62 in this volume, especially those treating of geology). Mechanical analyses have been made of all samples except those obtained in 1915, and the results of the chemical analyses of a selected set are here presented. The estimates of the percentage of the material contributed by different agencies is in progress and a report containing the results of all lines of investigation will be offered for publication.

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[1] Carnegie Inst. Wash. Year Book No. 14, p. 222, 1916.

[2] *Op. cit.*, pp. 222, 223.

The investigation of the source of the material, its mechanical state, and its chemical composition indicate certain classes of calcium carbonate deposits, some of them divisible into grades; and it is hoped that progress has been made toward outlining a method whereby an adequate classification of such sediments may ultimately be achieved. The deposits must not only be classified, but the areal extent of each must be determined, and, if possible, the volume of each should also be estimated.

PERCENTAGE OF INGREDIENTS ACCORDING TO SOURCE.

Calcium-carbonate deposits are derived initially from two sources: (1) through the activities of organisms which cause precipitation either inside or outside their tissues; (2) through chemical precipitation, either by inorganic agencies or by the activities of organisms which change the chemical composition of substances in solution in the water, producing supersaturation with reference to $CaCO_3$, or which by more purely physical processes may cause a state of supersaturation with reference to $CaCO_3$. In many marine sediments of to-day, in addition to that derived directly through the processes indicated, material is also derived from previously formed limestone which has been disintegrated and delivered to the sea.

In preparing for making percentage estimates of ingredients according to origin, a reliable reference collection had to be assembled. The preliminary working collection comprises oolitic limestones (thin sections and powders); calcium carbonate bacterially and inorganically precipitated in the laboratory; muds formed largely by bacterial action, although other agencies may have cooperated; coccolithophoridæ; thin sections and crushed fragments of calcareous algæ; a few radiolaria; over 100 named species and crushed fragments of common foraminifera; about 500 thin sections and crushed fragments of corals; mounted spicules of many species of alcyonaria; thin sections and crushed fragments of echinoids, bryozoa, mollusca, and crustacea. The collection is increased as the needs of the work require it.

Professor F. W. Clarke and Mr. W. C. Wheeler have rendered a valuable scientific service by chemically analyzing the skeletons of representatives of different groups of marine organisms. The completed results of the investigation have been brought together in a paper submitted for publication and entitled "The inorganic constituents of marine invertebrates and calcareous algæ," by F. W. Clarke and W. C. Wheeler.[1] Professor Clarke has kindly allowed the use of a copy of their manuscript while their paper is in press. The authors have shown that the chemical composition of the skeletons secreted by marine organisms varies from group to group, and that in certain groups, especially echinoids and alcyonaria, there is a definite relation between temperature and the ratio of $MgCO_3$ to $CaCO_3$, the magnesia being relatively higher in warm than in cold waters.

These investigations have rendered possible the correlation of the chemical composition of an entire sample with that of the various ingredients

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[1] U. S. Geol. Surv. Prof. Pap. No. 102, pp. 56, 1917.

according to their source. Mollusks and stony corals, for instance, contain almost no $MgCO_3$, whereas certain foraminifera contain from 9 to 11 per cent, and coralline algæ sometimes contain as high as 20 per cent. Later in this paper the chemical composition of the deposits as ascertained by analysis will be compared with the chemical composition as deduced from the percentage of the respective organic ingredients forming them. This may be said here: if a sand in a coral-reef area contains 7.5 per cent of $MgCO_3$, probably not over 50 per cent of the deposit is of coral origin (see analyses of corallinaceous algæ on p. 248); and as mollusk shells and *Halimeda* contain almost no $MgCO_3$, and are generally present in coral areas, the probability is that less than 50 per cent of the deposit is coral.

SIZING OF SEDIMENTS.

The mechanical condition of a sediment is important in many particulars, for from it a number of deductions may be made. The particles in bottom samples usually fall into two categories: (1) those which preserve their original form, for example, the shells of many foraminifera, alcyonarian spicules, etc.; (2) particles which have a secondary form, resulting from (*a*) disintegration of the body of which it originally formed a part, (*b*) secondary aggregation of particles, as in oolite grains.

Agencies causing disintegration and reduction of size need brief consideration. These are of two classes: (1) inorganic; (2) organic. The inorganic agencies causing disintegration are waves and currents. Waves by their impact break structures or reduce the size by hurling fragments one against another. Both waves and currents reduce the size of particles by the attrition of one against another.

The numerous organic agencies which cause disintegration have been investigated by many students, among whom are Duerden, Stanley Gardiner, Wood Jones, and myself. Among the disintegrating agents are boring algæ, sponges, worms, mollusks, and echinoids. These all render calcareous structures less able to withstand the effects of waves and currents. Gardiner has properly emphasized the importance of sand-feeding organisms in the production of silt. I have made a number of similar observations on echinoids and holothurians in the Bahamas and in Florida. Some worms, and probably other organisms, also tend to reduce the size of particles. Unfortunately the amount of work accomplished by these agents has not been evaluated. It is a difficult task, and it will probably be some time before the order of magnitude may be ascertained. I have weighed the inorganic content of the guts of a number of holothurians and echinoids, and tried to ascertain the rate at which some passed sand, but the results seem unsatisfactory, as so many factors are unknown that no reliable estimate of effect is at present possible. The subject seems to me of sufficient importance to warrant special investigation. According to Darwin, H. O. Forbes, and Wood Jones, two species of *Scarus*, a genus of fishes, browse on living coral and are thereby to be reckoned among the agents which break up calcium-carbonate structures.

Sizing is also of great importance, as it bears a most intimate relation to strength of waves and currents. Material of different sizes is not distributed in a haphazard way, but is collected according to definite physical laws in particular places. The relations of sediments to transporting agents and conditions of deposition have not yet been adequately studied; in fact, investigation of them is only now becoming definitely formulated; but enough is at present known to justify the statement in the preceding sentence.

The schedule of sizes here used is that of the Bureau of Soils, as Dr. Cameron, of that Bureau, was so kind as to have the mechanical analyses made there. This schedule meets the requirements of soil investigation, but geologic work needs something different. At present facilities for the special needs are not available, but it is the intention of the U. S. Geological Survey to install a laboratory equipped for this particular work as soon as practicable. The following statement gives the results of recent consideration of this problem by Messrs. M. I. Goldman, D. F. Hewett, G. S. Rogers, and E. W. Shaw:

> "*Method of describing size of grains.*—It was apparent that in order to give readily a correct idea of the mechanical composition of sediments, and to be philosophic, the system of sizing should have regular intervals. The great majority of sedimentary rocks are composed of particles which have settled through some moving fluid, and since the proportion of grains of various sizes depends on the resultant sorting (the rate of fall of particles, other things being equal, varying with the square of their diameter), the ratio of sizes should be constant and should preferably be 4, 2, the square root of 2, or the fourth root of 2. Such a system of sizing, in contrast with the prevalent ones in which variable ratios are used, has the advantage that it does not give undue weight to a separate whose range in size is greater than others. If a variable ratio is used, the result does not give so good an idea of the composition of the sediment and is less significant as to its origin. If the analysis is made by counting and not by sieving, the constant ratio is more easily applied than a variable one, and the results of variable ratio analyses can be converted more readily and accurately to a fixed ratio system than they could to some other variable ratio system.
>
> "In ordinary work it seems probable that the ratio 2 analysis will give sufficiently detailed information concerning the sediment. What will prove to be the most satisfactory starting-point is not yet evident, but presumably it will be either some point in the metric system, such as a centimeter, a millimeter, or a micron, or the figure adopted by the Bureau of Standards for a 200-mesh screen, viz, 0.074 mm."

It will be pointed out, in discussing the samples taken on the Murray Island reef flat and behind the reef off Cocoanut Point, Andros Island, Bahamas, that there is very little material of silt and clay size. The explanation of this condition demands consideration of the possibility of the removal of fine material (of the size of silt and clay) by means of solution by sea-water, a subject which will be discussed in its proper place (pages 265–268, and Dr. Wells's paper, pages 316–318).

BOTTOM DEPOSITS OF THE MURRAY ISLAND REEF.[1]

Dr. Mayer brought from Murray Island six bottom samples, five of which represent a section across the southeast reef along line I, and one is of a sand cast up on the reef 1,700 feet from shore, off the northwest end of the island. The five samples from line I are respectively from the following stations: above high tide, shore end; and 200, 600, 1,200, and 1,600 feet from shore. (See plate 2, of Dr. Mayer's article, for precise location.) He also brought specimens of the calcareous alga, *Goniolithon orthoblastum* (Heydrich) M. A. Howe, which is so important in the formation of the Lithothamnion ridge; of the limestone which is now elevated 500 to 700 feet above sea-level; and of the lava which, after being pushed upward through the limestone, was extruded over its surface. The lava has been examined by Professor Joseph P. Iddings, according to whom it is a basalt, rich in olivine. There is also some rotten volcanic tuff. The specimen of elevated limestone will be treated as if it were a bottom sample.

The following are Professor Iddings's notes on the basalt:

> "Four specimens of basalt from Murray Island, Australia, are finely vesicular varieties, black, gray, and reddish brown in color. They are almost aphanitic, but carry minute phenocrysts of olivine less than 0.5 mm. in diameter in 3 specimens, and 1 mm. and less in the gray variety. They may be said to be minophyric and sempatic, there being about equal amounts of minute phenocrysts and groundmass in each variety, and as there is a gradation in the sizes of the phenocrysts from the largest to those that are indistinguishable from the microscopic crystals in the groundmass, their fabric is seriate porphyritic.
>
> "The mineral composition of the four specimens is quite uniform, and consists of olivine, which forms the most noticeable phenocrysts, less augite, and about the same amount of strongly calcic plagioclase feldspar in microscopic prismoids.
>
> "The two black varieties have a brown-glass base, with abundant microlites of the minerals just named, besides much magnetite or titaniferous iron oxide in delicately dendritic clusters.
>
> "In the reddish-brown variety the iron oxide and outer portions of the mafic or ferromagnesian minerals are reddened. The gray basalt is apparently holocrystalline; is rich in olivine and violet-tinted augite, with dendritic magnetite and prismoids of plagioclase.
>
> "From the mineral composition it is to be inferred that this basalt is low in silica and the alkalies, and is rich in iron oxide, magnesia, and lime, with normal alumina, and considerable titanium oxide."[2]

The bottom specimens were collected by immersing a bottle and scooping up the material. It is believed that they are fairly representative, for they were taken where about an average amount of coarse material was present and probably very little fine material was washed out as the

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[1] For a preliminary note, see Carnegie Inst. Wash. Year Book No. 14, p. 220.

[2] Descriptions of the volcanic rocks of Maër Island are given by Haddon, Sollas, and Cole in Trans. Roy. Irish Acad., vol. 30, pp. 432-437, 1894.

sample was taken. The following work has been done on them: (1) mechanical analyses were made at the U. S. Bureau of Soils, under the direction of Dr. F. K. Cameron, formerly chemist of that Bureau; (2) chemical analyses were made of the samples and of certain important foraminifera by W. C. Wheeler and Alfred A. Chambers in the U. S. Geological Survey Chemical Laboratory; (3) Dr. Albert Mann, of the U. S. Bureau of Plant Industry, has furnished a list of the diatoms; (4) Dr. Marshall A. Howe, of the New York Botanical Garden, has prepared a report on the calcareous algæ; (5) Dr. J. A. Cushman, of the U. S. Geological Survey, has written a report on the foraminifera; (6) Dr. Marcus I. Goldman, of the U. S. Geological Survey, undertook to determine for two specimens the percentage of ingredients according to origin.

SOURCES OF THE MATERIAL.

Chemically precipitated material.—Inspection of the mechanical analyses on page 246 shows that on line I the maximum content of silt and clay is 600 feet from shore, where it is 2.8 per cent; while the minimum is at 1,200 feet from shore, where it is only 0.9 per cent. The analyses indicate the presence of very little bacterially or inorganically precipitated calcium carbonate, as such material originally, at least, is very finely divided. Should such precipitation have taken place, nearly all the material has been removed.

Coccolithophoridæ.—Some of these organisms are found in the sediments of silt size, and coccoliths occur in that of clay size, but in these samples they are of decidedly subordinate importance as contributors of material.

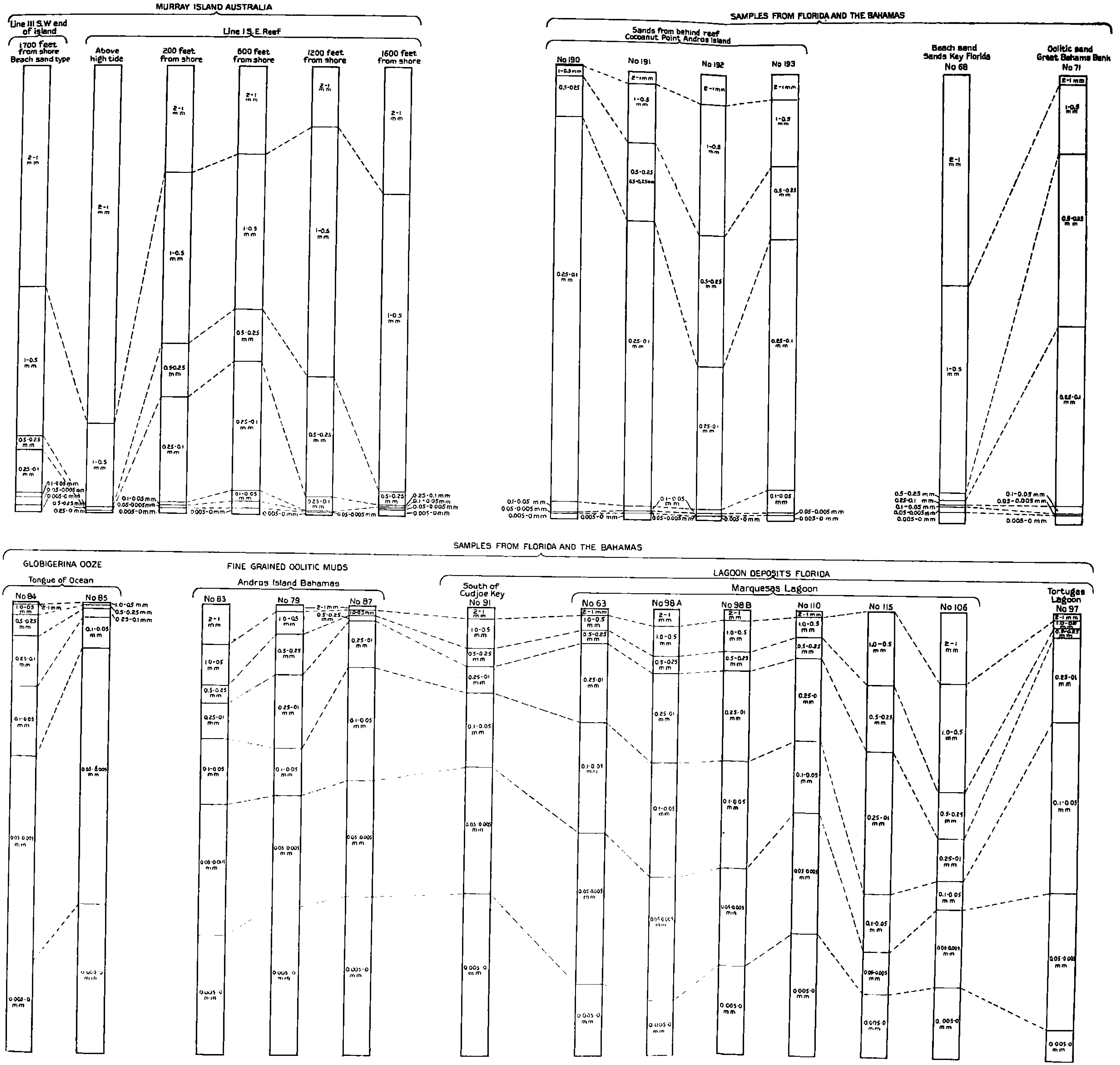
Diatoms.—These are present, but in an unimportant amount. An account of them by Dr. Mann may be found on page 297 of this volume.

Coralline algæ.—These organisms are of great importance and are specially described by Dr. Howe. (See pages 291–296 of this volume.) Besides forming what Dr. Mayer designates the "Lithothamnion ridge," they incrust nearly all the dead coral and are important contributors of $MgCO_3$.

Foraminifera.—This, another highly important group, is reported on in detail by Dr. Cushman, pages 289–290 of this volume. *Polytrema mineaceum* (plate 97, figures 1, 1*a*) incrusts much of the dead coral, as it does in nearly every place where reef-corals are found.

Madreporaria.—Dr. Mayer has discussed the abundance of this group, and I have described the fauna in the paper which precedes this one.

Alcyonaria.—This group is given a caption, as it is important in the Bahamas and Florida. Spicules occur in nearly every, if not every, shoal-water sample which I have examined from those areas, but there are few or none in the Murray Island specimens. The abundance of such spicules in samples from the former area, and their scarcity or absence in samples from the latter, constitute the most striking difference between reef samples from the two areas. However, in other Australian reef areas they are probably important, as Alcyonaria are abundant in many places, and especially in



Graphic illustration of mechanical analyses of bottom samples.

areas where silt is being deposited, for there *Sarcophyton* and *Xenia* grow plentifully.

Echinoids.—Very few echinoid fragments were observed.

Mollusca.—This is another important group, as it contributes a large proportion of the bottom material.

Bryozoa and Crustacea.—Some fragments of barnacle plates, ostracods, and other crustacea were found, but no bryozoa were recognized.

The four groups of organisms which are most important are, named in systematic order: (1) coralline algæ; (2) foraminifera; (3) madreporarian corals; (4) mollusca.

DISTRIBUTING AND SORTING AGENTS.

The following statement is quoted from Dr. Mayer's article (page 8 of this volume):

> "The strong southeast trade-wind, which prevails for about eight months of the year, causes the ocean water on the incoming tide to sheer near the middle of the southeast side of Maër Island, the currents parting, the stronger going around the southwestern and the weaker around the northern end of the island. The current around the southwestern side is reinforced by that around Dowar Island and is thus stronger than that around the northeastern end. The silt from Haddon and Hedley brooks is thus carried around the southwestern end of the island and contributes to form the sand dunes, which are about 20 feet high, and to cover partially and smother the reef-flats at the western corner of Maër Island. (See map, plate 2, and fig. 10.) Several smaller sand dunes on the northern corner of the island are also formed by the weaker northeasterly currents, and thus the northwest side of the island is concave and lined throughout by a sand beach formed of volcanic and calcareous fragments. It is interesting to observe that the sand derived from these currents is tending to change the original oval shape of the island into a crescent, reminding one of the manner in which an atoll islet acquires its typical crescentic shape, as shown by Guppy, Hedley and Taylor, Wood Jones, and Vaughan. The outflowing currents due to the falling tide are not competent to offset this effect, for they must make their way against the prevailing southeast wind. At the Murray Islands the tide rises between 7 and 8 feet, thus producing spring tide currents of nearly 4 knots an hour around the southern end and a flow of about half that rate around the northern end of the island."

As will later be shown, there is very little fine material in the samples from the southeast reef of Murray Islands and the proportion there is essentially the same as in the samples taken from behind the reef off Cocoanut Point, Andros Island, Bahamas. In both instances, in my opinion, the explanation of the small percentage of particles of silt and clay size is attributable to outwash by currents and not to submarine solution.

MECHANICAL AND CHEMICAL ANALYSES.

The following tables show the results of mechanical analyses of the Murray Island bottom samples and chemical analyses of the bottom samples, of certain foraminifera important as contributors to deposits in coral-reef areas, and of calcareous algæ from Murray Island and Cocos-Keeling Islands.

Mechanical analyses of samples from Murray Island.

(By U. S. Bureau of Soils.)

[The results of these analyses are graphically shown on plate 94.]

No., U. S. Bureau of Soils.	Description.	Fine gravel, 2 to 1 mm.	Coarse sand, 1 to 0.5 mm.	Medium sand, 0.5 to 0.25 mm.	Fine sand, 0.25 to 0.1 mm.	Very fine sand, 0.1 to 0.05 mm.	Silt, 0.05 to 0.005 mm.	Clay, 0.005 to 0 mm.
		p. ct.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
27336	Line I, above high tide, shore end	80.1	18.5	0.6	0.2	0.1	0.1	0.2
27337	Line I, 200 feet from shore	23.6	37.9	12.2	23.2	.7	.7	1.2
27338	Line I, 600 feet from shore	19.0	34.9	11.5	28.5	2.5	1.6	1.2
27339	Line I, 1,200 feet from shore	3.0	66.1	26.3	3.2	...	.2	.7
27353a	Line I, 1,600 feet from shore	27.1	66.2	4.0	.5	.1	.3	1.4
27340	Line III, north end, 1,700 feet from shore.	49.4	33.1	3.0	9.6	1.0	1.7	1.5

Chemical analyses of Murray Island bottom samples.

(By Alfred A. Chambers.)

Chemical analyses of bottom samples.						
	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	No. 6.
Loss on ignition	44.89	44.51	44.87	44.96	45.24	43.86
SiO_2	.23	.31	.09	.07	.22	.16
$Fe_2O_3+Al_2O_3$	.35	.30	.21	.10	.26	.27
CaO	50.80	51.54	50.86	51.41	49.80	55.35
MgO	2.69	2.58	2.75	2.68	3.49	.28
P_2O_5	.00	.00	.00	.00	.00	.00
SO_3	Trace.	Trace.	Trace.	Trace.	Trace.	.00
Na+K	Trace.	Trace.	Trace.	Trace.	Trace.	(?)
Total	98.96	99.24	98.78	99.22	99.01	99.92
CO_2 needed	42.87	44.34	42.98	43.33	42.87	43.72
Reduced analyses (hypothetical combinations).						
SiO_2	0.24	0.32	0.09	0.07	0.23	0.16
$(Al, Fe)_2O_3$	.36	.31	.22	.10	.27	.27
$MgCO_3$	5.83	5.52	5.95	5.76	7.57	.60
$CaCO_3$	93.57	93.85	93.74	94.07	91.93	98.97
$Ca_3P_2O_8$	.00	.00	.00	.00	.00	.00
$CaSO_4$	Trace.	Trace.	Trace.	Trace.	Trace.	.00
Total	100.00	100.00	100.00	100.00	100.00	100.00

No. 1, Murray Island, line I, southeast reef, 1,600 feet from shore. Water, 10 inches deep; low tide, October 2, 1913.
No. 2, Murray Island, line I, southeast reef, 200 feet from shore. Water, 4 inches deep.
No. 3, Murray Island, line I, southeast reef, 600 feet from shore. Water, 7 inches deep at low tide.
No. 4, Murray Island, line I, southeast reef, 1,200 feet from shore. Water, 12 to 16 inches deep at low tide.
No. 5, Murray Island, line III, north end, 1,700 feet from shore, washed up on reef above low-tide level.
No. 6, Murray Island, limestone from 500 to 700 feet above sea-level.

Chemical analyses of foraminifera important as contributors to deposits in coral-reef areas.

(1) *Tinoporus baculatus* (Montfort) Carpenter, from Murray Island.
(2) *Polytrema mineaceum* (Linn.), from Cocoanut Point, Andros Island, Bahamas.
(3) *Orbiculina adunca* (Fichtel and Moll), from Key West, Florida.
(4) *Orbitolites marginalis* (Lam.), from south of Tortugas, depth 17 fathoms.
(5) *Quinqueloculina auberiana* d'Orbigny, from south of Tortugas, depth 17 fathoms.
Analyses of 1, 2, 3, 4, by W. C. Wheeler; of 5 by Alfred A. Chambers.

	Chemical analyses of foraminifera.				
	(1) Tinoporus.	(2) Polytrema.	(3) Orbiculina.	(4) Orbitolites.	(5) Quinqueloculina.
SiO_2	0.03	0.02	0.11	0.30	0.54
$(Al, Fe)_2O_3$	.18		.09	.13	
MgO	5.03	5.09	4.64	4.93	4.32
CaO	27.35	47.35	48.79	48.92	49.02
P_2O_5	.00	(?)	Trace.	Trace.	(?)
Ignition[1]	46.57	46.24	45.56	45.20	45.54
Total	99.16	98.70	99.09	99.48	98.42

	Reduced analyses (hypothetical combinations).				
	(1) Tinoporus.	(2) Polytrema.	(3) Orbiculina.	(4) Orbitolites.	(5) Quinqueloculina.
SiO_2	0.03	0.02	0.11	0.31	0.56
$(Al, Fe)_2O_3$	.19		.09	.13	
$MgCO_3$	11.08	11.22	10.04	10.55	9.33
$CaCO_3$	88.70	88.76	89.76	89.01	90.11
$Ca_3P_2O_8$	.00	(?)	Trace.	Trace.	(?)
Total	100.00	100.00	100.00	100.00	100.00
	Murray Id.	Bahamas.	Key West.	Tortugas.	Tortugas.

[1] Organic matter + CO_2 + H_2O.

Analyses of Corallinaceous algæ (made by Alfred A. Chambers), presented on the next page, are additions to the series originally contained in the memoir by Messrs. Clarke and Wheeler, referred to on page 240 of this paper.

The specimen on shore, above high tide, line I, southeast reef, is composed of 80.1 per cent of fine gravel and 18.5 per cent of coarse sand, the two sizes aggregating 98.6 per cent of the sample. This specimen contains much basaltic gravel, as would be expected on the shore of a volcanic island. It is highly noteworthy that even 200 feet from shore on the southeast reef $SiO_2 + (Al, Fe)_2O_3$ together constitute only 0.63 per cent of the sample, showing that the volcanic material is not carried seaward in an appreciable amount. Reference to the quotation from Dr. Mayer's article (page 245) will give the explanation of the small percentage of these constituents.

The prevailing winds are from the southeast; the currents sheer around the island, and carry northwestward any material which has been sufficiently comminuted. Dr. Mayer mentions that lava boulders extend "fully 200 feet from mean low tide," but judging from the chemical analysis the fine material is not incorporated in the sediments. As the mouth of Haddon Brook is west of the line along which the samples were taken, the detritus brought to the sea by it would be moved westward. Furthermore, as the rainfall on Murray Island is rather low, only 32.66 inches per year, according to information furnished me by Dr. Mayer, the quantity of terrigenous material washed into the sea may be small.

The specimen from line III, north end of the island, cast up on the reef, 1,700 feet from shore, differs from the samples taken from below water-level in having a large percentage of fine gravel (49.4 per cent) and in having more $MgCO_3$ (7.57 per cent). There may have been some secondary concentration of magnesia.

Analyses of Corallinaceæ from Murray Island and Cocos-Keeling Islands.

(By A. A. Chambers.)

Chemical analyses of calcareous algæ.			
	Goniolithon frutescens Fosl., Cocos-Keeling Islands.	Goniolithon orthoblastum (Heyd.) M. A. Howe, Murray Island, Australia.	Lithophyllum kaiseri Heyd., Cocos-Keeling, Islands.
Loss on ignition....	46.70	50.97	45.72
$SiO_2+Fe_2O_3+Al_2O_3$.	.07	.11	.28
CaO.............	46.16	42.39	45.92
MgO.............	6.29	5.71	7.09
P_2O_5.............	Present.	Present.	Present.
SO_3.............	None.	None.	None.
Total.........	99.22	99.18	99.01
CO_2 needed........	43.19	39.59	43.88
Reduced analyses (hypothetical combinations).			
SiO_2, (Al, Fe)$_2$ O_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
Total.........	100.00	100.00	100.00

The specimen of limestone from 500 to 700 feet above sea-level is indurated, light yellowish-gray in color, somewhat horny in texture, with a conchoidal fracture. It is largely coral, with numbers of embedded foraminifera, of which Miliolidæ are the most noticeable in a thin section. The chemical analysis shows it to be 98.97 per cent $CaCO_3$, a remarkably pure limestone. As the percentage of $MgCO_3$ is only 0.60 per cent, there has been no dolomitization of this specimen, at least. This is coral-reef rock. Analyses of other specimens would probably show more $MgCO_3$, as a few fragments of Lithothamnion or a few foraminifera would increase its percentage. Haddon, Sollas, and Cole report that "analysis shows a fragment from the summit of Gilam to be largely dolomitic."[1]

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[1] Trans. Roy. Irish Acad., vol. 30, p. 433, 1894.

SUMMARY ON THE MURRAY ISLAND SAMPLES.

(1) The mechanical analyses show two classes, or grades, of deposits: (*a*) beach deposits, subject to wave-action at or above high-tide level. Fine gravel (1 to 2 mm. in diameter) constitutes from 50 to 80 per cent of the deposit; fine gravel and coarse sand combined range from a little more than 80 per cent up to nearly 99 per cent of the material; (*b*) sands between the reef and the shore, in which coarse gravel is from 35 to about 66 per cent of the material. Class (*b*) shows increase in percentage of medium and fine sand as the shore is approached until 600 feet offshore; at 200 feet from shore there is increase in the amount of fine gravel. In this class there is a larger percentage of coarse sand than of any other size. The small percentage of silt and clay is attributed to outwash by currents.

(2) The $MgCO_3$[1] content averages 5.745 per cent in the samples behind the reef. The relative importance of organisms 1,600 feet from shore is as follows: (*a*) corals, 41.9 per cent; (*b*) calcareous algæ, 32.6 per cent; (*c*) foraminifera, 12.4 per cent; mollusca, 10.2 per cent. At 200 feet from shore the order is: calcareous algæ, 42.5; corals, 34.6 per cent; mollusca, 15.2 per cent; foraminifera, 4.1 per cent. The investigation of Dr. Goldman shows the possibility of correlating the chemical composition of an entire sample with the chemical composition of its different constituents.

(3) The higher percentage of magnesia in the specimen washed up on the reef off the north end of the island may be due to secondary concentration. This subject needs further investigation.

COMPOSITION OF TWO MURRAY ISLAND BOTTOM SAMPLES ACCORDING TO SOURCE OF MATERIAL.[2]

The following are the results of an attempt to determine the group of organisms to which each grain in two different samples of "coral" sand belonged and to explain the chemical composition of the sands as determined by direct chemical analysis; especially to account for the relative amounts of calcium carbonate and magnesium carbonate. As far as possible, each of a lot of grains was identified either by its external characters or by its internal structure as revealed under the microscope. In this process, as many of the grains had to be destroyed, the weight of grains of each kind had to be calculated from the weight of those preserved. This proved more difficult than had been anticipated. From these weights the proportion of the leading chemical constituents present was calculated by using figures for the composition of each organism, obtained (by the courtesy of Dr. F. W. Clarke) from the manuscript of a paper by Clarke and Wheeler on the composition of the inorganic constituents of marine invertebrates and calcareous algæ. From the composition thus computed for each group of organisms the composition of the entire sand was calculated.

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[1] Hypothetical combination.

[2] The discussion of this topic is contributed by Dr. Marcus Isaac Goldman.

The count was based on the differentiation of the following groups of organisms:

- Madreporarian corals.
- Mollusks.
- Calcareous algæ.
- Foraminifera.
- Echinoids.
- Worm-tubes.
- Crustacea.
- Alcyonarian corals.
- Bryozoa.
- Millepores.

Wherever possible, further subdivisions, almost entirely by external characters, were made as follows:

Mollusks: Gastropods, Pelecypods, Scaphopods.
Foraminifera: Tinoporus baculatus, Amphistegina lessoni, Orbitolites.
Crustacea: Balanus or other barnacles (cirripeds), Malacostraca (crabs, lobsters, etc.), Ostracods.
Alcyonaria: Spicules, solid skeleton.
Echinoids: Spines, plates.

The recognition of the microscopic characters was based on a preliminary study of known material from the different groups, in thin section and more especially as crushed fragments. It is in the study of known material that the work needs particularly to be enlarged, for while the groups differentiated do undoubtedly have certain persistent characters, yet one constantly learns, in studying new, known material in a group, that the differences between members of a group are often more apparent than the resemblances; consequently, grains are occasionally encountered in the unknown material, all the most individual characters of which are unfamiliar, or characters are combined that seem to ally them to different groups—groups perhaps as remote from each other as algæ and crustaceans. The remedy for this confusion is, of course, to study a greater variety of known material under each group; in fact, the most satisfactory procedure would be to collect, at the same time that the sample of sand is collected, a specimen of the skeleton of every species inhabiting the neighborhood of the sample. Then, too, a more detailed and careful study of the materials should be made than the time available in preparation for the study here presented permitted.

In spite of the difficulties that many of the grains offered, it was deemed best to assign each of them to some form, since a majority of the doubtful grains will probably be correctly identified and the right result consequently more nearly approached than by leaving them unidentified and thus with no effect on the result. Accordingly, only two or three grains, all of one kind and resembling nothing that was known to me, were left undetermined.

In order to enable the reader to estimate the probability of accuracy in the results here presented, it will be well to indicate in a general way the ease or difficulty with which the groups were differentiated. One of the most important differentiations is that between corals and algæ, and this, fortunately, is one of the easiest and surest. But within each of these groups are two subgroups of very distinct chemical composition. The corals contain the madreporarians (which are nearly pure lime) and the alcyonarians, which (in addition to predominant $CaCO_3$) have about 15 per cent $MgCO_3$ and 8 per cent $Ca_3P_2O_8$. While the loose spicules, which are probably by far the most abundant skeletal representative of the alcyonarians, are easily recognized by their external form, the laminated solid skeleton of such forms as *Lepidisis* and *Isis* have characters very much like the madreporarian skeleton; the loose spicules, too, when their external form has been lost by wear, are not readily differentiated. Fortunately, the alcyonarians seem scarcely to be included in the materials studied from Murray Island. In the two samples only one spicule was noticed. Where spicules are so scarce it is improbable that there is an appreciable amount of the solid skeleton present and the failure to recognize any alcyonarian material may therefore have been justified. In the first examination of some of the portions a number of grains were tentatively classified as alcyonarian, but on re-examination the characters suggesting this group did not seem pronounced enough, in the absence of any evidence that the group was appreciably represented, to justify leaving them there. They were therefore placed with the madreporarians, which they resembled in their general characters.

The two distinct chemical groups in the algæ are the Corallinaceæ and the genus *Halimeda*. The Corallinaceæ that have been analyzed contain about 19 per cent of $MgCO_3$, *Halimeda* only about 0.5 per cent. This chemical difference was learned too late for the differentiation of the two groups in the study of the Murray Island sands; but it is very doubtful in any case whether such differentiation was possible except in the coarsest sizes of material. However, here is a question requiring the most careful attention and persistent effort, for both groups are well represented in the sands and the difference in their content of magnesium carbonate, the substance with which this study is most concerned, far exceeds that between the members of any other group considered.

Mollusks are one of the groups having generally the best-defined characters under the microscope. They tend a little at times to confusion with crushed madreporarian material; but, even if the two are occasionally not properly discriminated, it is not important from the chemical point of view, since both are nearly pure $CaCO_3$.

Foraminifera, at least those present in the Murray Island sands, are more often recognizable by their external characters than any other group. Under the microscope, too, the small perforations of the Perforata are unmistakable, but the Imperforata are a little more difficult, since they tend to resemble certain fragments of algæ or bryozoa.

Bryozoa were probably very scarce, if at all present. Their microscopic characters seem to be rather mixed, partly resembling corals, partly perhaps algæ, but recognition by external character would probably be possible with a large proportion of bryozoan grains.

Echinoid fragments are by far the most easily recognized under the microscope, by their reticulation in three planes and the curved, sharply defined outlines of the individual fragments of this structure, as also by the fact that each plate is apparently always a single crystal, extinguishing, as a consequence, simultaneously between crossed Nicol prisms.

Crustacea are characterized particularly by a vaguely fibrous structure, which tends, however, to be confused with a more pronounced fibrous structure in certain algal fragments. Not much familiarity with the group was acquired. Where cirripeds or ostracods have been differentiated from other crustacea it was by external characters.

Worm-tubes were recognized only by external form. Their microscopic characters seemed difficult to recognize, especially because the samples of known material generally contained, inside the tube, fragments of a number of other organisms, which after crushing appeared on the slide mixed with the fragments of the tube itself.

Characters for differentiating millepores from madrepores under the microscope were not worked out. On inspection they appeared extremely similar. It seemed, however, as though millepores if present should be recognizable externally by their cellular structures, even in very small grains.

The manipulation of the count varied somewhat in different sizes. Some effort was made to keep a proportion between the number of grains determined in the particular size-portion and the ratio that the portion bore to the entire sand, but to have kept the ratio at all exact would have necessitated counting more grains in the coarser portions or fewer in the fine than would be worth while, so that the ratio maintained was only rough. In the coarser portions the weight as well as the number of grains taken for identification was determined—except in the "fine gravel" of No. 27353*a*, which was the first studied, before the importance of determining the weight was recognized. The object, then, was to preserve from the weighed portions a large number of the original grains of each group and from their weight to calculate the weight of the total of grains of each group originally present, in such a way as to check with the original weight.

The method of calculating the weights of these portions will be presented later. At present the method of determining the number of different kinds of grains is to be described. As finally developed, it consisted in identifying as many grains as possible directly by their external appearance. These were put aside in small vials. It was found that this identification could be best conducted by grouping the grains that appeared to be most alike in color, texture, translucency, form, etc. By identifying a certain number of these from their internal structure under the microscope the identification, by external appearance, of those most closely resembling them was assured. It was found that generally the algæ were most certainly recognized by a certain rough, porous, opaque appearance. For determining the microscopic character the effort was made, as often as possible, to take only part of the grain. This on the one hand gives identified grains for future comparison and on the other gives more material for weighing. In order to get the true weight, however, it was necessary to know the fraction of the original grain that the portion preserved represented. This was estimated and recorded.

The slides of crushed grains or portions of grains were in the end prepared directly with a rather thin solution of Canada balsam in xylol. In this way slides that were interesting or difficult could be kept for future study.

With the fine and very fine sand the procedure developed was to lay out, in more or less accurate alinement, an indefinite number of grains taken from all parts of the sample. From one end of this row a suitable number of grains was then taken in the order in which they lay. This was done because it was found difficult to keep track of a definite number of these fine grains taken in advance, because the method was quicker, and because the original weight of the grains taken was too small to be worth determining.

The ratios of numbers of grains of different groups had to be converted into ratios of weights of the groups because of apparent difference in weight per unit volume; but to arrive at any accurate figures for these relative weights proved very difficult. In one portion the unit weight of mollusk grains would greatly exceed that of madrepores, in others the reverse. The difficulty lay mainly in the fact that the grains were very variable in size and that those identified by their external appearance or by removing a fraction for microscopic study tended to be the larger ones. Consequently their average weight could not be taken as the average weight of all the grains of that group originally present. Under these circumstances, with the small amount of data available, any attempt at a strictly mathematical determination of probable unit weights seemed inapplicable. It seemed best to adjust the weights of the coarser portion on the basis of general considerations derived partly from the portion itself and partly from portions previously studied. In one case the first assumptions led to a total weight for the grains studied which differed only 8 mg. in 383 mg. from the weight originally determined. In another case 4 trials had to be made, adjusting the assumptions in each case, before a sufficient correspondence was obtained.

For the portions finer than the coarse sand ratios of weight units were calculated from the results arrived at in the previous calculations. The important factors were the relative weights of algæ, corals, and mollusks. Since there were no observed unit weights to go by in these finer portions, much greater generalization of the results was necessary. The unit weights of corals and mollusks were therefore taken as equal. The actual adjustment was made in the "fine gravel" of No. 27337. Since large quantities were weighed in that portion, observations were careful and full, and the unit weights obtained seemed better balanced than in any other portion. The unit weight of coral and mollusk was taken at a round figure about the mean of the weights of each group in this portion and all other figures were kept in their original ratio. From these relative unit weights the relative weights of the total number of grains of each group present in a portion were calculated and from these the percentage by weight of each group was obtained.

In future it would be well to seek more direct and accurate results by some method like the following: Select from the sample laid out for determination some grain of fairly regular shape to be regarded as a unit of volume; then estimate and record for each grain studied the number of such units it contains. In this way there will be a record of the number of units of volume of each organic group originally present and thus direct comparisons of unit weights will be possible as far as the volumes were correctly estimated. In any case this will be more accurate than merely recording the number of grains of each group. Where part of a grain is taken for crushing and microscopic study, both the number of units of volume it originally contained and the number of units preserved for weighing must be recorded. Probably it will be best to take one of the smaller grains, though not necessarily the smallest, as the unit; or perhaps some more regular unit (as a piece of shot passing the same sieve as the sample) will be found best.

Chemical Composition.

The chemical composition of each size portion was obtained by calculating the percentage of the four principal salts, $CaCO_3$, $MgCO_3$, $CaSO_4$, and $Ca_3P_2O_8$, contained in each organic group. The assumed composition of the organic groups was derived from figures given in the manuscript of Dr. Clarke and Mr. Wheeler's unpublished paper.[1] Those used in the calculations for this paper are tabulated herewith:[2]

	$CaCO_3$	$MgCO_3$	$CaSO_4$	$Ca_3P_2O_8$
Corallinaceæ	80.00	19.00	1.00	......
Halimeda	99.00	.50	.50	......
Mean alga	89.50	9.75	.75	......
Madreporaria	99.30	.70	......	......
Alcyonaria	75.00	15.00	......	8.00
Mollusks	99.75	.25	......	......
Tinoporus	89.00	11.00	......	......
Amphistegina	95.20	4.80	......	......
Orbitolites	89.40	10.60	......	......
Polytrema	88.75	11.25	......	......
Approximate average foraminifera	89.50	10.50	......	......
Crustacea:				
(1) Malacostraca and ostracods	77.00	12.50	1.25	8.75
(2) Balanus	98.50	1.50	......	......
Sea-urchin spines	90.00	9.00	1.00	......
Worm-tubes	91.00	8.00	......	1.00

In a few cases of individual species of foraminifera, etc., these figures could be taken directly; but in most cases some sort of compromise, which was not at all a mathematical averaging, had to be made. The reason for not taking an average was mainly that many forms show a tendency to an increased percentage of $MgCO_3$ with increase in temperature of the water in which they live; hence forms from environments corresponding more or less to Murray Island had to be favored in deriving the figures. Further-

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[1] F. W. Clarke and W. C. Wheeler. The inorganic constituents of marine invertebrates and calcareous algæ.

[2] The combinations of acid and basic radicals in all the following tables are hypothetical and are used in order to conform with those given in Clarke and Wheeler's manuscript.

more, SiO_2 and $(Al, Fe)_2O_3$ were rejected as being probably extraneous impurities, very variable and generally very small in amount. The value used for the composition of the algæ as given in the preceding table is an approximate mean of the composition of Corallinaceæ and *Halimeda.*

The following tables give the essential portions of the results obtained:

Analysis of sample No. 27353a, line I, 1,600 feet from shore.

	No. of grains present.	Calculated weight.	Weight percentage.	Calculated percentage composition.			
				$CaCO_3$	$MgCO_3$	$CaSO_4$	$Ca_3P_2O_8$
1. FINE GRAVEL.		*gm.*					
Algæ................	44	0.0582	34.45	30.85	3.35	0.25	....
Corals..............	16	.0191	11.30	11.20	.10	....	....
Mollusks............	16	.0219	12.95	12.90	.05	....	....
Tinoporus baculatus..	51	.0449	26.60	23.70	2.90	....	....
Amphistegina lessoni..	25	.0175	10.35	9.85	.50	....	....
Orbitolites...........	2	.0028	1.65	1.50	.15	....	....
Barnacles (Balanus?)..	2	.0036	2.10	2.05	.05	....	....
Echinoid spine.......	1	.0010	.60	.55	.05	Tr.	....
	157	.1690	100.00	92.60	7.15	.25	....
2. COARSE SAND.							
Algæ................	27	0.0094	34.30	30.70	3.35	0.25	....
Corals..............	66	.0145	52.95	52.60	.35	....	....
Mollusks............	11	.0027	9.85	9.80	.05	....	....
Tinoporus...........	2	.0004	1.45	1.30	.15	....	....
Amphistegina........	3	.0003	1.10	1.05	.05	....	....
Polytrema...........	1	.0001	.35	.30	.05	....	....
	110	.0274	100.00	95.75	4.00	.25	....
3. MEDIUM SAND.		*wt. units*					
Algæ................	3	435	10.75	9.60	1.05	0.10	....
Corals..............	26	3,380	83.50	82.90	.60	....	....
Mollusks............	1	100	2.50	3.20	.05	....	....
Foraminifera.........	1	130	3.25	2.25	.25	....	....
	31	4,045	100.00	97.95	2.95	.10	....
4. FINE SAND.							
Algæ................	4	580	22.15	19.85	2.15	0.15	....
Corals..............	11	1,430	54.55	54.15	.40	....	....
Mollusks............	4	520	19.85	19.80	.05	....	....
Ostracods...........	1	90	3.45	2.65	.45	.05	0.30
	[1]20	2,620	100.00	96.45	3.05	.20	.30
5. VERY FINE SAND.							
Algæ................	1	145	8.00	7.15	0.80	0.05	....
Corals..............	7	910	49.80	49.45	.35	....	....
Mollusks............	2	260	14.25	14.20	.05	....	....
Foraminifera.........	3	300	16.45	14.70	1.75	....	....
Ostracod............	1	90	4.95	3.80	.65	.05	0.45
Coccolithophoridæ[2]...	1	[3]120	6.55	5.85	.65	.05	....
Clay................	3	([4])	....	....	....	....	....
	18	1,825	100.00	95.15	4.25	.15	.45

[1] Compound grains (4) regarded as proportionate mixture of other materials present and therefore ignored.

[2] Assume same chemical composition as other calcareous algæ.

[3] Estimated. [4] Ignore. SiO_2 and $(Al, Fe)_2O_3$ are not being calculated in the chemical composition.

Summaries, sample No. 27353a.

I. Numbers of grains of different organisms counted.

	Algæ.	Corals.	Mollusks.	Tinoporus.	Amphistegina.	Orbitolites.	Polytrema.	Undifferentiated foraminifera.	Barnacles.	Ostracods.	Coccolithophoridæ.	Echinoids.	Total.
Fine gravel	44	16	16	51	25	2	....	....	2	....	....	1	157
Coarse sand	27	66	11	2	3	....	1	....	....	....	....	....	100
Medium sand	3	26	1	....	....	....	....	1	....	....	....	....	31
Fine sand	4	11	4	....	....	....	....	....	....	1	....	....	20
Very fine sand	1	7	2	....	....	....	....	3	....	1	1	....	15
Total	79	126	34	53	28	2	1	4	2	2	1	1	333

II. Calculated percentages by weight of different organisms present.

	Algæ.	Corals.	Mollusks.	Tinoporus.	Amphistegina.	Orbitolites.	Polytrema.	Undifferentiated foraminifera.	Barnacles.	Ostracods.	Coccolithophoridæ.	Echinoids.	Total.
Fine gravel	9.3	3.1	3.5	7.2	2.8	0.4	....	....	0.6	....	....	0.2	....
Coarse sand	22.7	35.1	6.5	1.0	.7	....	0.2	....	....	....	....	....	....
Medium sand	.5	3.3	.1	....	....	....	....	0.1	....	....	....	....	....
Fine sand	.1	.3	.1	....	....	....	....	....	....	Tr.	....	....	....
Very fine sand	....	.1	....	....	....	....	....	....	....	....	Tr.	....	....
Total	32.6	41.9	10.2	8.2	3.5	.4	.2	.1	.6	Tr.	Tr.	.2	97.9

III. Calculated percentage chemical composition by organisms.

	Algæ.	Corals.	Mollusks.	Tinoporus.	Amphistegina.	Orbitolites.	Polytrema.	Undifferentiated foraminifera.	Barnacles.	Ostracods.	Coccolithophoridæ.	Echinoids.	Total.
$CaCO_3$	29.2	41.6	10.2	7.3	3.3	0.4	0.2	0.1	0.6	....	....	0.2	93.1
$MgCO_3$	3.2	.3	....	.9	.2	....	....	....	....	....	....	....	4.6
$CaSO_4$	.2	....	....	....	....	....	....	....	....	....	....	....	.2
$Ca_3P_2O_8$	....	....	....	....	....	....	....	....	....	Tr.	....	....	Tr.

IV. Calculated percentage chemical composition by size portions.

	Per cent present.	Per cent of constituents.			
		$CaCO_3$	$MgCO_3$	$CaSO_4$	$Ca_3P_2O_8$
Fine gravel	27.1	25.2	1.9	Tr.	....
Coarse sand	66.2	63.4	2.6	0.2	....
Medium sand	4.0	3.9	.1	Tr.	....
Fine sand	.5	.5	Tr.	Tr.	Tr.
Very fine sand	.1	.1	Tr.	Tr.	Tr.
	97.9	93.1	4.6	.2	....
Silt	.3	[1].3	Tr.	....	....
Clay	1.4	[1].9	Tr.	....	....
Total	99.6	94.3	4.6	.2	....

[1] See discussion following.

In the portions of silt and clay size the particles were too fine for quantitative identification, although a number of them could be recognized. Following are brief notes of a qualitative examination.

Silt (*sample No. 27353a*).—Of the larger fragments very many are foraminifera; coccolithophoridæ (*Pontosphæra*) are fairly frequent; spicules are scarce and are mainly siliceous.

Clay (*sample No. 27353a*).—Coccoliths are extremely rare. There are flakes with needle-shaped or lath-shaped, highly birefringent inclusions. These inclusions, according to Dr. H. E. Merwin, of the Geophysical Labora-

Analyses of sample No. 27337, line I, 200 feet from shore.

	No. of grains present.	Calculated weight.	Weight percentage.	Calculated percentage composition.			
				$CaCO_3$	$MgCO_3$	$CaSO_4$	$Ca_3P_2O_8$
1. FINE GRAVEL.		*gm.*					
Algæ	39	0.0569	39.75	35.60	3.85	0.30	....
Corals	31	.0383	26.75	26.55	.20	....	....
Mollusks	29	.0392	27.40	27.30	.10	....	....
Tinoporus	5	.0049	3.40	3.05	.35	....	....
Amphistegina	4	.0029	2.00	1.90	.10	....	....
Orbitolites	2	.0010	.70	.65	.05	....	....
Total	110	.1432	100.00	95.05	4.65	.30	....
2. COARSE SAND.							
Algæ	56	0.0195	50.90	45.60	4.95	0.35	....
Corals	58	.0135	35.25	35.00	.25	....	....
Mollusks	20	.0034	8.90	8.85	.05	....	....
Tinoporus	2	.0004	1.05	.95	.10	....	....
Amphistegina	1	.0001	.25	.25	Tr.	....	....
Orbitolites	1	.0003	.80	.70	.10	....	....
Foraminifera (undifferentiated)	3	.0006	1.55	1.40	.15	....	....
Crustacea	2	.0004	1.05	.80	.15	Tr.	0.10
Worm-tubes	1	.0001	.25	.25	Tr.	....	Tr.
Total	144	.0383	100.00	93.80	5.75	.35	.10
3. MEDIUM SAND.		*wt. units.*					
Algæ	11	1,595	31.05	27.80	3.00	0.25	....
Corals	20	2,600	50.65	50.30	.35	....	....
Mollusks	5	650	12.65	12.60	.05	....	....
Foraminifera (undifferentiated)	1	100	1.95	1.75	.20	....	....
Orbitolites	1	130	2.55	2.30	.25	....	....
Worm-tube	1	60	1.15	1.05	.10	....	Tr.
Total	39	5,135	100.00	95.80	3.95	.25	Tr.
4. FINE SAND.							
Algæ	21	3,045	42.40	37.95	4.15	0.30	....
Corals	20	2,600	36.20	35.95	.25	....	....
Mollusks	9	1,170	16.30	16.25	.05	....	....
Foraminifera	2	200	2.75	2.45	.30	....	....
Balanus	1	170	2.35	2.30	.05	.30	....
Total	53	7,185	100.00	94.95	4.75	.60	....
5. VERY FINE SAND.							
Algæ	6	870	34.00	30.45	3.30	0.25	....
Corals	11	1,430	55.85	55.45	.40	....	....
Mollusks	2	260	10.15	10.15	Tr.	....	....
Total	19	2,560	100.00	96.05	3.70	.25	....

tory of the Carnegie Institution of Washington, are "hexagonal plates set edgewise. They are optically positive, ω = about 1.535, ϵ = about 1.560. These are surely not aragonite, but I can find in the mineral tables nothing corresponding to them."[1] They require further study.

Summaries, sample No. 27337.

I. Numbers of grains of different organisms counted.

	Algæ.	Corals.	Mollusks.	Tinoporus.	Amphistegina.	Orbitolites.	Undifferentiated foraminifera.	Crustacea.	Balanus.	Worm-tubes.	Total.
Fine gravel........	39	31	29	5	4	2	..	..	..	..	110
Coarse sand.......	56	58	20	2	1	1	3	2	..	1	144
Medium sand......	11	20	5	..	..	1	1	..	..	1	39
Fine sand.........	21	20	9	..	..	..	2	..	1	..	53
Very fine sand.....	6	11	2	..	..	..	..	..	..	..	19
Total.........	133	140	65	7	5	4	6	2	1	2	365

II. Calculated percentage by weight of different organisms present.

	Algæ.	Corals.	Mollusks.	Tinoporus.	Amphistegina.	Orbitolites.	Undifferentiated foraminifera.	Crustacea.	Balanus.	Worm-tubes.	Total.
Fine gravel........	9.4	6.3	6.5	0.8	0.5	0.2	...	...	...	...	....
Coarse sand.......	19.3	13.3	3.3	.4	.1	.3	0.6	0.4	...	0.1	....
Medium sand......	3.8	6.2	1.5	...	...	.3	.2	...	...	.1	....
Fine sand.........	9.8	8.4	3.8	...	...	...	.7	...	0.6	...	....
Very fine sand.....	.2	.4	.1	...	...	...	...	...	...	...	....
Total.........	42.5	34.6	15.2	1.2	.6	.8	1.5	.4	.6	.2	97.6

III. Calculated percentage chemical composition by organisms.

	Algæ.	Corals.	Mollusks.	Tinoporus.	Amphistegina.	Orbitolites.	Undifferentiated foraminifera.	Crustacea.	Balanus.	Worm-tubes.	Total.
$CaCO_3$............	38.0	34.4	15.2	1.0	0.6	0.7	1.3	0.3	0.6	0.2	92.3
$MgCO_3$...........	4.2	.2	.0	.2	.0	.1	.2	.1	.0	.0	5.0
$CaSO_4$............	.3	....	....	...	...	...	...	...	...	...	.3
$Ca_3P_2O_8$..........	....	....	....	...	...	...	...	...	...	...	....

IV. Calculated percentage chemical composition by size portions.

	Per cent present.	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.	$Ca_3P_2O_8$
Fine gravel..........................	23.6	22.40	1.10	0.3	..
Coarse sand..........................	37.9	35.55	2.20	...	Tr.
Medium sand.........................	12.2	11.70	.50	...	Tr.
Fine sand............................	23.2	22.00	1.15	...	..
Very fine sand.......................	.7	.65	.05	...	..
	97.6	92.3	5.00	0.3	Tr.
Silt.................................	.7	[2].7	Tr.	...	..
Clay................................	1.2	[2].7	Tr.	...	..
Total............................	99.5	93.7	5.0	0.3	..

Silt (*sample No. 27337*).—Contains coccolithophoridæ (*Pontosphæra*), minute foraminifera, sponge spicules, etc.

Clay (*sample No. 27337*).—In this clay round coccoliths are abundant; "there are numerous calcite grains and rhombs which appear exactly like

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[1] Letter of May 9, 1916, from Dr. H. E. Merwin.

[2] See discussion following.

chemical precipitates, also [unidentified] material such as described for [the clay of] sample 27353*a*."[1] In regard to the calcite grains it should be noted that they considerably exceeded in diameter the maximum diameter of the "clay" portion. It must be concluded, therefore, that they were not originally present in the sample, but were precipitated in evaporating down the water in which the "clay" was suspended. The "clays" of two other samples from the same region were examined and like sample No. 27353*a* were not found to contain any precipitated calcite.

Before comparing the results of the final summary with the direct analysis of the sample, some allowance must be made for the contents of the silt and clay. Trustworthy indication as to the probable composition of these portions is lacking, but their amount is so small that unless some great divergence from the composition of the other portions were indicated, the effect in changing the ratio of Ca to Mg in the total sample would not be appreciable in any case.

Analyses of sample No. 27353a, line I, 1,600 feet from shore.

	Ratio $CaCO_3$: $MgCO_3$.	Ratio Ca : Mg organisms.[1]	
		Relative weights.	Weight ratio.
Fine gravel......	100:7.57	24.25:73.05	100:301
Coarse sand.....	100:4.09	62.80:37.20	100: 59.3
Medium sand....	100:2.56	86.00:14.00	100: 16.3
Fine sand.......	100:3.16	74.40:22.15	100: 29.8
Very fine sand....	100:4.47	64.05:31.00[2]	100: 48.4
Silt............	....	....	....
Clay...........	....	....	....

[1] Ca organisms = Corals and mollusks; Mg organisms = Algæ and foraminifera.
[2] Includes coccolithophoridæ (*Pontosphæra*).

The foregoing table indicates a tendency for the proportion of magnesia to increase in the finer portions, and this may continue into the silt; but whether it also continues into the clay is very uncertain. The assumption that it is carried into the silt is supported by the apparent abundance of foraminifera in this portion, which is in conformity with their relative increase in the very fine sand; but what effect the increasing abundance of coccolithophoridæ has on the chemical composition is not known, since these forms have not been segregated and analyzed. It has merely been assumed that they have a composition similar to the algæ; but, in any case, the amount of silt is so small that all of it must undoubtedly be thrown to the $CaCO_3$. In the "clay" the proportion of the coccolithophoridæ appears even greater; then, too, the undetermined mineral ingredient and probably other indeterminate factors enter, so that the factors controlling the composition of this portion are of an entirely new sort. Furthermore, it seems proper to place nearly all the SiO_2 and $(Al, Fe)_2O_3$ into this portion, though a small part is undoubtedly present in the other portions. Charge say 0.5 per cent out of

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[1] Letter of May 1916, from Dr. H. E. Merwin.

the total 0.6 per cent SiO_2 and $(Al, Fe)_2O_3$ to the "clay." That leaves 0.9 per cent "clay" to account for. Then assuming a composition of 96 per cent $CaCO_3$ and 4 per cent $MgCO_3$ the percentage of $MgCO_3$ becomes 0.046 or less than is being considered here. Comparing the calculated and directly determined results then we have, for sample No. 27353*a:*

	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.	$Ca_3P_2O_8$	SiO_2 and $(AlFe)_2O_3$.
Calculated.....	94.3	4.6	0.2	Tr.	.60
Observed......	93.6	5.8	Tr.	..	.60

Following a similar procedure with sample No. 27337, line I, 200 feet from shore, we have:

	Ratio $CaCO_3$: $MgCO_3$.	Ratio Ca : Mg organisms.[1]	
		Relative weights.	Weight ratio.
Fine gravel......	100 : 4.90	54.15 : 45.85	100 : 84.70
Coarse sand.....	100 : 6.20	44.15 : 54.55	100 : 123.50
Medium sand....	100 : 4.28	63.30 : 35.55	100 : 56.15
Fine sand.......	100 : 4.98	52.50 : 45.15	100 : 86.10
Very fine sand....	100 : 3.85	66.00 : 34.00	100 : 51.50

[1] Ca organisms = Corals and mollusks; Mg organisms = Algæ and foraminifera.

Here there is even less system and therefore less basis for assumptions as to the probable value of the $CaCO_3$: $MgCO_3$ ratio in the silt and clay. Foraminifera seemed abundant in the silt, but there is not in this sample, as there was in No. 27353*a*, any indication of a tendency in the fine sand towards their increase. Making the same assumptions as in No. 27353*a*, we have (deducting 0.50 per cent out of the 0.63 per cent of SiO_2 and $(Al, Fe)_2O_3$) 0.7 per cent "clay" to account for. Again, if we take $CaCO_3$ at 96 per cent of the silt and the "clay," the residue referable to $MgCO_3$ becomes negligible. The totals compared then are as follows, for sample No. 27337:

	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.	$Ca_3P_2O_8$	SiO_2 and $(Al, Fe)_2O_3$.
Calculated.....	93.7	5.0	0.3	Tr.	0.63
Observed......	93.85	5.5	Tr.	.00	.63

Considering the results for both samples together, we see at once that in No. 27337 there is a much closer agreement between calculated and directly derived results than in No. 27353*a*. I do not know the explanation of this. Undoubtedly by far the largest part of the discrepancy in both cases is due to error in the assumed proportion of Corallinaceæ to *Halimeda*—that is to say, the Corallinaceæ are usually more than half of the algæ. I do not believe that the greater experience brought to the study of No. 27337 is adequate to account for an appreciable part of the greater agreement of the two results in this portion. It is much more probable that the ratio of the two types of algæ to each other was more nearly the assumed ratio, that is, in this nearer shore area *Halimeda* was relatively more abundant than farther from the shore. The following calculations show the proportion in which the two types of algæ would have to be present in order to make the calculated and directly observed results for $MgCO_3$ agree. The results are not at all in conflict with what would be expected from field experience with coral reefs.

For sample No. 27353*a*, if the proportions of the two types of algæ were, Corallinaceæ 69.5 per cent, *Halimeda* 30.5 per cent, then there would be in the whole sample, Corallinaceæ 22.8 per cent, *Halimeda*, 9.8 per cent; and their respective contributions to the whole sample would be:

	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.
Corallinaceæ	18.25	4.35	0.20
Halimeda	9.70	.05	.05
Revised calculations	27.95	4.40	.20
Original calculations	29.2	3.2	.20
Difference	−1.3	+1.2	....

Correcting the calculated results by these amounts, we have, for sample No. 27353*a:*

	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.
Revised	93.0	5.8	0.2
Observed	93.6	5.8	Tr.

The fact that now the calculated amount of $CaCO_3$ has fallen below the observed amount proves that these revised calculations are not quite adequate to account for the discrepancies, though they bring about a closer agreement.

If in sample No. 27337 the Corallinaceæ were 57.05 per cent and *Halimeda* 42.95 per cent of the total algæ, then there would be in the whole sample Corallinaceæ 24.25 per cent, *Halimeda* 18.25 per cent, and their respective contributions to the whole sample would be:

	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.
Corallinaceæ	19.35	4.65	0.25
Halimeda	18.10	.05	.05
Revised calculations	37.45	4.7	.30
Original calculations	38.0	4.2	.30
Difference	−0.55	+0.5	....

For the total of sample No. 27337, we then have:

	$CaCO_3$.	$MgCO_3$.	$CaSO_4$.
Revised	93.15	5.5	0.3
Observed	93.85	5.5	Tr.

Here the error in the calculated amount of $CaCO_3$ is increased, indicating that there is no consistent error running through the counts and calculations to explain all the discrepancies in chemical composition.

The discrepancy between the calculated and directly observed percentage of $CaSO_4$ in both samples is probably to be accounted for by greater solubility of the $CaSO_4$ than of the carbonates under the conditions in which they both exist in the sands. The sulphate in the calculated results is derived, as will be seen from the tables, almost entirely from the algæ. The determinations of the composition of algæ were made on fresh material, while the sands have lain for some time, in their disintegrated condition and free from their organic covering, in ocean water.

BOTTOM SAMPLES FROM THE BAHAMAS.

The Bahaman samples represent the following conditions:

(1) The area just behind the barrier reef off Cocoanut Point, Andros Island. These samples are Nos. 190 to 193. The general position of the area from which they were obtained is indicated on the small-scale map, plate 95, and the more precise position is shown on the map, figure 3.

(2) The finely divided mud accumulating in stagnant areas in South Bight. Sample No. 79, see plate 95.

(3) The finely divided, oolitic mud forming off the west end of South Bight. Sample No. 87, see plate 95.

(4) Shore material, subject to tidal overflow on the west side of Andros Island, near the mouth of South Bight. Sample No. 83, see plate 95.

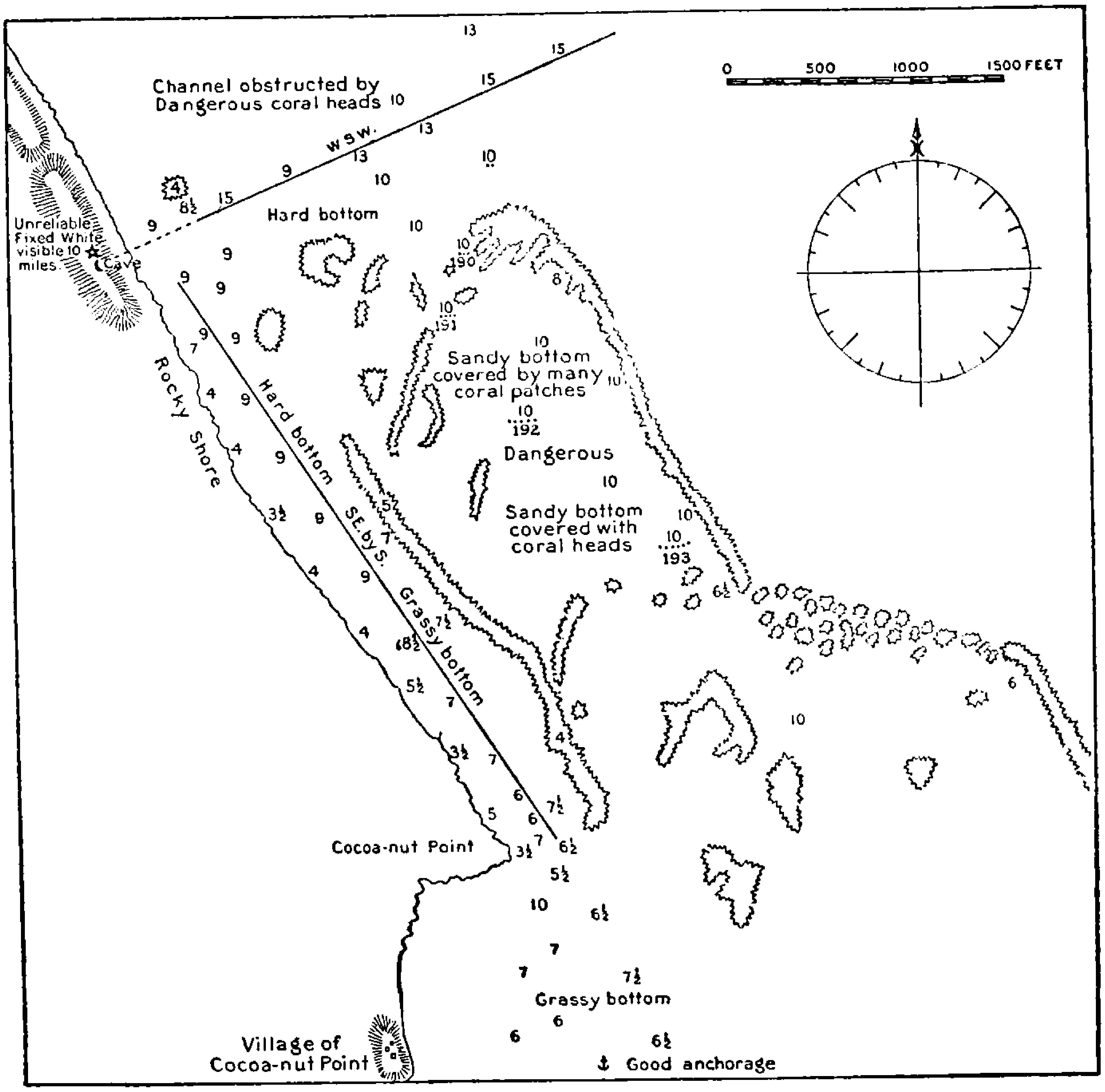

FIG. 3.—Map of Bethel Entrance, Andros Island, Bahamas.
Position of light, Lat. 25° 8″ N., Long. 78° 0′ 30″ W. From a plane-table survey by Alfred G. Mayer, May 1914.

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MAP OF GREAT BAHAMA BANK AND SOUTHERN FLORIDA, SHOWING POSITION OF BOTTOM SAMPLE STATIONS
(Locations and their numbers shown in red)

(5) Oolitic sand from Great Bahama Bank, between Gun Cay Light and Northwest Passage, water about 9 feet deep. Sample No. 71, see plate 95.

(6) Globigerina ooze from depths of 825 fathoms (sample 84), and 800 to 820 fathoms (sample 85), see plate 95.

(7) Oolitic rock, from (*a*) Sharp Rock Point, Andros Island, marine-bedded oolite; (*b*) Queen's Stairway, Nassau, wind-blown oolite; (*c*) north ridge of Seven Hills, New Providence Island, wind-blown oolite.

SAMPLES FROM BEHIND THE REEF OFF COCOANUT POINT, EAST SIDE OF ANDROS ISLAND.

(Bottom samples 190–193; for precise location see fig. 3.)

Figure 3 shows the general relations of reefs to depths and kind of bottom. The country rock is oolite. The bottom material is composed mostly of calcareous algæ, foraminifera, fragments of madreporarian corals, alcyonarian spicules, and mollusk fragments. There are also some coccolithophoridæ, sponge spicules, echinoid fragments, and grains derived from the oolite which is exposed along shore and extends under sea. *Polytrema* and crustaceous calcareous algæ (*Lithothamnion æmulans* Foslie and Howe) are abundant here, as in Murray Islands. *Goniolithon strictum* Foslie is common in areas of quieter water.

The following are the results of mechanical analyses of the samples:

Mechanical analyses of bottom samples Nos. 190 to 193, from the Bahamas.[1]

[Graphic illustrations of the results of these analyses, plate 94.]

No., U. S. Bureau of Soils.	Field No. (of T. W. Vaughan).	Fine gravel, 2 to 1 mm.	Coarse sand, 1 to 0.5 mm.	Medium sand, 0.5 to 0.25mm.	Fine sand, 0.25 to 0.1 mm.	Very fine sand, 0.1 to 0.05 mm.	Silt, 0.05 to 0.005 mm.	Clay, 0.005 to 0 mm.
27316	190	0.2	2.0	9.2	85.5	2.5	0.1	1.4
27317	191	2.8	13.5	27.7	53.2	1.2	.4	1.4
27318	192	6.9	29.5	29.2	31.9	.9	.6	1.1
27319	193	5.6	15.0	16.5	55.8	5.2	.7	1.2

[1] By the U. S. Bureau of Soils.

The following is a chemical analysis of a composite sample of all four samples, made by taking equal portions of each of the four and mixing them:

Chemical analysis of composite of samples 190 to 193 from behind reef off Cocoanut Point, Andros Island.

(By Alfred A. Chambers.)

Analysis.		Reduced.	
Constituent.	Per cent.	Constituent.	Per cent.
Loss on ignition	44.84	SiO_2	0.09
SiO_2	.09	$(Al, Fe)_2O_3$	.08
Fe_2O_3 Al_2O_3	.08	$MgCO_3$	5.24
CaO	51.56	$CaCO_3$	94.59
MgO	2.43	$Ca_3P_2O_8$	.00
P_2O_5	None	$CaSO_4$	Trace
SO_3	Trace		
Summation	99.00	Summation	100.00

COMPARISONS WITH SAMPLES FROM BEHIND MURRAY ISLAND REEF.

A comparison of both the mechanical and chemical analyses of the Murray Island material from the southeast reef, line I, at stations 200, 600, 1,200, and 1,600 feet from shore, with that from Cocoanut Point reveals close similarity. The following table shows the relative amounts of silt and clay in both localities:

Percentages of silt and clay in samples from Murray Island and Cocoanut Point.

Murray Island.		Cocoanut Point.		Remarks.
200 feet from shore......	1.9 p. ct.	Sample 190........	1.5 p. ct.	It should be noted that as fine and medium sand are predominant in the Cocoanut Point samples, they average finer than the Murray Island specimens.
600 feet from shore......	2.8	191........	1.8	
1,200 feet from shore......	.9	192........	1.7	
1,600 feet from shore......	1.4	193........	1.9	
Average.............	1.75	Average.......	1.725	

The following table gives the relative amount of $MgCO_3$[1] in the two sets of bottom samples from behind Murray Island and Cocoanut Point reefs:

Percentages of $MgCO_3$ in samples from Murray Island and Cocoanut Point.

Murray Island.		Cocoanut Point.	
200 feet from shore......	5.52 p. ct.	Composite of samples 190 to 193...	5.24 p. ct.
600 feet from shore......	5.95		
1,200 feet from shore......	5.76		
1,600 feet from shore......	5.83		
Average.............	5.745	Average.......	5.24

The $MgCO_3$[1] is 0.505 per cent higher in the Murray Island sample, a difference of roughly 10 per cent, when the $MgCO_3$ ratio of the two samples is compared.

The estimates of the percentages of the different ingredients in the Cocoanut Point samples have not been completed, but it will be seen from the statements on page 263 that the agencies contributing to the bottom deposits in the two areas are similar, except that alcyonaria are more important in the Bahaman than in the Australian material. Another similarity should be indicated: Murray Island is south of the equator in the track of the southeast trade winds, while Cocoanut Point lies north of the equator near the northern limit of the northeast trades. In both areas the winds blow across the reef. The relations are such in both areas that currents induced by winds and tides tend to remove fine sediment and transport it to other areas. Therefore in these two areas, on nearly opposite sides of the earth, there are complexes of similar factors at work, which produce geologic results essentially identical.

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[1] Hypothetical combination.

PRECIPITATION OF $CaCO_3$ IN THE OCEAN AND THE POSSIBILITY OF ITS SOLUTION IN THE SEA.

In the foregoing paragraph I have expressed it as my opinion that the small percentage of particles of silt and clay size in both the Murray Island and Cocoanut Point samples is due to the washing away of the fine material—that is, to mechanical sorting. The only other possible explanation is that its removal is due to solution by sea-water. The latter hypothesis will be briefly discussed.

My personal experience with the problem of the chemical precipitation of $CaCO_3$ from sea-water and the consideration of the reverse of the process of precipitation, that of solution of $CaCO_3$ by sea-water, began in the winter of 1907–08, when I first examined the exposures of the oolitic limestones in the vicinity of Miami, Florida. There were associated in this work Messrs. Samuel Sanford, G. C. Matson, and F. G. Clapp. All of us agreed that the origin of the oolites could not be explained on the "wind-blown coral sand" hypothesis of Mr. A. Agassiz. Because the oolites are not of detrital origin, but are zonal in structure, showing outward growth from a central nucleus, and because embedded in them there are marine fossils which have not suffered notable attrition, we interpreted the deposits as marine formations due partly to chemical processes which we did not understand.[1] As it seemed to me that oolite might be found forming in the bays and sounds behind the Florida keys, I began in 1908, in connection with the Tortugas Laboratory, a systematic study of the shoal-water bottom deposits of southern Florida. The result of the first season's field work, in 1908, was stated in the following words:

> "In the shallow waters near the shore the opportunity for re-solution as the material settles to the bottom is not afforded and the accumulation on the sea bottom of large quantities of amorphous calcium carbonate apparently not of detrital orgin, is undeniable."[2]

Although an attempt was made to explain the precipitation of the $CaCO_3$ by suggesting processes whereby the CO_2 content of the water might be reduced (*op. cit.*, p. 135), it was said in the introduction (p. 106): "The chemical processes of precipitation have not been sufficiently studied." The work of Drew, 1911–12, extended by Kellerman after the former's unfortunate death, as it showed that denitrifying bacteria evolve ammonia, resulted in knowledge of one factor capable of producing precipitation of calcium carbonate from sea-water. But as will later be made evident, notwithstanding the great abundance of ammonifying bacteria, they are almost certainly not the only agents.

Prosecution of the study of the bottom deposits showed that in all areas not swept by relatively strong currents, fine sediment is accumulating, and that a considerable proportion of this material is a chemical precipitate (the

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[1] See Carnegie Inst. Wash. Pub. 133, pp. 173-177, 1910.

[2] *Op. cit.*, p. 136.

result of either bacterial or of inorganic agencies). One of the striking features of many shoal-water bottom deposits is the perfection of the preservation of the minute sculpture of foraminiferal shells and alcyonarian spicules. All the facts tend to show that precipitation and not solution is taking place, and it is inconceivable that precipitation and solution could be taking place in the same spot at the same time.

In order to get more information on the subject, Mr. R. B. Dole kindly undertook, at my request, certain chemical examinations of the waters of the Florida reef tract, and of some samples I collected in the Bahamas. The results of studies he made in 1913 were published in an article entitled "Some chemical characteristics of sea-water at Tortugas and around Biscayne Bay, Florida;"[1] and subsequent studies appear in this volume, pages 299–315. As a part of a discussion of the formation of atoll rims, I summarized in the following words the results obtained up to 1914:[2]

> "There are two rival hypotheses for the formation of atolls: one of these attributes them to the submarine solution of the interior of a mass of limestone; the other accounts for them by constructional agencies. In order thoroughly to test the solution hypothesis the results of four lines of investigations were brought to bear upon it, and all are accordant. (1) All the bays, sounds, and lagoons within the Florida reef and key region are filling with sediment; (2) Drew's investigations of denitrifying bacteria show that chemical precipitation of calcium carbonate is taking place in the lagoons; (3) the chemical examination by R. B. Dole of samples of sea-water flowing into and out of the Tortugas lagoon, collected twice daily for a lunar period, show that although both carbonate and bicarbonate radicles are in solution uncombined carbon dioxide is not present, and that the water possesses no capacity for further solution of calcium carbonate by virtue of its content of free carbon dioxide; (4) the determinations by Dole of the salinity of the water within the Tortugas lagoon and at the southern end of Biscayne Bay show a higher concentration than that in the open sea-water on the outside, indicating that tidal inflow and outflow are not sufficient completely to mix the water in the lagoons with the water of the surrounding sea and that concentration by evaporation is taking place. As the results of these lines of inquiry are so positive, the formation of lagoons by submarine solution may be definitely eliminated from consideration."

Recently two highly valuable contributions to this subject have emanated from the Geophysical Laboratory of the Carnegie Institution. One is entitled "The rôle of inorganic agencies in the deposition of calcium carbonate," by John Johnston and E. D. Williamson;[3] the other is "The several forms of calcium carbonate," by John Johnston, H. E. Merwin, and E. D. Williamson.[4] Messrs. Johnston and Merwin have kindly lent me copies of their manuscripts, in advance of publication, and have granted me permission to make such citations as were germane to the subjects here under consideration.

Johnston and Williamson say that "the titration methods which have usually been employed for the determination of free CO_2—and to some

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[1] Carnegie Inst. Wash. Pub. 182, pp. 69–78, 1914.

[2] Jour. Acad. Sci. Wash., vol. 4, pp. 27–28, Jan. 19, 1914.

[3] Jour. Geol., vol. 24, pp. 729–750, 1916.

[4] Am. Jour. Sci., vol. 41, pp., 473–512, 1916.

extent of combined CO_2—are altogether untrustworthy, since the results depend on the amount of indicator added and upon other factors which have not been adequately controlled." The inference from this statement is that in the writers' opinion the method used by Dole in his work[1] is subject to question. However that may be, geologically speaking the results of Dole and of Johnston and Williamson are identical.

Johnston and Williamson have paid particular attention to the solubility-product constant $[Ca^{++}]$ $[CO_3^{=}]$, the concentration of H_2CO_3, the effect of temperature on H_2CO_3 concentration, and the relation of the solubility-product constant to rise in temperature. Two quotations from this paper follow:

> "Now it is possible that calcium carbonate may through the intervention of biologic agencies be precipitated within a medium which is not saturated with it, yet a *permanent* deposit can hardly result unless either (1) the solution in contact with it is saturated with respect to $CaCO_3$, or (2) the precipitated carbonate is protected from the solution by an organic tissue or otherwise, or (3) that the process of deposition is rapid, in water circulating very slowly or not at all, under which con-conditions re-solution by diffusion is very slow. The fact therefore that permanent deposits are being formed in many regions of the sea is of itself good evidence that the water in those regions is substantially saturated with respect to $CaCO_3$. Indeed recent experiments of A. G. Mayer[2] show that the sea-water about the coast of Florida is substantially saturated, for shells exposed to it for a year lost no significant weight. Moreover, the investigations of T. W. Vaughan[3] on coral reefs 'show that submarine solution is not effective there [about Florida], as all the bays, sounds, and lagoons are being filled with sediment,' a conclusion which accords 'with the conclusions reached by numerous investigators in the Pacific, which are that the more or less continuous walls inclosing lagoons have been formed by constructional geologic processes and that lagoon channels and atoll lagoons are not due to submarine solution.' We believe therefore that the surface layers of the ocean, except in the Polar regions, and within currents of cold water—in other words, the warmer portions of the ocean—are substantially saturated with $CaCO_3$; but the truth of this belief can not be regarded as established until trustworthy determinations of the several quantities concerned have been made."

They summarize their conclusions as follows:

> "In discussions of the mode of deposition of calcium carbonate there is a point which has not received adequate recognition; namely, the concentration of calcium relative to the limiting saturation concentration of calcium carbonate under the particular conditions, or, in other words, the relative degree of saturation of calcium carbonate, and its local variation, throughout the ocean. The neglect of this important point is without doubt due to the erroneous and misleading statements as to the solubility of $CaCO_3$ which have been prevalent. Its solubility under specified conditions can now be calculated with the requisite accuracy; it is affected materially by variations of temperature and of concentration of free CO_2 such as occur in nature. For example, a change in the proportion of CO_2 in the air from

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[1] Carnegie Inst. Wash. Pub. 182, p. 71, 1914.

[2] Mayer, A. G., Proc. Nat. Acad., 2, 28, 1916.

[3] Vaughan, T. W , Am. Jour. Sci. 41, 133, 1916; see also his earlier papers, especially in the publications of the Carnegie Institution of Washington.

3.2 to 3.0 parts per 10,000, or an increase of temperature 2° C. would result ultimately in the precipitation of about 2 grams $CaCO_3$ from every cubic meter of a solution saturated with it. Consequently, since there is reason to believe that the surface layers of the sea (except in the Polar regions and within cold currents) are substantially saturated with calcite, precipitation is to be expected wherever the water is being warmed, or is losing CO_2, or both, and this independently of any other agencies. Indeed, these inorganic factors may not safely be left out of account, no matter what be the agency inducing the precipitation; for there appears to be a correlation in that calcareous organisms are more abundant the more nearly satuated with $CaCO_3$ the water is. The view, here emphasized, of the importance of the inorganic factors, does not exclude the other views which have been proposed to account for the deposition of limestones, and is not in conflict with any facts which have been definitely ascertained. Its precise importance could be established only by accurate determination of temperature, salinity and, particularly, of concentration of CO_2—free and total—of the water, carried out systematically over the ocean; such an investigation would have an important bearing on many biological as well as geological questions, and would enable us ultimately to correlate the position and rate of growth of some limestone deposits with cosmogonic factors in a much more satisfactory way than has yet been done."

A very important contribution to the study of the solubility of calcite in sea-water, by Dr. R. C. Wells, appears on pages 316–318 of this volume.

It seems to me that all lines of evidence converge and give the same result, which is that in the shoal waters of the tropics ocean water does not dissolve calcium carbonate, but that the contrary process—precipitation by both inorganic and organic (bacterial) agencies—is taking place. Conditions in the deep sea, and perhaps in the cold waters of high latitudes, are different. For the reasons stated, it is my conclusion that the disappearance of fine material from behind the reefs at Murray Island, Australia, and Cocoanut Point, Andros Island, Bahamas, is due to washing away of the fine material by currents, which are probably caused, in large part at least, by winds and tides.

Such phenomena as those exhibited at Murray Island and at Cocoanut Point are localized. Coral reefs and their associated phenomena do not occur everywhere, but under certain definite ecologic conditions. Bottom deposits formed under other conditions will now be discussed.

FINELY DIVIDED MUD FROM STAGNANT AREAS IN SOUTH BIGHT.

(Sample No. 79, see plate 95.)

The results of a mechanical analysis of a specimen, No. 79, are given in the first table on page 269; the percentage of $MgCO_3$ (hypothetical combination) is stated in the table on page 270. For position of stations indicated by the field numbers see plate 95.

Comparison of the mechanical analysis of sample 79 with the Murray Island and Cocoanut Point samples shows that in the former the percentage of particles of silt and clay size is 57.6, and only from 1.725 to 1.75 (averages) in the latter; while the chemical analyses indicate 2.56 per cent $MgCO_3$ for the former, and from 5.24 to 5.745 (averages) for the latter. The deposits obviously belong to different classes. At station 79, besides the accumulation of fine

Mechanical analyses of Bahaman bottom samples.

[Graphically illustrated on plate 94.]

No., U. S. Bureau of Soils.	Field No. (T.W.V.)	Positions of stations.	2 to 1 mm.	1 to 0.5 mm.	0.5 to 0.25 mm.	0.25 to 0.1 mm.	0.1 to 0.05 mm.	0.05 to 0.005 mm.	0.005 to 0 mm.
26863	71	Great Bahama Bank, between Gun Cay and Northwest Passage; depth about 9 feet.	2.1	16.3	38.2	40.1	1.7	0.3	2.0
26864	79	South Bight; depth 2 or 3 feet........	1.2	5.0	9.1	16.5	10.6	24.5	33.1
26865	83	Shore material; subject to tidal overflow, west side, Andros Island.	9.4	9.6	4.0	8.0	14.4	29.1	26.3
26866	84	Tongue of the Ocean; depth 825 fathoms.	.4	2.2	4.5	11.3	15.5	45.2	20.5
26867	85	Tongue of the Ocean; depth 800 to 820 fathoms.	.1	.5	.6	2.3	7.1	55.3	34.6
26868	87	1 mile west of west end of South Bight; depth about 6 feet.	1.0	1.6	1.7	10.2	25.1	25.8	35.4

Chemical analyses of oolite and bottom samples from Florida and the Bahamas.

(By W. C. Wheeler.)

	Oolite, Boca Grande Key, Florida.	Oolite, Everglades, Miami, Florida.	Oolite, Sharp Point, Andros Island.	Bottom sample[1] (98), east side Marquesas Lagoon, Florida.	Bottom sample[2] (87), 1 mile west of west end of South Bight, Bahamas
Chemical analyses.					
	p. ct.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
SiO_2.......	0.03	[3]8.23	0.07	1.13	0.28
Al_2O_3......	.18	.00	.00	.14	.03
Fe_2O_3......	.22	.21	.13	.21 (total Fe).	.11 (total Fe).
MgO......	Trace.	Trace.	Trace.	1.31	1.25
CaO.......	53.77	51.60	54.57	51.04	52.30
Na_2O......	.90	.11	.14	.....	.....
K_2O.......	Trace.	Trace.	Trace.	.....	.....
H_2O.......	1.21	.17	1.72	2.03 (and organic).	3.16 (and organic).
CO_2.......	42.34	40.11	43.07	41.50	42.45
P_2O_5.......	Trace.	Trace.	Trace.	.....	.....
SO_3.......	.28	Trace.	.14	.....	.....
Cl.........	1.02	.08	.03	.....	.....
Soluble....	.....	.....	.....	[4]2.21	.....
Total..	99.95	100.51	99.87	99.57	99.58
Reduced analyses (hypothetical combinations), H_2O, organic matter, and soluble salts rejected; silica not essential.					
SiO_2.......	0.03	8.19	0.07	1.18	0.29
$(Al, Fe)_2O_3$.	.42	.21	.13	.37	.15
$MgCO_3$....	Trace.	Trace.	Trace.	2.88	2.72
$CaCO_3$.....	99.05	91.60	99.56	95.57	96.84
$Ca_3P_2O_8$....	Trace.	Trace.	Trace.	.....	.....
$CaSO_4$.....	.50	Trace.	.24	.....	.....
Total..	100.00	100.00	100.00	100.00	100.00

[1] Sample washed and dried over H_2SO_4.

[2] Sample filtered, washed, and dried over H_2SO_4.

[3] 25 per cent soluble SiO_2; the rest of the silica appears to be white sand.

[4] Saline salts not washed out by water in the preparation of the sample.

material by settling in relatively stagnant water, bacterial precipitation is also effective. The country rock is slightly elevated marine oolite and there are some oolite grains derived from it in the deposits. Dr. Cushman has listed the foraminifera and some of the other organisms obtained at this and other stations along South Bight. As the lists show the character of the foraminiferal fauna through the Bight they are all presented on the next page. Station 77 is 5½ sea miles southeast of the northeast end; station 82 about 7½ sea miles east of the west end; the other stations are intermediate in position over a distance of about 10 sea miles, measured in a straight line.

Partial chemical analyses of oolite and bottom samples from Florida and the Bahamas.
(By W. C. Wheeler.)

No.	Locality.	Analyses.				Reduced analysis, hypothetical combinations.			Remarks.
		Insoluble.	CaO.	MgO.	CO_2. calculated.	Insoluble.	$MgCO_3$.	$CaCO_3$.	
		p. ct.	*p ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	
68	Beach sand from east side of Sands Key, Florida.	1.15	[1]51.77	1.73	42.55	1.11	3.73	95.08	As received.
71	Great Bahama Bank between Gun Cay Light and Northwest Passage, Bahamas.	.13	53.98	.18	42.42	.13	.38	99.49	An oolite.
79	South Bight, Andros Island, Bahamas.	.46	51.75	1.16	42.92	.47	2.56	93.36	Washed and dried in air.
83	Shore material, west side of Andros Island, Bahamas.	.89	43.47	5.82	40.49	.98	13.36	85.66	
84	Tongue of the Ocean, Bahamas.	1.05	51.30	1.85	42.31	1.09	4.02	94.89	Depth 825 fathoms, washed and dried over H_2SO_4.
85	Tongue of the Ocean, Bahamas.	1.34	51.05	1.30	41.52	1.40	2.89	95.71	Depth 800 to 820 fathoms, washed and dried over H_2SO_4.
91	Mud flat, north side Loggerhead Key, east of Sugar Loaf Key, Florida.	1.04	[2]47.86	1.22	38.93	1.18	2.87	95.95	As received.
97	Near obstruction buoy at southwest entrance to Fort Jefferson Channel, Tortugas, Florida.	1.11	51.02	1.77	42.01	1.16	3.86	94.98	Sample washed and dried in air and over H_2SO_4.
100	South of Sand Key, Florida.	1.32	46.76	2.14	39.07	1.48	5.03	93.49	Depth 60 fathoms, as received.
A	Oolite, Queen's Stairway, Nassau, New Providence.	.04	54.47	.36	43.17	.04	.77	99.19	
B	Oolite, north ridge of Seven Hills, New Providence.	.02	55.11	Trace	43.30	.02	Trace	99.98	

[1] Loss up to 150°, 0.44 per cent moisture. [2] Loss up to 150°, 6.77 per cent moisture.

The following are the lists of foraminifera and associated small organisms from South Bight, Andros Island, Bahamas, contributed by Dr. Cushman:

No. 77. South Bight, Andros Island, Bahamas: Material includes fragments of calcium carbonate, worm-tubes, pelecypods and gastropods, ostracods, and numerous foraminifera.

Foraminifera:
- Orbiculina adunca, frequent.
- Peneroplis pertusus, few.
- Quinqueloculina reticulata, few.
- Triloculina linneiana, few.
- Clavulina angularis, few.
- Quinqueloculina agglutinans, few.
- Verneuilina affixa, few.
  - Quinqueloculina sp.

No. 78. South Bight, Andros Island, Bahamas. Material very similar to No. 77.

Foraminifera:
- Orbiculina adunca, few.
- Quinqueloculina agglutinans, few.
- Clavulina angularis, few.
- Polystomella striatopunctata, few.

No. 79. South Bight, Andros Island, Bahamas. Material similar to Nos. 77 and 78; more ostracods, fewer mollusca.

Foraminifera:
- Orbiculina adunca, common.
- Quinqueloculina agglutinans, few.
- Verneuilina affixa, few.
- Polystomella striatopunctata, few.
  - Several Quinqueloculina and Triloculina.

No. 80. South Bight, Andros Island, Bahamas. Material similar to No. 78.

Foraminifera:
- Orbiculina adunca, frequent.
- Quinqueloculina agglutinans, few.
- Triloculina linneiana, few.
- Verneuilina affixa, few.
- Clavulina angularis, few.
- Polystomella striatopunctata, few.
  - Numerous Quinqueloculina and Triloculina.

No. 81*a*. Shore material, South Bight, Andros Island, Bahamas. Many shell fragments. (No. 81*b*, similar.)

Foraminifera:
- Orbiculina adunca, frequent, worn.
- Quinqueloculina agglutinans, few.
- Quinqueloculina reticulata, few.
- Triloculina linneiana, few.
- Verneuilina affixa, few.

No. 82. South Bight, Andros Island, Bahamas. Material rather poor in organisms except foraminifera.

Foraminifera:
- Orbiculina adunca, frequent.
- Quinqueloculina agglutinans, few.
- Verneuilina affixa, few.
- Clavulina angularis, few.
- Polystomella striatopunctata, few.

No large testaceous organisms were observed along the Bight, indicating conditions in general unfavorable for life, except bacterial.

SAMPLES FROM OFF THE WEST END OF SOUTH BIGHT.

Sample No. 87 is from 2 miles off the west end of South Bight (for location, see plate 95). I have previously described it and other samples of finely divided mud taken from nearby, and present in slightly modified form the account referred to in the footnote.[1]

A field examination of a bottom sample, No. 177, from 2 miles west of the west end of South Bight, gave the following:

Color: light gray, tinged bluish. Reaction to litmus: strikingly alkaline. Odor: fetid, some H_2S. Cobalt-nitrate test: showed presence of aragonite.[2]

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[1] Carnegie Inst. Wash. Year Book 13, pp. 227–228, 1915.

[2] For notes on the aragonite needles in this specimen, see Johnston, Merwin, and Williamson, Amer. Jour. Sci., vol. 41, pp. 508, 509, 1916. They contain 0.7 per cent of $CaSO_4$.

The following is a description of the separates according to size, but the percentage estimates are omitted, as accurate physical analyses of samples are subsequently given:

Description of separates from bottom sample No. 177.

Held on $\frac{1}{20}$ mesh.	Tests of *Orbiculina adunca*.
Held on $\frac{1}{40}$ mesh.	Quantities of soft, non-indurated as well as indurated oolite grains, the former easily crushed by a touch with the point of a needle. Foraminifera present.
Held on $\frac{1}{80}$ mesh.	Many perfect oolite grains; also foraminifera.
Held on $\frac{1}{100}$ mesh.	Many soft oolite grains; foraminifera; fragmental particles.
Held on $\frac{1}{200}$ mesh.	Small oolite grains and fragmental particles; material predominantly oolitic.
Passed $\frac{1}{200}$ mesh.	Quantities of small, globular bodies, minute oolites, and flocculent material.

The separates were compared with the powder of the oolite forming Golding Cay. The mud is clearly oolitic.

The following are accurate physical analyses, made in the Bureau of Soils, Department of Agriculture, of two specimens collected by Mr. Drew in 1912, and of sample No. 177, all of which are oolitic. Specimen No. 87 is from a depth of 7 feet, 2 miles west, and specimen No. 88 from a depth of 8 feet, 3 miles west of the west end of South Bight.

Mechanical analyses of bottom specimens Nos. 87, 88, and 177.

[Graphically illustrated on plate 94.]

No.	2 to 1 mm.	1 to 0.5 mm.	0.5 to 0.25 mm.	0.25 to 0.1 mm.	0.1 to 0.05 mm.	0.05 to 0.005 mm.	0.005 to 0 mm.
	p. ct.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
87	1.0	1.6	1.7	10.2	25.1	25.8	35.4
88	0.6	1.9	4.3	16.1	27.9	19.5	30.3
177	1.6	4.5	5.0	6.3	12.2	31.1	40.1

The calcium carbonate of the specimens comprises both aragonite and calcite.

Dr. Cushman has furnished the following lists of microzoa from samples 87 and 88:

No. 87. A little fragmental calcium carbonate, occasional ostracod valves, and a few foraminifera.

Clavulina angularis.
Orbiculina adunca.
Verneuilina affixa.
Polystomella striatopunctata.
Quinqueloculina, etc.

No. 88. A few shell fragments, fragmental calcium, ostracod valves, and some foraminifera.

Orbiculina adunca.
Peneroplis pertusus.
Peneroplis pertusus var. discoideus.
Verneuilina affixa.
Polystomella striatopunctata.
Quinqueloculina and Triloculina.

The results of a chemical analysis of specimen 87 are given on page 269.

The mechanical analyses give the following percentages of silt and clay for the three samples: No. 87, 61.2 per cent; No. 88, 49.8 per cent; No. 177, 71.1 per cent; average of the three 60.7 per cent, a higher figure than for specimen 79, from South Bight. It was from this locality that Drew collected the samples he used in his study of the bacteria "of the chalky mud flats which are being deposited to the west of Andros Island."[1] Here he found "160,000,000 bacteria per 1 c.c." He says: "The actual number in the mud possibly exceeds this figure, since a large proportion of the bacteria would probably settle with the larger particles after the first dilution." Dr. Kellerman studied a part of specimen No. 177, which I sent him, and essentially confirmed Drew's results.[2] This mud is largely a bacterial precipitate, but, as will presently be shown, other factors which might cause precipitation need to be considered.

Drew did not sound the mud to find out how deep it is. I found the mud at station 177 to be 2 feet thick over hard rock; water 6 feet deep. On the west side of the channel into the west end of South Bight, the water is 2 feet deep, mud 7 feet thick. Except some foraminifera and a few other small organisms, bacteria are almost the only forms of life present. I searched specimen 177 for Coccolithophoridæ and occasionally found one. The almost complete absence of these minute organisms is in contrast to their frequent presence in the samples from Cocoanut Point and Murray Island.

The percentage of $MgCO_3$ is 2.72, a figure about the same as that for specimen 79 (2.56 per cent), but much lower than the one for Cocoanut Point (5.24 per cent). The muds off the west side of Andros are closely similar to those along South Bight.

Some other facts of the physical conditions need consideration. Mr. Dole has determined the salinity of water samples I brought back,[3] and found that at Station 177 to be 3.886 per cent, while two water samples at Cocoanut Point had salinities of 3.64 per cent and 3.66 per cent respectively, showing a distinctly higher concentration on the west than on the east side of Andros Island. Drew obtained the following surface salinities in the Tongue of the Ocean:[4] 6 miles east of Golding Cay, 3.624 per cent; 13 miles east of Golding Cay, 3.658 per cent; figures essentially the same as those reported by Dole.

Data on the surface temperatures of the water on the two sides of the island are deficient. Drew reports surface temperatures of 26.90°, 26.30°, 27.10° C., during May, and I have some additional records, but they are so fragmentary as not to be worth publishing. There are no records for the west side of the island.

The less concentration of salts in solution in the water on the east side of Andros, as compared with that on the west, is to be explained by deep water coming very near shore on the east side, the 50-fathom curve being

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[1] Carnegie Inst. Wash. Pub. No. 182, pp. 41–43, 1914.

[2] Carnegie Inst. Wash. Year Book No. 13, pp. 228–229, 1915.

[3] The results of Mr. Dole's investigations of the salinity of the Florida reef tract and of some areas in the Bahamas are given in a subsequent article in this volume, pp. 299–315.

[4] *Op. sup. cit.*, pp. 37, 38.

usually less than 2 miles from shore, and depths ranging from 800 to 1,000 fathoms are only a short distance farther seaward. On the west side there is an enormous flat, which is over 60 sea miles wide along an east and west line, and on it the maximum recorded depth is 3½ fathoms. In a way there is here a great evaporating pan, and a concentration of saline ingredients results. This concentration would cause the precipitation of some $CaCO_3$ even were there no bacteria. It is probable that, especially during the summer months, the temperature of the shoal waters is higher than on the surface of the ocean where the depths are greater. Such an increase in temperature would cause the water to lose CO_2 and produce precipitation of $CaCO_3$. Surface agitation of the water would accelerate the loss of CO_2 and thereby increase the rate of precipitation of $CaCO_3$.

From the foregoing discussion it is obvious that there are at least three cooperating factors tending to produce precipitation of $CaCO_3$, viz: (1) ammonifying bacteria, (2) concentration of salts in solution through evaporation, (3) expulsion of CO_2 by increase in temperature. As these factors have not been evaluated, a satisfactory solution of the complicated problem awaits further research.

SHORE SPECIMEN, NORTH OF WEST END OF SOUTH BIGHT.

(Specimen No. 83; see plate 95 for location.)

This specimen was subject to alternate wetting and drying by the rise and fall of the tide. The mechanical analysis of it is given on page 269 and it is graphically illustrated on plate 94; the percentages of $MgCO_3$[1] and $CaCO_3$ are given on page 270. The percentage of particles of silt and clay size is 55.4; that of $MgCO_3$, 13.36. According to the mechanical analysis, this specimen groups with specimens 79 and 87; but it is higher in $MgCO_3$ than any other of the specimens here considered. There has evidently been secondary concentration of magnesia, perhaps due to alternate wetting and drying by the rise and fall of the tides. The specimen from the northwest end of Murray Island, washed up on the reef, 1,700 feet from shore, has 7.57 per cent of $MgCO_3$, 2.175 per cent higher than the average of the samples taken from the bottom along line I, southeast reef, suggesting that secondary concentration has also taken place in it. Dr. Cushman says regarding this sample (No. 83): "Little of interest in the material. Foraminifera, few, minute, technical species, unlike preceeding (No. 82)."

OOLITIC SAND FROM GREAT BAHAMA BANK.

(Specimen No. 71; see plate 95.)

The Great Bahama Bank is remarkable in its topographic features. There are thousands of square miles of its surface over which the water ranges in depth from 6 feet as a minimum to about 21 feet as a maximum. I know no other plain so extensive in area and so small in the range of the relief of its surface. Along the line from Gun Cay to Northwest Passage,

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[1] Hypothetical combinations.

although the distance is 67 nautical miles, the range in depth is only from 7 to 12 feet. Gun and Cat Cays on the west are composed of oolite, as is Andros Island on the west. This rock extends under sea, and a series of samples taken at intervals across the bank shows its continuity from one side to the other. The last movement of this area with reference to change in sea-level has been by submergence of what was a land area, some parts of which stood at least 198 feet above the sea.[1] During the period of emergence the previously formed oolite was indurated; after its resubmergence waves have broken up the rock and the bottom is now largely covered by an oolitic sand, some grains of which are still embedded in a hard matrix. The paucity of life on this enormous flat is as remarkable as the uniformity of its depth and the continuity of one geologic formation.

The results of a mechanical analysis of sample 71 are given on page 269 and are graphically shown on plate 94. The percentage of particles of silt and clay size is 2.3, very nearly the same as that for Cocoanut Point and Murray Island. The small proportion of material of this size is probably due to currents, both wind-induced and tidal, which set across the bank, as there is open water at the east end of the course indicated, and at its west end there are only a few small cays. The water is also open both to the north and to the south.

The chemical analysis (see page 270) shows only 0.38 per cent of $MgCO_3$, the lowest percentage in any specimen so far considered. The percentage of $CaCO_3$ is 99.49, almost pure calcium carbonate.

It has already been stated that the material is an oolitic sand. The following lists of foraminifera, by Dr. Cushman, show how rare foraminifera are at each of five stations occupied:

No. 71. Great Bahama Bank, 22½ sea miles from Gun Cay, between Gun Cay Light and Northwest Passage.

Foraminifera (few):
- Orbiculina adunca, few.
- Orbiculina compressa, one.
- Quinqueloculina reticulata, one.
- Verneuilina affixa, one.
- Polystomella striatopunctata, one.
- Two or three Quinqueloculina and Triloculina.

No. 72. Great Bahama Bank, 30½ sea miles from Gun Cay.

Foraminifera:
- Orbiculina adunca, few.
- Quinqueloculina reticulata, few.
- Peneroplis pertusus, few;
- Peneroplis pertusus var. discoideus, few.
- Articulina sagra, one.
- Planispirinia exigua, one.
- Clavulina angularis, one.
- Verneuilina affixa, few.
- Few Quinqueloculina and Triculina.

No. 73. Great Bahama Bank, 38½ sea miles from Gun Cay.

Foraminifera:
- Orbiculina adunca, few.
- Peneroplis pertusus var. discoideus, one.
- Quinqueloculina reticulata, few.
- Planispirinia exigua, few.
- Verneuilina affixa, few.

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[1] Vaughan, in Carnegie Inst. Wash. Year Book No. 13, p. 230, 1915.

No. 74. Great Bahama Bank, 45½ sea miles from Gun Cay. Material largely sand, much worn, occasional mollusk shells, foraminifera few.

Foraminifera:

Orbiculina adunca, few.
Peneroplis pertusus, few.
Quinqueloculina reticulata, one.
Planispirinia exigua, few.
Articulina sagra, one.
Verneuilina affixa, few.
Calvulina angularis, one.

No. 75. Great Bahama Bank, 52½ sea miles from Gun Cay. Material similar to No. 74. Foraminifera few and poor.

Foraminifera:

Orbiculina adunca, few.
Peneroplis pertusus, few.
Planispirinia exigua, few.

It is obvious that this represents a third distinct class of calcium carbonate deposit.

GLOBIGERINA OOZE FROM THE TONGUE OF THE OCEAN.

(Samples 84, depth 825 fathoms, and 85, depth 800 to 820 fathoms, collected by G. H. Drew, see plate 95.)

The mechanical analyses are given on page 269 (graphically illustrated on plate 94); percentage of $MgCO_3$ on page 270. Particles of silt and clay in 84, 65.7 per cent; in 85, 89.9 per cent. Silt in 84, 45.2 per cent; in 85, 55.3 per cent. The large percentage of particles of silt size is striking; it is larger than in any of the other specimens. Percentage of $MgCO_3$, in 84, 4.02; in 85, 2.89. No. 84 has only about 1.5 per cent less $MgCO_3$ than the Cocoanut Point specimens; No. 85 has almost the same as the fine-grained lagoonal deposits (see specimen No. 87). However, the sources of the material in these two samples are different (at least in large part) from that composing No. 87. The following are Dr. Cushman's lists of the organisms, to which Coccolithophoridæ should be added. The material includes a few sponge spicules, occasional alcyonoid spicules, numerous pteropods, some gastropods, few pelecypods, ostracod valves, occasional echinoid spines and fragments of plates, numerous foraminifera of Globigerina ooze species.

No. 84. Tongue of the Ocean (Drew) 825 fathoms.

Foraminifera:

Peneroplis pertusus, few.
Globigerina bulloides, frequent.
Globigerina æquilateralis, frequent.
Globigerina dubia, abundant.
Globigerina rubra, frequent.
Pulvinulina menardii, frequent.
Pulvinulina truncatulinoides, abundant.
Pulvinulina canariensis, few.
Articulina sagra, few.
Pullenia obliqueloculata, frequent.
Bulimina buchian, few.
Cristellaria variabilis, few.
Truncatulina reticulata, few.
Biloculina murrhyna, few.

No. 85. Tongue of the Ocean (Drew) 800 to 820 fathoms.

Foraminifera:

Pulvinulina truncatulinoides, frequent.
Pulvinulina menardii, few.
Globigerina rubra, frequent.
Globigerina dubia, frequent.
Globigerina æquilateralis, frequent.
Globigerina bulloides, frequent.
Pullenia obliqueloculata, frequent.
Pullenia sphæroides, few.
Orbulina universa, few.
Cymbalopora poeyi, few.
Cassidulina subglobosa, few.
Biloculina murrhyna, few.

ELEVATED BAHAMAN OOLITES.

No mechanical analyses of these were attempted, as they would have been impracticable because of induration of the rocks.

Marine-bedded oolite: Sharp Rock Point, Andros Island, Chemical analysis, page 269. $MgCO_3$, trace; $CaCO_3$, 99.56 per cent.

Wind-blown oolite: (*a*) Queen's Stairway, Nassau. Partial chemical analysis. $MgCO_3$, 0.77 per cent; $CaCO_3$, 99.19 per cent. (*b*) North ridge at Seven Hills, New Providence Island. Partial chemical analysis, page 270. $MgCO_3$, trace; $CaCO_3$, 99.98 per cent.

These samples differ from all others, except the oolite sand from Great Bahama Bank, specimen No. 71, in the low percentage of $MgCO_3$, and the high percentage, over 99, of $CaCO_3$. Specimen No. 71 has 0.38 per cent of $MgCO_3$ and 99.49 per cent of $CaCO_3$. Therefore in chemical composition these oolites are more nearly pure calcium carbonate than any other samples at present known from Florida and the Bahamas. This means that although certain leading facts in the formation of oolites have been discovered, conditions absolutely similar to those under which the Bahaman and Floridian oolites formed have not yet been discovered among processes now in operation. The conditions for the formation of such rocks require a more complete suppression of organisms which can contribute $MgCO_3$ to the sediments than those which now prevail in Florida and the Bahamas. The evaluation of the difference between the oolitic muds now forming in Floridian and Bahaman waters and the oolites of greater geologic age exposed in the same areas must be left for future investigation, but that they are not precisely the same is apparent, and the significance of the difference should be investigated.

Here it should also be pointed out that although a certain amount of zonal structure is sometimes found in the oolites of the oolitic muds, there is never so large a number of well-defined concentric shells (or "skins," to use a word suggested by Dr. Merwin) in the mud grains as are usual in the grains of the older rock. That the material has accumulated zonally is obvious, but the precise processes which have determined the zonal arrangement have not been discovered.

A plausible hypothesis is illustrated by the formation of pisolites in hot springs, in which $CaCO_3$ is deposited as more or less spherical bodies from a supersaturated solution. The concretions are kept in motion by ebullition, thereby permitting the formation of successive concentric shells of $CaCO_3$.[1] The principle involved is that the movement of a nucleus or a concretion already initiated within a solution in which $CaCO_3$ is being precipitated furnishes an opportunity for concentric enlargement. Occasional desiccation will emphasize the zonal structure. Of course there is no evidence of hot-spring action in areas underlain by marine oolites, but agencies favoring periodic precipitation combined with the occasional shifting of the position of oolites once started apparently will account for the phenomena.

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[1] Hayes, C. W., Science, n. s., vol. 33, p. 550, 1911.

The strong cross-bedding of the Floridian oolites shows that waves and currents did move the oolite grains, and thereby gave them access to more chemically precipitated material.[1]

This brief review of the status of the investigation of the origin of oolites will be closed with the statement that, notwithstanding the appreciable advance toward explaining the formation of these bodies, considerable work remains to be done before we shall adequately understand all the processes involved.

SUMMARY ON BOTTOM DEPOSITS OF THE BAHAMAS.

(1) The foregoing account of the Bahaman bottom deposits shows three prominent classes of shoal-water deposits and one class of deep-water deposits, as follows:

(*a*) Sands such as those forming behind the reef off Cocoanut Point. There is but little silt and clay in this deposit, 1.725 per cent; it is composed mostly of the remains of organisms, entire or comminuted, which live upon or are associated with coral reefs; the percentage of $MgCO_3$ is high, 5.24 per cent; although coral detritus is present in the sand it constitutes less than 50 per cent of the material. This deposit is essentially the same as that forming behind the reef at Murray Island.

(*b*) Lagoon deposits or deposits forming on extensive flats which are protected by land areas on their windward side. These deposits are very fine-grained, the percentage of particles of silt and clay size averaging 60.7 and are largely chemical precipitates. Bacteria appear to be the most important known agents in causing the precipitation, but evaporation and high temperature need further consideration as cooperating factors. Oolite is forming in these muds. $MgCO_3$ constitutes from 2.56 to 2.72 per cent of these deposits, only about 50 per cent as much as in the reef sands. A similar deposit, which had been subjected to alternate wetting and drying by the rise and fall of the tide, has the $MgCO_3$ (hypothetical combination) percentage raised as high as 13.36 per cent (see specimen No. 83).

(*c*) Oolitic sand derived from the breaking up of indurated oolite through wave action. This class of deposit contains but little material of silt and clay size (2.3 per cent) and is mostly composed of coarse and medium sand, 1 to 0.25 mm. in diameter (54.5 per cent). There are few organic remains, and the percentage of $MgCO_3$ is low (0.38 per cent). This oolitic sand differs from the oolitic muds in its larger grain and its lower $MgCO_3$ content. It is identical with the oolite now elevated above sea-level. Comparison of this material with the oolitic muds indicates that, notwithstanding the advance made toward the understanding of the formation of oolite grains, considerable work remains to be done on the processes involved in the formation of the concentric shells of the grains.

These three appear to be the most important classes of shoal-water deposits; but some beach deposits should be placed in a different category.

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[1] Vaughan, Carnegie Inst. Wash. Pub. 133, p. 177, 1910.

(*d*) Globigerina ooze, which covers the bottom of the Tongue of the Ocean.

(2) Although the areas covered by the three classes of shoal-water sediments have not been accurately determined, it can be said that the coral reefs off the east side of Andros Island are narrow and interrupted. Figure 4 shows diagrammatically the relations. If all the living corals and the dead coral skeletons forming the modern reefs were put together, I doubt if they would make a continuous ridge 100 feet wide and 12 feet thick the entire length of the east face of the island. The barrier stands from about 0.5 mile to about 2 miles offshore; and the sands form a thin veneer over the oolitic rock which passes below sea-level. Solution wells occur in the oolite beneath sea-level as well as along shore above sea-level. I have already published the estimate "that on Andros Island, Bahamas, the ratio of the constructive work of the present reef to that of agencies that previously resulted in the formation of the Pleistocene oolite is approximately as 1 to several thousand, or, as a constructive agent, chemical precipitation has been several thousand times more effective in forming limestone than corals."[1] The classes designated (*b*) and (*c*) are the deposits now forming which are of most importance in shoal water. The growing reef and the sands forming behind it are decidedly subordinate in amount. The area of the deep-water Globigerina ooze has not been ascertained, but it appears safe to assume that it covers the bottom at all depths beyond somewhat less than 800 fathoms.

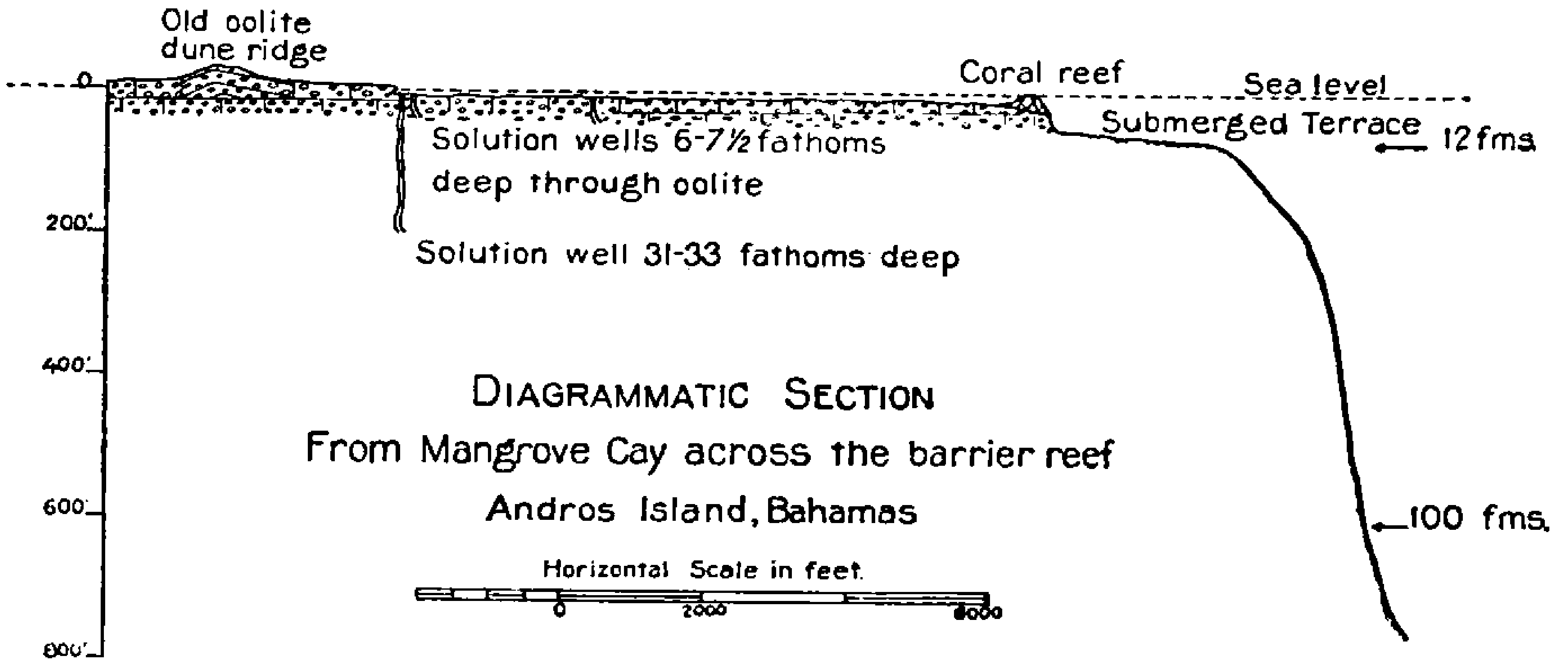

FIG. 4.

(3) Examination of the evidence bearing upon the precipitation of $CaCO_3$ in the ocean and the possibility of the solution of $CaCO_3$ leads to the conclusion that in the shoal waters of tropical and subtropical regions precipitation is caused by both organic (bacterial) and inorganic agencies which reduce the CO_2 content of the sea-water; and that no solution of $CaCO_3$ by sea-water is taking place. More detailed studies of the salinity, the temperature, and the CO_2 relations in the ocean are greatly needed.

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[1] Jour. Wash. Acad. Sci., vol. 4, pp. 26, 27, Jan. 19, 1914.

(4) The minor chemical constituents of the bottom samples and rocks are as follows: SiO_2, which ranges from 0.07 to 0.29 per cent, an amount so small as mostly to be accounted for by sponge spicules and the few diatoms; $(Al, Fe)_2O_3$ ranges from 0.08 per cent to 0.15 per cent. It is evident that in the Bahamas no appreciable amount of earthy material has been derived from land areas. The small amount of Fe_2O_3, about 0.12 per cent, is sufficient to produce iron stains and red earth when secondarily concentrated. One oolite sample shows a trace of $Ca_3P_2O_8$, but none was found in the bottom samples examined for it. $CaSO_4$ ranges from a trace to 0.24 per cent. The presence of a small amount of $CaSO_4$ seems necessary for the production of aragonite at ordinary temperatures;[1] and as the oolitic muds and oolites are largely aragonite, the importance of $CaSO_4$ is evident.

BOTTOM SAMPLES FROM FLORIDA.

Five bottom samples and two oolite specimens are specially considered. In a previous publication[2] I have discussed in a preliminary way the marine bottom deposits forming in the bays and sounds behind the Florida Keys and Mr. G. C. Matson contributed to the same paper a report on his examination of a set of samples. A smaller number of samples will here be described in more detail than those dealt with in the paper cited.

Specimen No. 68 is a beach sand from the east side of Sands Key, which is near the north end of the line of the Florida keys. (See plate 95.)

Specimen Nos. 91, 97, and 98 are examples of lagoon deposits. No. 91 is from a mud flat north of Loggerhead Key, south of Cudjoe Key and east of Sugarloaf Key; water 3 or 4 feet deep. No. 97 is from near the obstruction buoy, off the northwest entrance to Fort Jefferson channel, Tortugas; depth about 7 fathoms (specimen collected by Dr. A. G. Mayer). No. 98 is from the east side of Marquesas lagoon; water about 1 foot deep. (For position of the stations according to number, see plate 95.)

Specimen No. 100 was taken by Mr. John B. Henderson in water 60 fathoms deep, south of Sand Key light, off Key West. (See plate 95.)

The oolite samples are from Miami and Boca Grande Key.

The following are the results of mechanical analyses (by the U. S. Bureau of Soils) of samples of sea-bottom specimens from Florida:

Mechanical analyses of sea-bottom samples from Florida.

[For graphic illustration, see plate 94.]

No., U. S. Bureau Soils.	No., T. W. V.	Description.	2 to 1 mm.	1 to 0.5 mm.	0.5 to 0.25 mm.	0.25 to 0.1 mm.	0.1 to 0.05 mm.	0.05 to 0.005 mm.	0.005 to 0 mm.
26862	68	Beach sand, Sands Key	47.2	46.1	1.8	1.1	0.3	1.9	2.4
26869	91	Between Loggerhead and Cudjoe Keys	1.7	6.3	4.1	5.9	16.6	27.9	36.6
26870	97	Tortugas lagoon	1.7	2.2	2.3	18.7	37.9	31.0	6.9
26872	100	South of Sand Key, depth 60 fathoms	19.0	22.9	10.1	16.8	7.6	13.0	11.4

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[1] Johnston, Merwin, and Williamson, Am. Jour. Sci., vol. 41, p. 509, June 1916.

[2] Carnegie Inst. Wash. Pub. 133, pp. 114–125, 1910.

BEACH SAND FROM SANDS KEY.

The mechanical analysis (sample No. 68) shows that 93.3 per cent of the material is between 2 and 0.5 mm. in diameter, while there is 4.3 per cent of silt and clay size. According to the partial chemical analyses, page 270, there are 3.73 per cent of $MgCO_3$ and 95.08 per cent of $CaCO_3$. There is less $MgCO_3$ than in the material behind Cocoanut Point Reef, but more than in the finely divided muds in South Bight and off the west side of Andros Island.

The following is a list (by Joseph A. Cushman) of the foraminifera from beach sand from east side of Sands Key, Florida, No. 68:

No. 68. Beach sand from east side of Sands Key, Florida.
Orbiculina adunca, abundant.
Orbitolites marginalis, few.
Peneroplis pertusus, few.
Quinqueloculina agglutinans, few.
Triloculina linneiana, few.
Biloculina carinata, few.
Clavulina angularis, few.
Trochammina inflata, one.
Verneuilina affixa, one.
Discorbina vilardeboana, one.
Planorbulina mediterranensis, few.
Quinqueloculina, etc.

The foraminifera in the beach sands on the sea face of keys seem rather consistently to be nearly the same species. Those found on Lisbon Beach, Mangrove Cay, South Bight, Andros Island, Bahamas (identifications by Dr. Cushman), are as follows:

No. 90. Beach sand from Lisbon Beach (east of mouth of Lisbon Creek), South Bight, Mangrove Key, Andros Island, Bahamas. Material fragmentary and water-worn.

Foraminifera:
Orbiculina adunca, frequent.
Quinqueloculina agglutinans, few.
Verneuilina affixa, few.
Triloculina linneiana, one.
Quinqueloculina sp.

The beach sands, naturally, are the coarsest material in the areas here considered. The sizing varies according to local conditions of winds, currents, etc., and as yet has not been adequately studied. The composition also varies from place to place, according to differences in the organisms from which the sands are derived. Efforts are under way to ascertain the sources of the components of a number of beach sands taken from selected localities.

LAGOON SAMPLES.

Sample from between Loggerhead and Cudjoe Keys.

According to the mechanical analysis, 64.5 per cent of specimen No. 91, from between Loggerhead and Cudjoe Keys, is of silt and clay size, nearly the same percentage as in the fine muds in South Bight and west of Andros Island (see plate 94); the percentage of $MgCO_3$ is 2.87, also nearly the same as in the Andros Island specimens. The following is a list of the foraminifera (identification by Dr. Cushman):

No. 91. Mud flat, dredged material, north side of Loggerhead Key, east of Sugar Loaf Key.

Foraminifera:
Polystomella striatopunctata, most frequent species.
Quinqueloculina agglutinans, frequent.
Orbiculina adunca, few.
Triloculina linneiana, few.
Quinqueloculina and Triloculina sp.

This obviously groups with the Bahaman specimens mentioned, Nos. 79, 87, 88, and 177.

Samples from Marquesas Lagoon.

Specimen 98 is from the east side of Marquesas Lagoon (see plate 95). The dimensions of Marquesas Atoll between sea fronts are 4 nautical miles along a line from northeast to southwest and 3 nautical miles from northwest to southeast. The width of the rim ranges up to about 0.625 nautical mile on the northeast side, which is a crescent bowed against the northeast winds. There are entrances to the lagoon in the southeast, southwest, and northwest quadrants.[1] The maximum height of the rim is about 10 feet above low tide. The depths outside the rim range up to about 15 feet within a mile of the shore; within the lagoon the water except along tidal channels is usually less than 3 feet deep, along the channels it is as much as 9 feet in a few places. The bottom of the lagoon is limy mud resting on a floor which lies at a strikingly uniform depth of about 12 feet below low-tide level; one place was found where the depth of mud is 15 feet, below which is rock. The floor underlying the mud is indurated oolite. The lagoon has been filled with mud to an average depth of about 9 feet.

The first cultures Drew made of denitrifying bacteria to ascertain if they would precipitate calcium carbonate were from specimens obtained in Marquesas Lagoon, and Kellerman used specimens from there in his work on the same subject.

I have collected samples at many stations within the lagoon, and have had several mechanical analyses made, but only one chemical analysis. The results of the mechanical analyses of specimens from Marquesas Lagoon (made by U. S. Bureau of Soils) are herewith presented (for graphic representation see plate 94).

Mechanical analyses of bottom samples from Marquesas Lagoon.

No., U. S. Bureau Soils.	No., T. W. V.	Description.	2 to 1 mm.	1 to 0.5 mm.	0.5 to 0.25 mm.	0.25 to 0.1 mm.	0.1 to 0.05 mm.	0.05 to 0.005 mm.	0.005 to 0 mm.
27250	63	SW. quadrant (surface)	1.7	3.1	3.1	17.3	24.8	33.3	16.3
26467	98	SE. quadrant (surface)	4.0	6.4	4.0	19.8	25.6	27.4	12.6
26871	98	.....Do	2.8	6.9	4.5	19.8	24.2	22.0	19.9
27251	106	.....Do	15.9	24.1	10.6	9.1	6.6	17.3	16.4
27252	110	SE. quadrant (9 feet below surface)	1.9	4.3	4.7	18.2	16.5	26.5	28.1
27253	115	SE. quadrant (surface)	.0	17.4	14.0	32.0	13.0	9.7	14.3
27254	117	Outside SE. entrance, water 5 feet deep	.0	17.9	17.5	38.6	7.8	6.5	11.7

The analyses of the surface material indicate an appreciably greater coarseness than that of the muds from South Bight and from off the west side of Andros Island. Only hypothetical explanations can be advanced for this. These are: (*a*) there is greater outwash of fine material; (*b*) bacteria are less abundant. Drew found 800 bacteria per cubic centimeter in a sample sent

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[1] For description of the Marquesas, see Vaughan, Carnegie Inst. Wash. Pub. 182, pp. 57–68, 1914; and Vaughan and Shaw, Carnegie Inst. Wash. Year Book No. 14, pp. 232–238, 1916.

to England from the Marquesas; Kellerman found from 3,000 upward per cubic centimeter, but the greatest number per cubic centimeter appears to be off the west side of Andros Island, where, as already stated, it was 160,000,000 per cubic centimeter. As Marquesas Atoll is relatively small and as there are tidal currents across the lagoon, tidal currents aided by wind might remove more fine material than is done on the west side of Andros Island; and the removal of the fine material might reduce the number of bacteria. Other possible factors might operate.

Specimen No. 110 is from 9 feet below the surface on which No. 115 was taken. Specimen No. 110 in sizing is nearly the same as specimen No. 88 from the west side of Andros Island, having 54.6 per cent of particles of silt and clay size, while No. 88 has 49.8 per cent. Specimen 87 has 61.2 per cent of particles of the same size. The deeper material in the core is finer in grain than that on the surface, indicating a change in conditions not now understood.

The chemical analysis of specimen No. 98 (see page 269) shows 2.88 per cent of $MgCO_3$, nearly the same as that for specimen No. 87, from Andros Island. Dr. Cushman furnishes the following notes:

No. 95. Marquesas Lagoon, Florida, small mangrove key east of northwest entrance, inside the lagoon. Worn material with a few pelecypods and fewer gastropods, a very few ostracod valves and few foraminifera.

Foraminifera:

- Polystomella striatopunctata, frequent.
- Orbiculina adunca, few.
- Quinqueloculina.

No. 98. Marquesas Lagoon, Florida, east side. Material includes fragmental calcium carbonate, gastropod and pelecypod shells, numerous ostracod valves, and numerous foraminifera.

Foraminifera:

- Orbiculina adunca, few.
- Obitolites marginalis, few.
- Articulina sagra, few.
- Quinqueloculina reticulata, few.
- Quinqueloculina agglutinans, few.
- Triloculina linneiana, few.
- Polystomella crispa, few.
- Polystomella striatopunctata, frequent.
- Numerous species of Quinqueloculina and Triloculina.

Besides the organisms noted by Dr. Cushman, *Halimeda* is very abundant in places in the lagoon, and the atoll rim is largely composed of more or less broken *Halimeda* joints. There are almost no corals in the lagoon; there is an occasional specimen of *Mæandra areolata*, and, although I seem to have no notes on them, there are almost certainly some colonies of branching species of *Porites*.

Samples from Tortugas Lagoon.

Specimen No. 97 is from Tortugas Lagoon, obstruction buoy, near northwest entrance to Fort Jefferson Channel; depth about 7 fathoms. Many samples have been collected within the Tortugas Lagoon and outside the atoll perimeter, and when properly worked up will add much to the knowledge of the bottom deposits in this area. Only sample No. 97 will be considered here. The mechanical analysis on page 280 shows 31 per cent of particles of silt, and 6.9 per cent of particles of clay size, 37.9 per cent of the two sizes (see plate 94). The percentage of silt is about that usual in the Tortugas Lagoon deposits; but the percentage of particles of clay size is below the average. The low percentage of the latter size is probably due to outwash by tidal currents. Three samples were collected in the channel off the east side of Garden Key. The clay ranged from 7.7 to 11.5 per cent; silt from 17.9 to 36.3 per cent; silt and clay combined from 25.6 to 47.8 per cent. Where the tidal currents are constricted, much fine material is washed away. The maximum clay in any specimen from the lagoon is 15 per cent; this specimen has 37.9 per cent of silt; the two sizes aggregating 52.9 per cent. The maximum silt in any specimen (one from Bird Key Harbor, depth 6 fathoms) is 56.2 per cent; the clay is 12.6 per cent; the two aggregating 68.8 per cent. In the Tortugas Lagoon deposits there is definitely less material of clay size than in any of the other lagoon deposits here considered; but the percentages of silt and very fine sand seem fairly high.

The percentage of $MgCO_3$ is 3.86 (partial analyses on page 270), distinctly higher than in the other lagoon specimens from Florida and the Bahamas. This higher ratio of $MgCO_3$ is probably to be correlated with the abundance of foraminifera and gorgonian spicules.

Dr. Cushman furnishes the following list:

No. 97. Near the obstruction buoy at southwest entrance to Fort Jefferson Channel, Tortugas, Florida. Material includes fragmental calcium carbonate, fragments and spicules of alcyonoids, fragments of pelecypod and gastropod shells, fragments of worm-tubes, numerous ostracod valves, occasional echinoid spines, and numerous foraminifera.

Orbiculina adunca, few.
Orbiculina compressa, few.
Orbitolites marginalis, few.
Peneroplis pertusus, few.
Quinqueloculina agglutinans, few.
Cornuspira involvens, one.
Virgulina squamosa, few.
Textularia gramen, few.
Textularia agglutinans, few.
Bigenerina nodosaria, few.
Discorbina vilardeboana, few.
Truncatulina rosea, few.
Amphistegina lessoni, few.
Nonionina scapha, few.
Polystomella striatopunctata, few.
Many Quinqueloculina, Triloculina, Biloculina, etc.

It is obvious that according to size the lagoon deposits of Florida represent three grades: (*a*) the finest, is represented by the specimen No. 91 from between Loggerhead and Cudjoe Keys; (*b*) Marquesas Lagoon; (*c*) Tortugas Lagoon. Grade (*a*) is the same as that found off the west side of Andros Island.

SAMPLE FROM OFF KEY WEST.

Specimen No. 100 (see plate 95) (J. B. Henderson, collector) was taken from off Key West, south of Sand Key light, depth 60 fathoms.

As this specimen was taken from the dredge, the mechanical and chemical analyses are not so trustworthy as are those of the other specimens described. (For mechanical analysis see page 280; graphic illustration, plate 94.) The percentage of silt is 13; that of clay, 11.4; the two aggregate 24.4 per cent, an amount rather less than that in any of the lagoon deposits and strongly contrasting with the Globigerina oozes from the Tongue of the Ocean, specimens 84 and 85. The percentage of $MgCO_3$, however, is higher, being 5.03 per cent. (For chemical analysis see page 270.) This is probably due to the bottom-living foraminifera contributing so largely to the deposit, but Messrs. Clarke and Wheeler have shown that alcyonaria and echinoids are to be counted as other sources of $MgCO_3$. Dr. Cushman furnishes the following list:

No. 100. South of Sand Key, Florida, depth 60 fathoms. Material includes gastropod and pelecypod shells, alcyonoid spicules, some sponge spicules, echinoid plates and spines, a few pteropods, a few ostracod valves, and foraminifera in quantity of Globigerina ooze types as well as bottom foraminifera.

Foraminifera:

Textularia barrettii, frequent.
Textularia trochus, frequent.
Textularia sagittula, few.
Bigenerina nodosaria, few.
Bulimina marginata, few.
Reophax scorpiurus, few.
Saccammina sphærica, few.
Nodosaria vertebralis, few.
Cristellaria calcar, few.
Cristellaria italica, few.
Marginulina costata, few.
Uvigerina tenuistriata, few.
Globigerina conglobata, frequent.
Globigerina sacculifera, frequent.
Globigerina rubra, frequent.
Globigerina dubia, abundant.
Globigerina cretacea, abundant.
Globigerina bulloides, abundant.
Pullenia obliqueloculata, frequent.
Cymbalopora poeyi, few.
Pulvinulina menardii, few.
Pulvinulina elegans, few.
Pulvinulina auricula, few.
Discorbina bertheloti, few.
Nonionina umbilicatula, few.
Polystomella striato punctata, few.
Amphistegina lessoni, few.
Spiroloculina grata, few.
Spiroloculina arenaria, few.

This represents a type of deposit different in a number of characters from the others considered. It is (*a*) relatively coarse grained; (*b*) it has a high $MgCO_3$ content; (*c*) it is composed of both pelagic and bottom-living foraminifera, some of the latter habitat extending into shallow water. There are no *Orbiculina*, *Orbitolites*, or Miliolidæ.

ELEVATED OOLITE.

Only chemical analyses of these rocks are given (see table, page 269). One of the two specimens is from Boca Grande Key, the other, from Miami, Florida. If the SiO_2 is rejected from the analysis of the Miami oolite, the Florida samples are seen to be essentially like those from the Bahamas, and the remarks made on the latter, see pages 277, 278, apply to both.

SUMMARY ON BOTTOM SAMPLES FROM FLORIDA.

(1) Three classes of bottom deposits from Florida have been considered, as follows:

(*a*) Beach sand, which is mostly composed of particles of the size of fine gravel (47.2 per cent) and coarse sand (46.1 per cent), and contains 4.3 per cent of particles of silt and clay size. *Orbiculina adunca* is an abundant foraminifer. The percentage of $MgCO_3$ in the single specimen analyzed is 3.73. As yet a sufficient number of beach sands have not been studied for a comprehensive discussion of them, but they seem to represent a distinctive class.

(*b*) Lagoon deposits, some of which are essentially like the fine-grained muds forming on the west side of Andros Island. Sizing indicates three grades of these deposits; the finest corresponds to the Andros Island muds; the next grade is represented by the surface deposits in Marquesas lagoon (clay range from 14.3 per cent to 19.9 per cent; silt range from 9.7 per cent to 33.3 per cent); the specimens from Tortugas Lagoon average less clay than those from the Marquesas, but there is overlapping of the grades. The $MgCO_3$ percentage of the Tortugas material (3.86) is somewhat higher than in the other specimens, a fact probably to be accounted for by the abundance of foraminferal shells and alcyonarian spicules.

(*c*) The deposit in 60 fathoms, south of Sand Key light, is intermediate in character between a Globigerina ooze and a shoal-water deposit. It relatively is coarse grained, has a high (5.03 per cent) $MgCO_3$ content, and contains both bottom-living and pelagic foraminifera.

Specimens of sands from behind the reefs have been collected, but will not now be described. The classes of deposits are closely similar to those recognized in the Bahamas.

(2) As compared with other agents, corals are subordinate as extractors of $CaCO_3$ from the sea-water; but a more accurate evaluation of the work of the different agents must wait until the completion of the study of the composition of the samples from the standpoint of the source of its ingredients.

(3) The remarks on the precipitation and possible solution of $CaCO_3$ made on pages 265–268 apply to Florida as well as to the Bahamas.

(4) The SiO_2 content of the Miami oolite (8.19 per cent) is strikingly different from that of the Bahaman oolites and bottom deposit. The silica is clear sand, around which oolite grains have often formed. The oolite on Boca Grande Key, however, contains only 0.03 per cent SiO_2, showing that in Pleistocene time, during the formation of the latter oolite, terrigenous material did not reach so far westward. The beach sand at Sands Key contains 1.15 per cent insoluble matter; the Marquesas Lagoon sample (No. 98) 1.18 per cent SiO_2. Except in Biscayne Bay and the sounds just southward, next the shore, there is almost no sand in the bottom deposits along the east coast of southern Florida and there is none in the other parts of the key and reef area.[1] The amount of $(Al, Fe)_2O_3$ ranges from 0.21 to 0.42 per cent in the Pleistocene oolites; it is 0.37 per cent in the Marquesas sample, No. 98—somewhat more than in similar deposits in the Bahamas. The waters of the Florida reef tract afford a superb example of almost pure limestone forming near a land-mass which is of low relief and across whose surface no large streams flow. $Ca_3P_2O_8$ is absent or is represented only by traces. $CaSO_4$ ranges from traces to 0.50 per cent. The relations of the latter ingredients are as in the Bahamas.

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[1] See Carnegie Inst. Wash. Pub. 133, pp. 114–129, 1910.

CONCLUSIONS.

(1) An attempt has been made to outline a method of studying calcium-carbonate bottom deposits, in the hope that progress may be made toward an adequate classification of such sediments. The method includes the consideration of the following subjects, viz: (*a*) mechanical analyses; (*b*) study of the composition of the separates of different sizes and the determination of the percentage composition of each separate according to the origin of its constituents; (*c*) the chemical composition of the different constituents; (*d*) the chemical composition of the entire sample; (*e*) the correlation of the chemical composition of the entire sample with that of its different constituents according to their percentages; (*f*) the conditions under which the deposit is formed, viz: its relations to land areas, the configuration of the bottom, winds, and currents, and the depth, temperature, and salinity of the water in which formed; (*g*) the areal extent, and if possible the volume of the deposit.

(2) Only one class of deposits, the sands forming on the flat behind the reef, is specially considered for Murray Island. The beach sand and gravel, however, represent a deposit of another class.

(3) Three classes of deposits are recognized in the shoal waters of the Bahamas, viz: (*a*) the sands forming behind the reefs are mostly of organic origin and are essentially identical with the sands from Murray Island; (*b*) the fine-grained muds forming in South Bight and on the west side of Andros Island are largely chemical precipitates, the precipitation being due to bacteria, probably acting concomitantly with inorganic agencies, evaporation and expulsion of CO_2 from the sea-water by heat and by surface agitation of the water; (*c*) the oolitic sands of the Great Bahama Bank are due to the breaking up by wave-action of a previously formed oolite. Of the three classes of deposits (*a*) is of least areal extent; the areas covered by (*b*) and (*c*) have not been delimited, but together they cover an area at least 60 times as great as that covered by (*a*). The beach sands probably constitute another class of shoal-water deposit. Globigerina ooze covers the floor of the Tongue of the Ocean.

(4) Deposits similar to classes (*a*) and (*b*) of those from the Bahamas occur in Florida: Class (*b*) (the lagoon deposits) may be subdivided into grades, according to size of grain. The Tortugas Lagoon samples are coarser than those in Marquesas Lagoon, and those from the latter locality are coarser than the Bahaman samples from South Bight and the west side of Andros Island. The beach sands represent a distinctive class of deposits. The relative area occupied by the different classes has not been determined. Corals, however, are subordinate agents. A deposit from an intermediate depth, 60 fathoms, off Sand Key light, presents distinctive characters, as it contains large bottom-living as well as pelagic foraminifera.

(5) Other classes of deposits will be recognized, but at present it appears advisable to concentrate attention on the five or six mentioned in the foregoing paragraphs.

(6) No appreciable terrigenous material (SiO_2 and Al_2O_3) reaches the Bahamas. The percentage of Fe_2O_3, although only about 0.1 per cent, is sufficient to produce iron stains and red earth when secondarily concentrated. Some terrigenous material, mostly quartz sand, is washed into Biscayne Bay, Florida, and into the sounds south of it, but otherwise practically none reaches the key and reef region. The Florida area is therefore a perfect example of limestones forming in shoal water near a land area which is not crossed by large streams. The Fe_2O_3 content of the Florida samples seems somewhat higher, up to about 0.37 per cent, than that of the Bahama samples. A small amount of $CaSO_4$ seems persistently present; this fact is to be correlated with the formation of aragonite, which is so abundant in the chemically precipitated muds and in the Pleistocene oolites; $Ca_3P_2O_8$ is present only as traces.

(7) Shore material, subjected to wetting and drying by the rise and fall of the tides, shows a higher magnesia content than material otherwise similar but not subject to such influences. There has apparently been a secondary concentration of magnesia.

(8) Reconsideration of the evidence bearing upon the precipitation of $CaCO_3$ in tropical and subtropical waters and the possibility of its re-solution by ocean-water leads to the conclusion that precipitation is resulting from both organic and inorganic agencies, and that no appreciable re-solution is taking place in such waters; but there is solution in the depths of the ocean where the temperature is low, and perhaps in the surface waters of high latitudes.

(9) Although much progress has been made toward understanding the formation of oolite grains, the oolitic muds, should they be indurated, would not be precisely the same as the oolitic rocks now elevated above sea-level. The former contain a larger percentage of $MgCO_3$ than the latter, and the zonal structure is not so highly developed. The agencies involved in the formation of the concentric shells of the grains need further study.

(10) Requisites for adequately understanding the CO_2 and $CaCO_3$ relations in sea-water are (*a*) more accurate records of temperature and salinity in the ocean; (*b*) accurate determinations of the CO_2 content of the air above the water; and (*c*) further study of the CO_2 content (free and total) of the water.[1]

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[1] It is my desire to give such support as I can command to the suggestions made by Messrs. Johnston, Merwin, and Williamson. The article by Messrs. Dole and Chambers (pp. 299–315) is a valuable contribution to the salinity of the ocean-water at Fowey Rocks, Florida, and in it may be found references to variations in salinity in the Floridian and Bahaman regions. Dr. Wells's study of the solubility of calcite in sea-water in contact with the atmosphere, and its variation with temperature, is based on the same water on which Messrs. Dole and Chambers report, and his results follow theirs, pages 316–318. The large amount of information on the temperature of Florida waters is presented immediately after the paper by Dr. Wells.

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FLORIDA KEYS AND REEFS, FROM KEY BISCAYNE TO RAGGED KEYS

Part of United States Coast and Geodetic Survey Chart No. 166. Scale $\frac{1}{80000}$

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