CARBONATE SEDIMENTATION AND DIAGENESIS OF PLEISTOCENE LIMESTONES IN THE BERMUDA ISLANDS

Thesis by

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ABSTRACT

The Recent carbonate sediments in the Bermuda Islands consist largely of skeletal fragments of marine organisms. Benthonic foraminifera and lithothamnoid algae contribute high-Mg calcite ($>$ 10 mol % $MgCO_3$). Low-Mg calcite ($<$ 5 mol % $MgCO_3$) appears to be derived from erosion of Pleistocene limestones. Aragonite, which makes up 30 to 70% of the Recent sediments, is derived from molluscs and Halimeda.

The Pleistocene limestones are composed of fragments of the same types of marine organisms which make up the Recent sediments. The limestones vary from unconsolidated, unaltered carbonate sands to well consolidated, crystalline limestones. Lithification of the limestones is caused by the removal through solution of aragonitic skeletal fragments and the deposition of secondary calcite. Obliteration of the internal structure and the formation of replacement mosaics is observed in some of the fragments. The high-Mg calcite phase, which is present in the poorly consolidated limestones, is absent in highly altered limestones which contain only low-Mg calcites. No limestones were found which contained only a single Mg-calcite of intermediate composition (between 5 and 10 mol % $MgCO_3$). Mg-calcites containing between 5 and 10 mol % $MgCO_3$ were found only in the fragments of Homotrema. The $SrCO_3$ originally present in the calcites and aragonites is removed during diagenesis of the limestones. No dolomites were found in the Bermuda limestones, which suggests that the Mg and Sr removed during diagenesis is not retained in the limestones. Dolomite containing 57 mol % $CaCO_3$ was found in limestones recovered from drilling operations on Plantagenet Bank, off Bermuda.

With the exception of Halimeda fragments, the skeletal fragments making up the Recent sediments have δO^{18} values between 0 and -1‰ and positive δC^{13} values. Most of the Recent sediments have δO^{18} and δC^{13} values in this range. Fresh water carbonates deposited on the islands have δO^{18} values from -3 to -5‰ and δC^{13} values from -4 to -9‰ . The δO^{18} and δC^{13} values of the diagenetically altered limestones exhibit a change from values similar to the Recent sediments to δ values similar to those of the fresh water carbonates. This change in δ values is shown to result from the precipitation of secondary calcite in the limestones and is interpreted as indicating that the secondary calcites have the same origin as the fresh water carbonates.

The diagenetic environment of the Bermuda limestones was characterized by temperatures less than 30°C and essentially surface pressures. Most of the Pleistocene limestones have probably been in the fresh water zone since their deposition. The mineral assemblage and Sr and Mg content of the limestones is discussed in terms of the equilibrium mineral assemblage at these temperatures and pressures.

Cursory studies were made of limestones from Bikini and Eniwetok Atolls and mid-Ordovician limestones from Oklahoma in order to test the usefulness of the δO^{18} and δC^{13} values for distinguishing different diagenetic environments. The data from the analyses of the Bikini and Eniwetok Atoll samples substantiate the geological evidence that portions of these limestones have been subaerially exposed during the Pleistocene epoch. The data from the mid-Ordovician limestone indicate that the diagenetic environment was different from that of the Bermuda limestones.

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INTRODUCTION

The purpose of such a study is to gain a better understanding of the processes by which a carbonate sediment is changed into a limestone and to develop criteria by which various types of diagenetic alteration can be recognized.

The basic approach used throughout the study involves a comparison of the Recent carbonate sediments and the Pleistocene limestones. Therefore the composition of the constituent grains in the Recent sediments is compared to the composition of the constituent grains in the Pleistocene limestones to see which formations are useable for this type of study.

Thin sections of the Pleistocene limestones were studied to determine the magnitude of the changes which result from diagenetic alteration. The results of the petrographic examination provide a basis for the interpretation of some of the chemical changes which are discussed in the study.

Determinations were made of the amount and $MgCO_3$ content of calcite in Recent sediment contributing organisms, the Recent carbonate sediments and the Pleistocene limestones. Similarly the $SrCO_3$ content of the total sample was determined for the Recent sediments, the Pleistocene limestones,fresh water carbonates and secondary calcites from the Pleistocene limestones. Comparison of the data from the Recent sediments and the Pleistocene limestones shows the changes which are due to diagenetic alteration.

O^{18}/O^{16} and C^{13}/C^{12} ratios were determined for the major sediment contributing organisms, the Recent sediments, the Pleistocene limestones, the fresh water carbonates, and the secondary calcites from the Pleistocene limestones. The results of these total rock analyses are compared with the O^{18}/O^{16} and C^{13}/C^{12} ratios of Pleistocene limestones in various stages of consolidation.

The diagenetic environment for the Pleistocene limestones is discussed in terms of the temperature, pressure and the type of water in which the diagenesis took place. The mineral assemblage, $MgCO_3$ and $SrCO_3$ content of the Pleistocene limestones is discussed as an approach to equilibrium under the conditions of the diagenetic environment. The O^{18}/O^{16} and C^{13}/C^{12} ratios and their variation between the Recent sediments and the Pleistocene limestones are discussed.

With the criteria developed from the study of the Bermuda limestones, cursory studies were undertaken of limestones from Bikini and Eniwetok Atolls and the McLish limestone (mid-Ordovician) Oklahoma to test the applicability of the criteria to other diagenetic environments.

Diagenesis

Diagenesis is the change that takes place in sediments during and following deposition (Ginsburg, 1957). Pettijohn (1957, p. 648) states that "diagenesis refers primarily to the reactions which take place within a sediment between one mineral and another or between one or several minerals and the interstitial or supernatant fluids." In this definition all that distinguishes diagenesis from metamorphism is that the latter normally occurs at higher temperatures and pressures. The diagenetic changes seem to tend toward mineral assemblages or sedimentary structures which are stable at the temperature and pressure involved.

Physical changes in the sediment may occur in response to the increased pressure resulting from burial in the sedimentary environment. Compaction is the most common physical change (Krumbein, 1942). Pressure solution (Weyl, 1959) can occur at the points of grain contact as a result of the increased pressure.

Among the diagenetic processes which are primarily chemical are cementation, recrystallization, replacement, and the growth of any new mineral phases not originally part of the sediment (Krumbein, 1942). Recrystallization will be used in this study as defined by Moore et al. (1952, p. 4): "The process whereby the original microstructure of a shell is blurred or lost and the shell is converted into a mosaic of interlocking crystals." When the term recrystallization is used, no implications are intended as to the exact process involved.

Looking at diagenesis in these terms it appears that any discussion of the diagenetic environments must include the temperature and pressure at which diagenesis occurred, as well as the chemical composition of the whole system. The chemical system includes not only the sediments but the chemical composition of the water phase as well.

Previous work

Relatively few studies of diagenetic alterations of limestones have been undertaken, and in general, these have emphasized the petrographic aspects of the alteration with little attention given to the chemical changes which accompanied or caused the petrographic changes. The previous studies which are most pertinent to this problem are those which dealt with the petrography of Tertiary limestones or early diagenetic changes in Recent marine carbonate sediments. No attempt has been made to survey the literature relating to the petrography or petrographic alterations of pre-Tertiary limestones.

Crickmay's study of the Tertiary limestones of Lau, Fiji (1945) was concerned with the petrographic description of the deposits. Many of his observations bear directly on the problems of early diagenesis of the Bermuda rocks.

From his analysis of the rocks in thin section and hand specimens, Crickmay formulated the following order of susceptibility to change of the various organic constituents making up the limestones (in order of decreasing susceptibility to alteration):

Coral (never observed unaltered)
Molluscs
Pelagic foraminifera
Beach foraminifera
Larger foraminifera
Echinoids
Calcareous red algae

The last three he considers to be roughly equal in their degree of susceptibility to change.

Crickmay does not explicitly state the type of change upon which this order of susceptibility is based. From analysis of his text, however, three different types of alteration seem to be involved.

1. Recrystallization of aragonite to form calcite.

2. Obliteration or alteration of the original organic structure in calcitic skeletal debris to form a medium to coarsely crystalline limestone.

3. Formation of dolomite in the medium to coarsely crystalline limestone and attendant destruction of the original organic structure.

When the order of susceptibility is considered in terms of the processes involved its significance becomes more apparent. In these rocks all of the coral has been recrystallized, as have many of the mollusc fragments. The foraminifera, which are calcitic, are altered through the deposition of calcite on the surfaces of the radially crystalline forms, and there is also an obliteration of the internal structure in many of the fine crystalline forms. From the text it appears that the main alteration of the larger foraminifera, echinoids and calcareous red algae is caused by the formation of dolomite.

A study of the petrography of the cores and cuttings from the boring operations on Bikini Atoll has been made by Emery, Tracey and Ladd (1954, pp. 88-90, pp. 214-261). The sequence penetrated in these borings extends from the Recent sediments on the surface to the Oligocene. The alteration observed in the limestones is similar to that which has been shown to occur in the carbonate rocks in Bermuda. None of the rocks in Bikini appear to be as altered as the highly altered rocks in Lau as described by Crickmay. From the observations made on the thin sections of the Bikini sample, an order of susceptibility was formulated (Emery *et al.*, p. 88).

Coral
Molluscs
Halimeda
Thin-walled (pelagic) foraminifera
Thick-walled (beach) foraminifera
Larger foraminifera
Echinoids
Lithothamnion

This is essentially the same as the results reported by Crickmay.

Three different types of alteration of the sediment to form the limestones are mentioned (p. 88). These are:

1. Disintegration or breaking down of the skeletal carbonates to microgranular and cryptocrystalline material.

2. Consolidation of the rock by addition of calcite (cementation).

3. Recrystallization of the aragonite to calcite.

In addition the local abundance of shells preserved as casts or molds indicates that in many cases the aragonite is completely dissolved, leaving a cavity. At some later time calcite is precipitated in the cavity to form the mold.

In conjunction with his classical study of the shell structure of the molluscs Bøggild (1930) noticed many instances of the transformation of aragonite to calcite in the shells which he examined. Two different processes are mentioned; the first is replacement and the second is apparently recrystallization. These two processes are described by Bøggild (1930), p. 244) as follows:

> "The way in which the original aragonite is transformed into calcite may be somewhat different in the different rocks. In most instances it seems that the aragonite is gradually loosened, and in many places we find it reduced to a loose

> powdery mass still possessing traces of the original structure; afterwards the aragonite may entirely disappear. If the surrounding rock is of a more solid kind, a cavity is left which, in most instances, is filled up by calcite, forming in this manner, a perfect cast of the original shell which may look quite fresh as to the external appearance, whereas, in thin sections, it is seen to consist of irregularly grained calcite. If the surrounding rock is not of such a solid consistency, the aragonite shells may entirely disappear, and no trace of them will be found. In chalk, e.g., most aragonitic shells have disappeared, and only some of the largest of them are seen as impression.
>
> "In other rocks the aragonite may behave in quite a different manner; in the alpine Triassic we may find shells possessing a perfectly unaltered aragonite while in others we may find that only part of the shell possesses such a consistency while other parts are transformed into calcite, and there is a sharp boundary line between both parts."

Bøggild also noticed that the presence of 10 to 20% of clay in a carbonate rock had a marked effect on the preservation of aragonite. In such impure rocks the aragonite was often found preserved even in rocks of Mesozoid age. In pure carbonate sediments the aragonite was found to be quickly converted to calcite.

Ginsburg (1957) described the processes which were active in the early diagenesis of the shallow-water carbonate sediments of South Florida. Most of his work dealt with examination of the sediments in their depositional environment and did not discuss the petrographic aspect. Ginsburg (1957), p. 80) was concerned primarily with the processes of early diagenesis which he defined as:

> "...the relatively brief, intense processes which alter original sediment properties at the water-sediment interface, and to a depth of burial of several feet."

He divided the processes into three groups:

1. Organic processes - effects of organisms on sedimentary textures and structures, and biochemical effects resulting from activities of animals.

2. Physico-chemical processes - non-organic effects involving the solution, precipitation and transformation of carbonates, sulfides and various silicates.

3. Physical processes - includes compaction, dessication shrinkage and penecontemporaneous deformation.

The petrography of the cores obtained from the boring at Funa-futi was discussed by Cullis (1904). Detailed interpretation of the observations is difficult due to unresolved problems of facies changes in the sediments. Complications probably also result from changes of sea level during the Pleistocene (Fairbridge, 1957). All the processes of sediment alteration observed at Bikini were also observed by Cullis in the rocks from various depths in the boring. Cullis (1940, p. 404) found that following the disintegration of the original organic structure, the process of complete solution of the aragonite was much more common than the process of recrystallization of the aragonite to calcite. Many of these molds as well as the intergranular pores were later filled by fine grained carbonate detritus which Cullis referred to as calcite mud. From his description this mud appears to be what Crickmay (1945) called paste. Much of the discussion of the alteration of the Funa-futi samples is concerned with the changes in this calcite mud or paste.

A suite of surface samples from Christmas Island, Paumotus, Niue, the Fiji Islands, and the Ladrone Islands in the Pacific were studied by Skeats (1903). Essentially the same sequence of processes was observed here. The aragonitic skeletal fragments were observed to disintegrate and gradually disappear as the amount of total alteration in the rock increased. Some recrystallization occurred in which the tubes formed by boring algae are still preserved in the recrystallized material.

Regional Setting

The Bermuda Islands are situated in the western North Atlantic Ocean about 550 miles east-south-east of Cape Hatteras, North Carolina, and about 760 miles southeast of New York City. The islands are located at North Latitude 32°15' and West Longitude 64° (figure 1).

With the exception of North Rock, the islands of the group lie along the southeastern edge of an oval, shallowly submerged platform. The chain is arranged in the general form of a "fish hook" about 13.5 miles long and approximately 2.5 miles wide at its widest point. The group is generally oriented in a northeasterly-southwesterly direction. Five large islands make up most of the total land area of slightly less than 20 square miles; the other islands are small (Livingston, 1944).

The islands are located on a bank which is approximately 300 square miles in area (figure 2). Below 30 fathoms, the bank drops off sharply with slopes of 1:5 to 1:30 to the depths of the surrounding ocean bottom, approximately 2500 fathoms (Admiralty Chart 360, 1926, H.O. 27). Challanger and Plantagenet Banks lie to the southeast, and are submerged to depths of 23 and 26 fathoms respectively. Bermuda and the associated banks are situated on the northeast trending Bermuda Rise (Heezen, 1959).

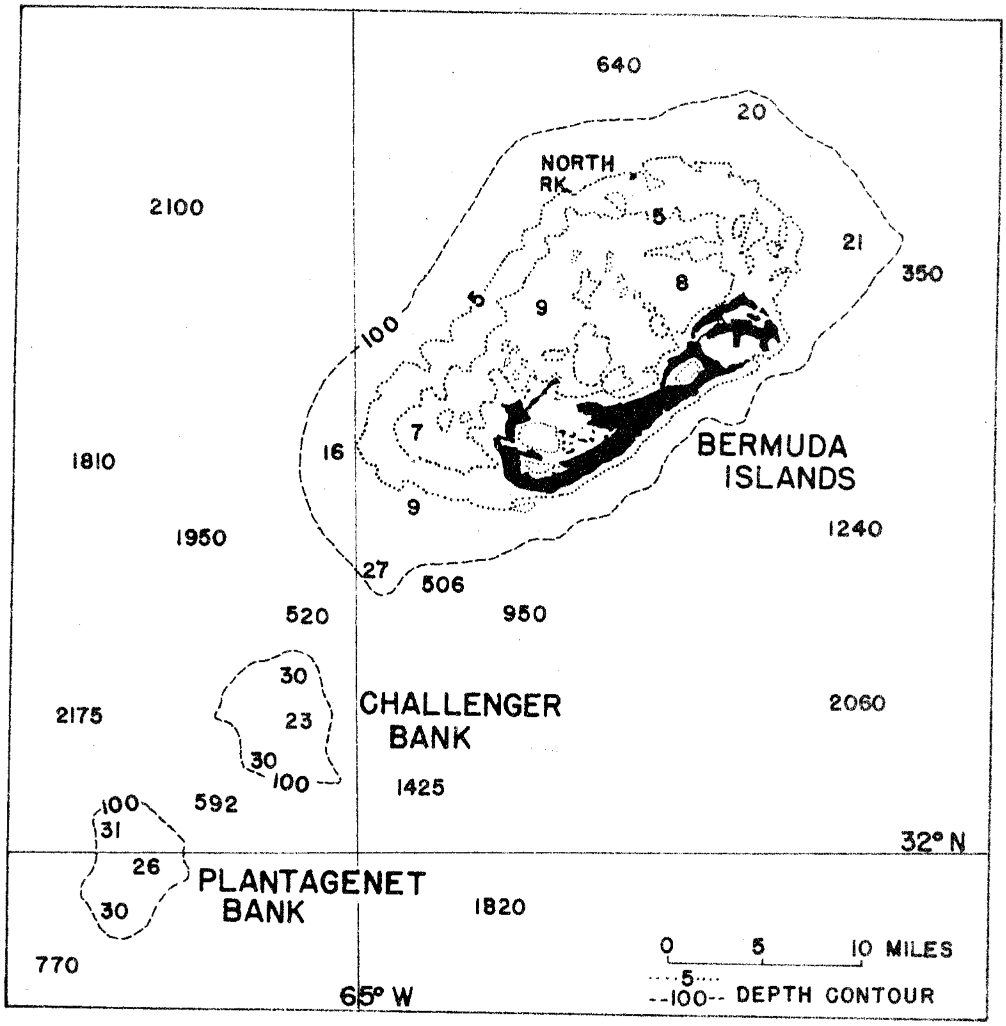


Figure 1. The Bermuda Islands and adjacent banks. (after Sayles, 1931; Admiralty Chart 360).

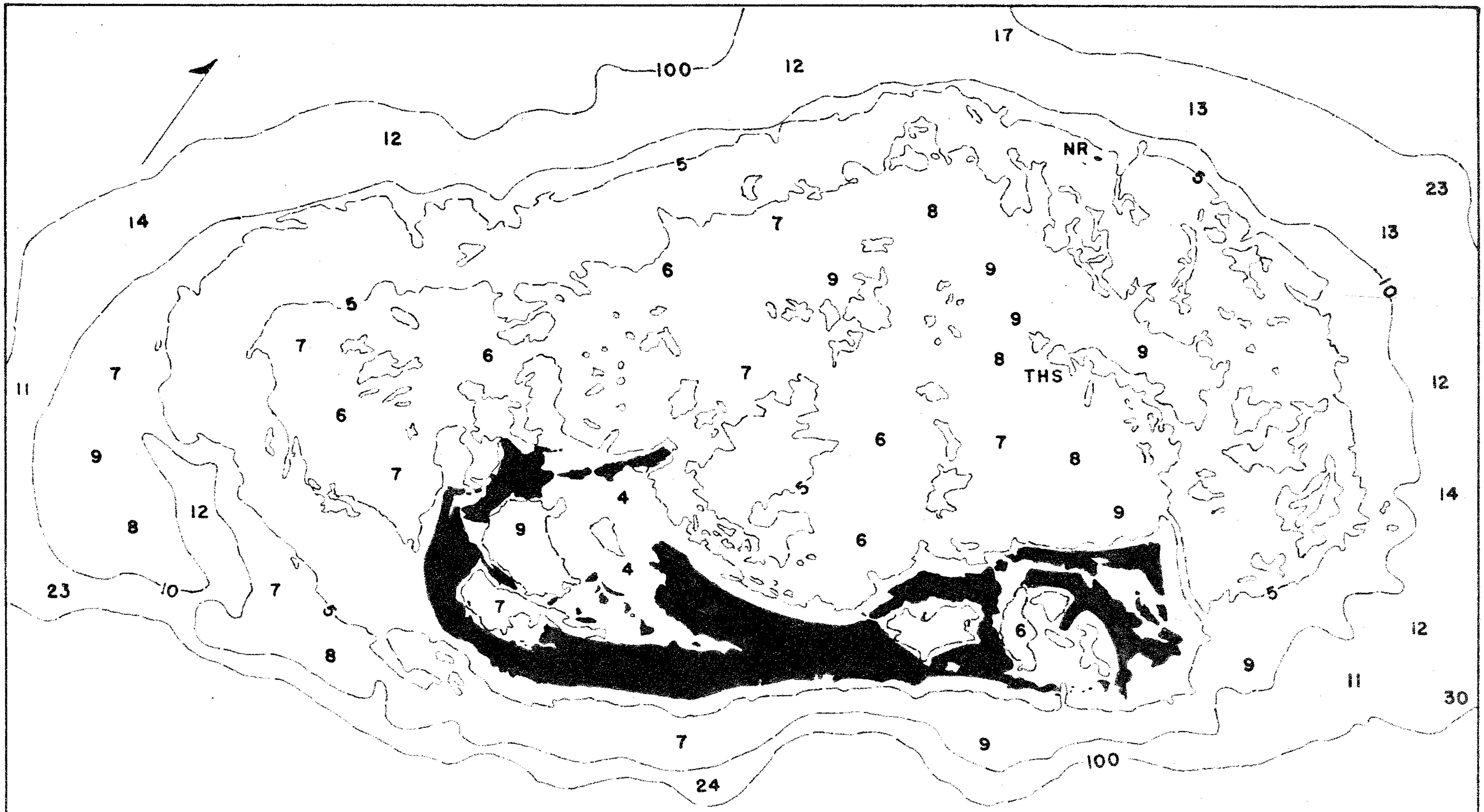


Figure 2. The Bermuda Bank (after U. S. Hydrographic Chart 27, 5 and 10 fathom contours by the writer). NR - North Rock, THS - Three Hill Shoal.

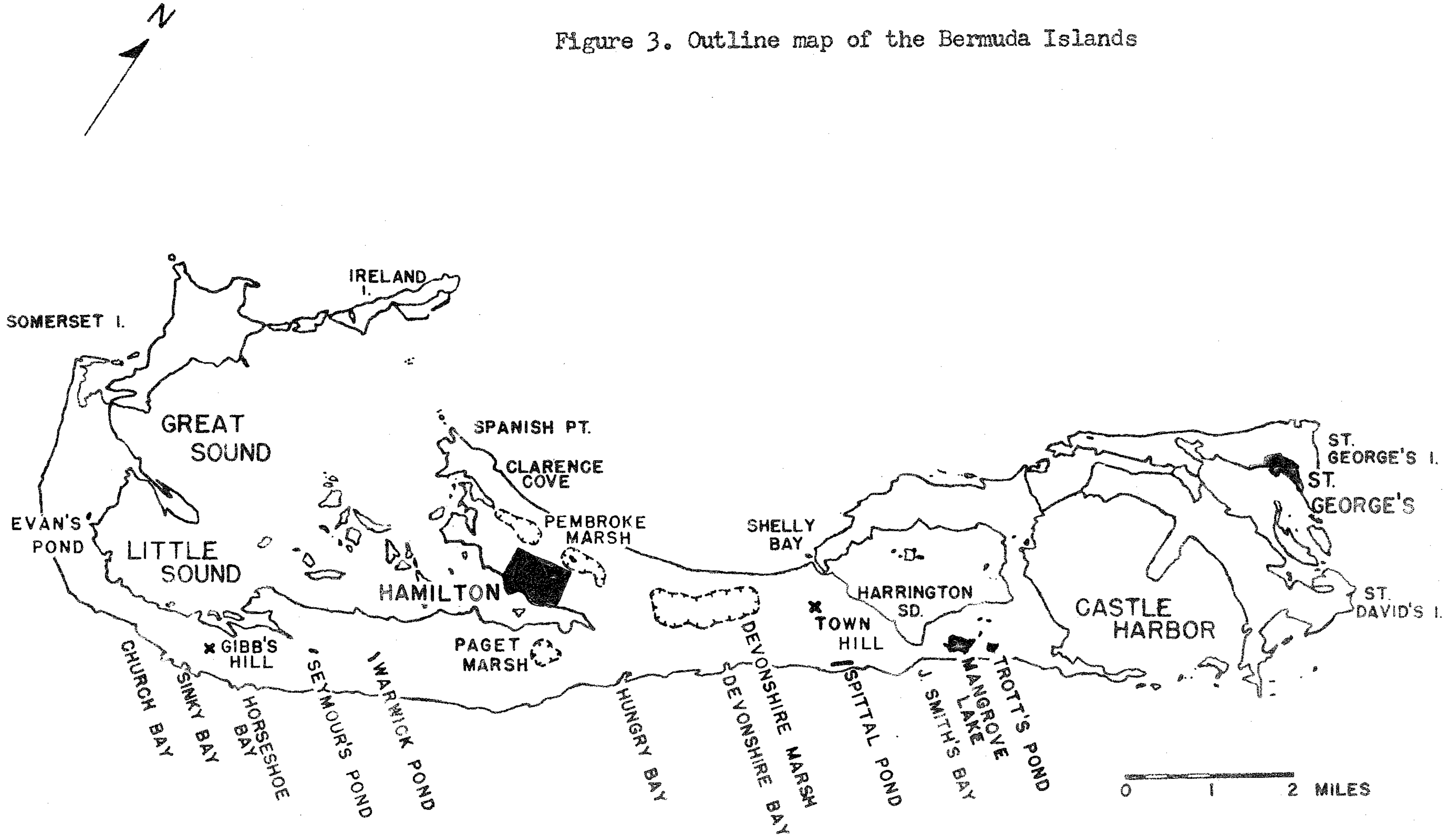
Numerous beaches of carbonate sand occur on the eastern and southeastern shores of the island group, interspersed with small rocky headlands. The northern shore of the islands is much more rocky, with sand beaches developed only in the infrequent small inlets.

An almost continuous chain of small reefs, locally known as "Boilers," parallel the south shore, usually less than 1 mile offshore. This chain of reefs continues beyond the islands to the west and marks the outer edge of the bank. Only small breaks occur in the reefs so that all the shipping channels have been dredged.

A lagoon, approximately 20 miles long and 6 miles wide, lies to the northwest of the islands. The islands and associated reefs completely surround the lagoon. Between the numerous reefs and shoals the lagoon is 5 to 7 fathoms deep, although depths of 12 fathoms are found along the northeastern margin. Numerous patch reefs are found in the lagoon.

The maximum depths of 11 to 12 fathoms reported in Harrington Sound, Little Sound, and Great Sound correspond to those found in the lagoon. Hydrographic charts of the area indicate that wide terraces exist on the eastern and western ends of the banks. These terraces occur at depths of 9 and 13 fathoms (figure 2). Elongate shoals and reef developments are found in the lagoonal area and within Great and Little Sound.

Figure 3. Outline map of the Bermuda Islands



Topography of the Bermuda Islands

Most of the islands are made up of elongate, gently rolling hills, from 100 to 200 feet above sea level. Town Hill, just west of Flatts Inlet, is the highest point; its summit is 259 feet above sea level (Livingston, 1944). The next highest point is Gibb's Hill at 245 feet above sea level.

In general the topography has the appearance of a slightly modified dune system (Bretz, 1960). The Walsingham district, which separates Castle Harbor and Harrington Sound, has a well developed karst topography and contains numerous caves (Nelson, 1940; Verrill, 1905; Bretz, 1960). Caves are also known to exist on Ireland Island and in the vicinity of Somerset (Nelson, 1840), within Hamilton Harbor (Sayles, 1931) and on St. David's Island (Bretz, 1960). The caves in the Walsingham district have tidewater pools (Bretz, 1960).

Trott's Pond, Mangrove Lake and Spittal Pond are the largest lakes on the island. Trott's Pond and Mangrove Lake are both brackish (see Appendix 5); Spittal Pond is reported to be slightly brackish (Moore, 1946) and during exceptionally high tides small amounts of sea water have been observed to flow into the pond. Smaller ponds occur in the marshy interdune areas. Along the South Shore these marshes and ponds are slightly brackish but the pond in

Pembroke Marsh, East contains fresh water (see Appendix 5).

Climate

Bermuda has a mild, humid climate with few extremes in temperature. The mean annual temperature is 21.7°C (71°F); extremes of 34.4°C (94°F) and 6.7°C (44°F) have been recorded (Macky, 1948). The mean monthly air temperatures for the islands are shown in figure 4. The air temperatures are very closely related to the water temperatures for the surrounding open ocean and the water on top of the bank, as shown in figure 6. This close correspondence of temperature extends to depths of approximately 100 meters in the surrounding open ocean (Schroeder et al., 1959).

Bermuda's mean annual temperature is somewhat higher than might be predicted on the basis of its latitude alone. This higher temperature is caused by the Gulf Stream, flowing to the northeast of Bermuda, which brings warm Caribbean water into the area. The Bermuda Islands lie within the large semi-closed circulation system in the North Atlantic Ocean commonly referred to as the Sargasso Sea.

The mean annual rainfall of 57.6 inches is well distributed throughout the entire year (figure 5). Precipitation occurs in 1 out of every 2 or 3 days on the average (West Indies Pilot). Most of the very heavy rains are associated with cold fronts moving southeastward off

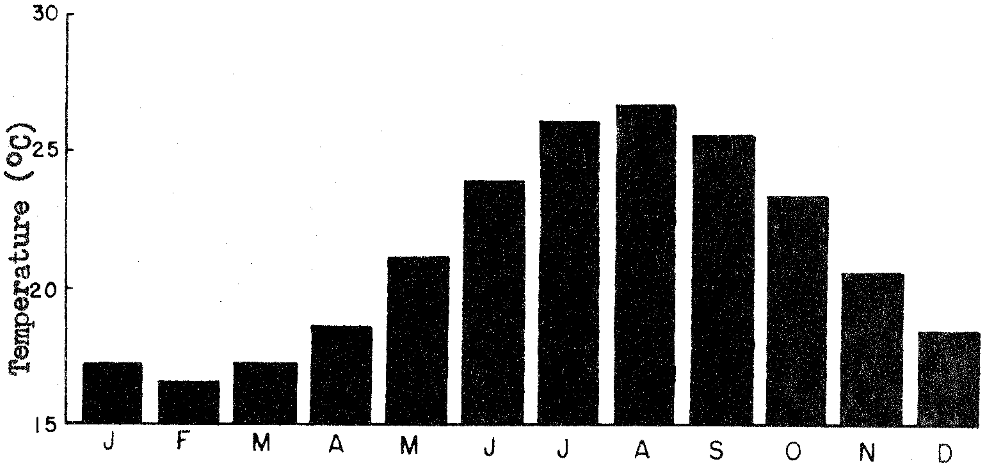


Figure 4. Mean monthly air temperatures in the Bermuda Islands, 1891-1947. (Macky, 1948)

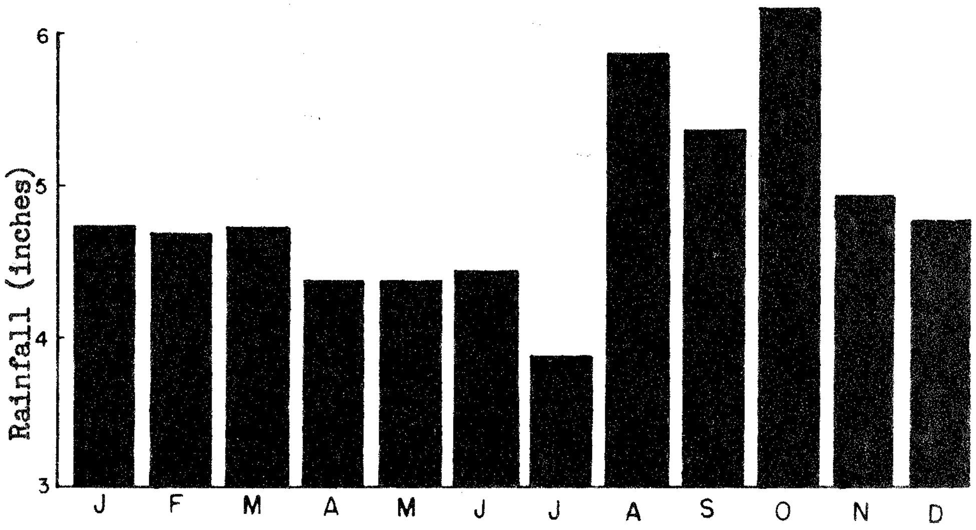


Figure 5. Mean monthly rainfall in the Bermuda Islands, 1891-1942. (Macky, 1943).

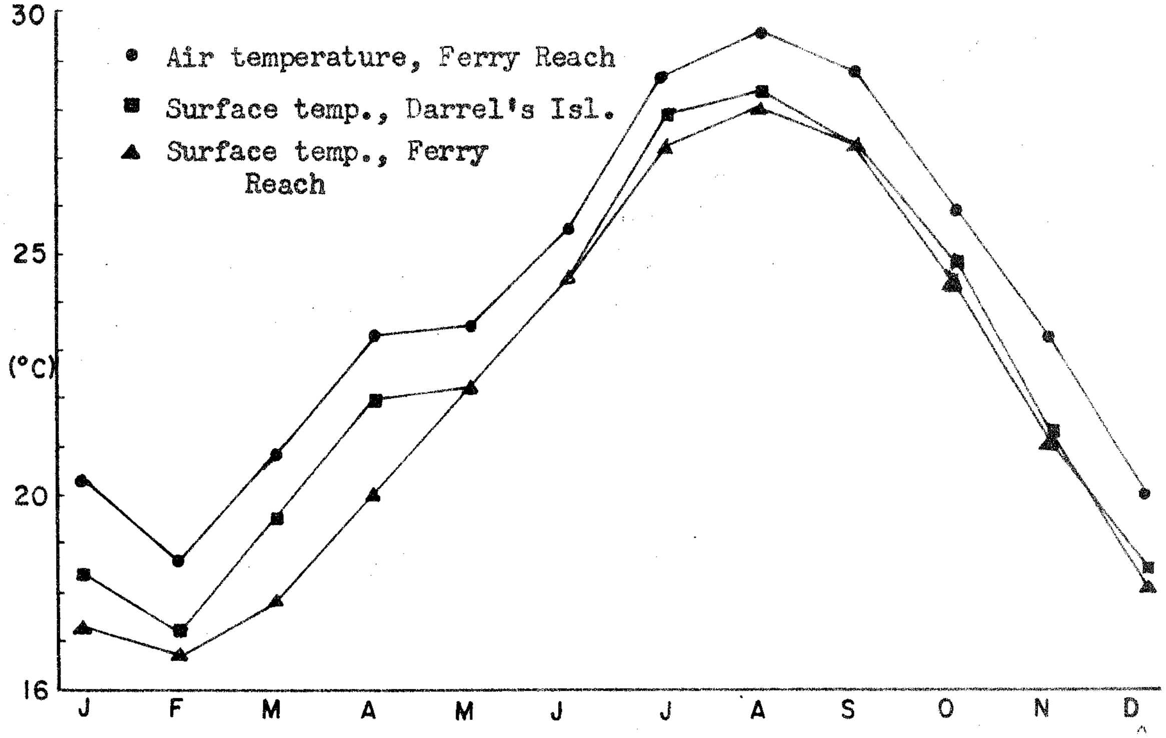


Figure 6. Mean monthly air temperatures at Ferry Reach, St. George's Island and mean monthly surface water temperatures at Ferry Reach and Darrel's Island, Little Sound, 1945-1946. (Moore, 1946; Macky, 1948)

the North American coast. Although such storms are somewhat modified by passing over the warm waters of the Gulf Stream, they are often quite intense (Macky, 1943). These cyclonic systems are most common during the fall but may occur at any time of the year except the summer. Occasional heavy rains from local thunderstorms and tropical disturbances may occur at any time of the year.

Moderate southwesterly or westerly winds prevail during the summer. During the rest of the year, periods of light and variable wind alternate with the cyclonic storms. Winds of gale force are infrequent during the summer, but 5 to 7 days per month of gale winds occur during December and March. Gales from the northeast and southeast occur only during hurricanes, which occur on the average of one a year (Macky, 1943; West Indies Pilot).

From his long observations of Bermuda meteorological conditions, Macky (1943) concluded that the climate of Bermuda is controlled by the climate of the surrounding open ocean.

Geologic Structure of the Bermuda Islands

The volcanic origin of the Bermuda Banks has been established by the borings which penetrated volcanic rocks or pyroclastics (Pirrson, 1917; Newman, 1959). Dredgings in Castle Harbor also recovered weathered volcanic materials (Moore and Moore, 1946; Foreman, 1951).

In addition, outcrops of the Belmont and Walsingham formations contain appreciable quantities of ilmenite, magnetite, quartz, pyroxene, and orthoclase (Sayles, 1931; Woolard, 1954) which are presumably derived from volcanic rocks.

Seismic work by Wooland and Ewing (1939) indicated that the volcanic rocks occur at a depth of 273 feet below sea level on the north side of Castle Harbor and 243 feet below sea level in Ferry Reach. Further work by Officer *et al.* (1952) indicated that the depth to the volcanics varies from 118 to 316 feet below sea level in the lagoonal area. The presence of amgyduloidal basalt at shallow depths in Castle Harbor (Newman, 1959) indicates that the truncated volcanic cone has a somewhat irregular top. Officer *et al.* (1952) considered that the average depth to the volcanic rocks was approximately 250 feet below sea level.

Geologic Structure of Challanger and Plantagenet Banks

The shape of Challanger and Plantagenet Banks and their relationship to the Bermuda Banks has long been interpreted as indicating a volcanic origin for all three structures (Verrill, 1905; Sayles, 1931). Both of the banks have irregular surfaces and both are submerged to depths of approximately 30 fathoms.

The banks appear to have calcareous deposits on the surfaces. Eight feet of calcareous sand was recovered in a core taken on Plantagenet Bank (Ewing *et al.*, 1960, p. 2857), and during the summer of 1960, drilling operations were conducted on the Bank. The boring from which the cuttings were examined penetrated approximately 60 feet of carbonates and limestones. No volcanics were encountered although some volcanic grains were found in the cuttings.

Pre-Pleistocene Stratigraphy of the Bermuda Banks

Borings made on the Bermuda Islands have demonstrated the existence of a thick sedimentary sequence below sea level. These sediments are poorly known and no attempt has been made to define formations in them.

The deepest boring was drilled to a depth of 1278 feet below sea level on a site approximately 1 mile west of the Gibbs Hill Lighthouse. The bore hole was drilled by churn drill and the cuttings were analyzed by Pirrson (1917) and Vaughan (1919).

Cuttings of limestone recovered from the well were examined by Vaughan (1919). On the basis of foraminiferal identifications by J. A. Cushman, Vaughan gave the following sequence:

Depth below sea level	Sediment description	Age
+135 to -106'	Eolian deposits	Recent or Pleistocene
-106 to -206'	Chalky marine limestone containing oolites (?)	Upper 45' is Pliocene or Miocene
-206 to -258'	Impure foraminifera marl abundant *Nummulites*	Oligocene or Eocene
-258 to -350'	Contained *Polystromella* but no *Nummulites*	Probably late Eocene

Cushman later reexamined these foraminifera and concluded that the sediments were probably Miocene age or younger (Sayles, 1931).

More recently a series of shallow holes has been drilled at Coney Island Inlet and Longbird Channel in Castle Harbor. The cuttings from these wells were examined by Newman (1959). These borings encountered a foraminiferal sand at approximately 80 feet below sea level. Samples of foraminiferal sand were examined by Dr. O. L. Bandy (written communication, November 30, 1960), who stated that they were *Amphistegina angulata* (Cushman) which is common in parts of the lower Miocene rocks (Burdigalian) of the West Indies. From Newman's data it appears that calcareous sediments occur below this Miocene sediment. Pyroclastics were encountered in several of these wells and one of them cored amygduloidal basalt at a depth of 120 feet below sea level (Newman, 1958).

The well penetrated more than 200 feet of weathered volcanic materials overlying basaltic lava flows which appear to be part of the cone (Pirrson, 1917). Officer et al. (1952) thought that these weathered volcanics lie on the flank of the cone. The top of the weathered volcanic rocks in the well lies approximately 250 feet below sea level. This agrees with the average depth to the volcanic basement of around 250 feet as determined by Woolard (1954) and Officer et al. (1952).

Pleistocene Stratigraphy of the Bermuda Islands

The exposed Pleistocene limestones on the islands have been studied and several formations have been defined (Verrill, 1905; Sayles, 1931). The stratigraphic sequence (see Table 1) established by Sayles, is most commonly used. Because of difficulty in correlating the upper units, only the terminology of the basal portion of the section is retained in this study.

Walsingham Formation

Sayles (*ibid.*, p. 392) defined the Walsingham formation as to the "eolianite beneath the Belmont limestone." Sayles (*ibid.*, p. 390) defined an eolianite as "a consolidated sedimentary rock deposited by the wind." No type section was designated for the formation although it was named for the Walsingham district. The best exposures are located at Government Quarry and Wilkinson's Quarry on the west side of Castle Harbor. The base of the formation is not exposed on the islands.

Table 1

Stratigraphy of the Exposed Pleistocene Limestones in the Bermuda Islands (after Sayles, 1931).

Recent soil - usually gray or light colored pink soil; red in small pockets.

Southampton eolianite - white, loosely consolidated eolianite; compact only near the surface.

McGall's soil - mainly a light colored calcareous soil of accretion; locally red.

Somserset eolianite - white, loosely consolidated eolianite; compact only near the surface.

Signal Hill soil - gray to pink soil, in large part due to accretion.

Warwick eolianite - white, loosely consolidated eolianite; compact only near the surface.

St. George's soil - thick, deep red soil in depressions; pink to red on slopes; from 1/2 to 2 feet thick; a soil of weathering.

Pembroke eolianite - white to cream colored eolianite; not as compact Walsingham, but better consolidated than younger eolianites.

Harrington soil - light colored to red soil, 4 feet thick at maximum; mainly a soil of accretion.

Devonshire formation - loosely consolidated or compact organic limestone composed of marine mollusc shells and a few corals.

Shore Hills soil - deep red or brown soil from one to four feet thick; mainly a residual soil.

Belmont limestone - a compact limestone composed mainly of marine mollusc shells.

Walsingham eolianite - usually a cream colored compact crystalline eolianite; in places loosely consolidated.

In Government Quarry, the portion of the formation lying above sea level is approximately 100 feet thick. The limestone is very pale orange to very light yellowish gray, well consolidated calcarenite. The Walsingham formation is the most uniformly consolidated limestone on the islands. Throughout the quarry, the limestone contains many limonite (?) grains which are widely disseminated and give the rock a speckled appearance. The formation is rather uniformly bedded; individual beds are approximately four inches thick. In the quarries along the west side of Castle Harbor, the beds strike N40°W to N10°E and dip uniformly eastward with dips of 26° to 32°.

Thin sections of the Walsingham eolianite show that foraminifera (Table 4) similar to Amphistegina angulata, which forms the Miocene foraminiferal sands, are very common. This may be used to identify the formation in the vicinity of Castle Harbor. It is not known whether this type of foraminifera is characteristic of the entire Walsingham formation.

Rounded fragments of well consolidated limestone containing this type of foraminifera were found in the Belmont limestone at Whalebone Bay, St. George's Island. This suggests that locally the Walsingham sediments were well consolidated by the time the Belmont sediments were deposited.

Marine Limestone Units Associated with the Walsingham Formation

In the central part of Government Quarry, at approximately 80 feet above sea level, is a small unit which is apparently a marine deposit. Volcanic pebbles and coarse fragments of marine organisms clearly differentiate this unit from the typical Walsingham eolianite. The unit, which is completely enclosed in typical eolianites of the Walsingham formation, is 6 feet thick at its maximum and pinches out to the west. A stained soil zone overlies the unit, separating it from the overlying eolianite. The soil can be traced for a short distance into the eolianite before it disappears. The bedding in the unit is essentially horizontal.

At Wilkinson's Quarry, near Coney Island Inlet, occurs a sequence of horizontal beds, whose top is approximately 25 feet above high tide. These beds appear to have been deposited on the Walsingham formation although the relationships are somewhat obscured by the presence of a cave between the outcrop and the nearby Walsingham eolianite. In thin section, the limestone lacks the large number of foraminifera *Amphistegina sp.* which is so characteristic of the Walsingham formation in the rest of the quarry. The types of sediment contributing organisms in the unit are similar to those found in the Belmont limestones.

Belmont Limestone

Sayles (*ibid.*, p. 393) defined the Belmont limestone as the marine formation overlying the Walsingham formation and lying beneath the Shore Hills soil (see Table 1). The formation was described as "a compact, cream colored, marine formation composed dominantly of well preserved mollusc shells and some foraminifera." The type locality is the Shore Hills Quarry, located on the Esso Tank farm, Ferry Reach Road, St. George's Island. In the quarry, the gently dipping Belmont limestone is 15 feet thick and is overlain by the well developed Shore Hills soil. The base of the Belmont formation is known to be exposed on the islands.

The Belmont limestone is widespread over the islands. It occurs in outcrops on the western half of St. George's Island from Mullet Bay to Ferry Point. Along the south shore of Hamilton Island, it can be followed almost continuously from Pink Beach to beyond Grape Bay (H. A. Lowenstam, personal communication). The formation is well exposed in the cliffs along the open coast and in the bays along the south shore.

The degree of consolidation varies between samples from outcrops of the Belmont formation. At the Esso Tank Farm on St. George's Island, the limestone is well consolidated and in many places the molluscs are represented by cast and mold preservation. On the south shore of Hamilton Island, the formation is less altered and in the cliffs at Hungry Bay, some of the limestone is so poorly consolidated that it can be dug out by hand.

Devonshire Limestone

The formation was defined by Sayles (ibid., pp. 393-394) as "the marine limestone overlying the Shore Hills soil." The type locality is Devonshire Bay; there Devonshire limestone lies unconformably on the Belmont limestone. The lower portion of the formation is conglomeratic, containing limestone pebbles four to five inches long. The upper part of the formation is medium to coarse carbonate sand. At Grape Bay the formation is approximately 5 feet thick; elsewhere it may be as thin as two feet.

Outcrops of the Devonshire formation are discontinuous. At Devonshire Bay and at Hungry Bay, the limestone was deposited on a wave cut surface of the Belmont formation. Sayles (ibid., p. 394) mentions other localities where the formation occurs.

Younger Eolianites

A sequence of eolianites interbedded with paleosols overlie the marine limestones. Sayles (ibid, pp. 394-397) differentiated four formations using the interbedded fossil soils to distinguish them.

The description of the lithologies given by Sayles in Table 1 illustrates the fact that there is no basic lithologic difference between them. As Bretz (1960) has shown, the use of the interbedded fossil soils to distinguish the eolianites is not reliable because of the complicated relationships involved in soil. Until further work is done on the soils, correlations using them must be considered somewhat suspect.

Because of these difficulties, the formations distinguished by Sayles were not used in this study. At McGall's Bay and St. George's Island, where Sayles found a complete sequence of the "younger eolianites", his terminology has been employed. In these instances it is used to indicate superposition of the samples. At all other sample localities on the islands the post-Walsingham eolianites are referred to as the "younger eolianites."

Geologic History of the Bermuda Islands

Verrill (1905) thought that the volcano which underlies the Bermuda Banks was probably formed in Triassic time because of abundant Triassic volcanism extending from Nova Scotia to North Carolina. Schuchert (1935, p. 738) argued that the volcanism was most probably of Cretaceous age. He considered Bermuda to be more closely related to the Caribbean region where the Cretaceous was a time of great volcanic and tectonic activity. The volcanic rocks have not been dated by radioactive dating.

A core recovered from a depth of about 1510 meters on the southeastern slope of the Bermuda Banks contains an assemblage of late Oligocene foraminifera in volcanic mud (Ericson et al., 1961, p. 238). The sedimentary textures of the volcanic mud and the distribution of foraminifera in it suggested to Ericson and his coworkers that the sediment was originally deposited on the volcanic cone and then redeposited in its present location during the planation of the top of the volcano. If this interpretation is correct, the volcanic cone is pre-Oligocene and was subjected to wave action during late Oligocene or early Miocene times.

By early Miocene times, the top of the volcano was apparently largely truncated by wave action. Vaughan (1919) postulated that the calcareous deposits may have been 100 feet thick by the end of Miocene time. The existence of oolites (?) (Vaughan, 1919) and the nature of the benthonic foraminiferal fauna suggest that the bank was only shallowly submerged following its planation.

The abundance of Amphistegina sp. in the Walsingham formation suggests that these deposits were formed at a time when foraminiferal sands were widely exposed on the banks, possibly during an early period of emergence during Pleistocene time. These foraminifera are not found in the overlying Pleistocene limestones. The occurrence of volcanic minerals in the Walsingham and Belmont formations indicates that volcanic sands were present on the exposed Bermuda Bank and their absence in later formations suggests that they were covered by these early deposits.

The occurrence of reworked Walsingham fragments in the Belmont outcrops of Whalebone Bay indicates that the Walsingham formation was well consolidated by Belmont times.

Despite their disagreement on many aspects of Bermuda's Pleistocene history, Sayles and Bretz feel that most of the material which is now incorporated in the "young eolianites" is carbonate skeletal fragments which were originally deposited on the banks during interglacial times when the sea was near its present level. Sayles and Bretz disagree on the exact process which caused these carbonate materials to be formed into dunes.

The dune system formed during Pleistocene times covered much more of the bank than is now preserved in the Bermuda Islands. The eolianite which forms North Rock indicates the existence of a dune which has been destroyed. The various elongate shoals in the lagoon and within Great and Little Sounds may represent submerged dune systems now largely covered by coral and algal growths.

Movement of some dunes is known to have occurred in Bermuda during historic times. The dunes at Elbow Bay and Tuckers Town have advanced within the last 200 years (Nelson, 1840; Verrill, 1905).

This is thought to have been the result of cutting the vegetation which protected the dunes. These dunes are now stabilized, primarily by a plant cover.

CONSTITUENT COMPOSITION OF THE RECENT SEDIMENTS AND PLEISTOCENE LIMESTONES IN BERMUDA

Introduction

Samples of Recent sediments and Pleistocene limestones were analyzed to determine the source of the carbonate in the sediments and limestones. Recent sediments from the beaches and near shore locations around the island (Fig. 7) were supplemented with samples from Castle Harbor and the lagoonal area north of the islands. Samples of the Pleistocene formations were selected from outcrops on various parts of the island (Fig. 8). In addition, samples of the cuttings from drilling operations on Plantagenet Bank were analyzed. Thin sections of the Recent sediments and Pleistocene limestones were prepared and analyzed using techniques discussed in Appendix 4.

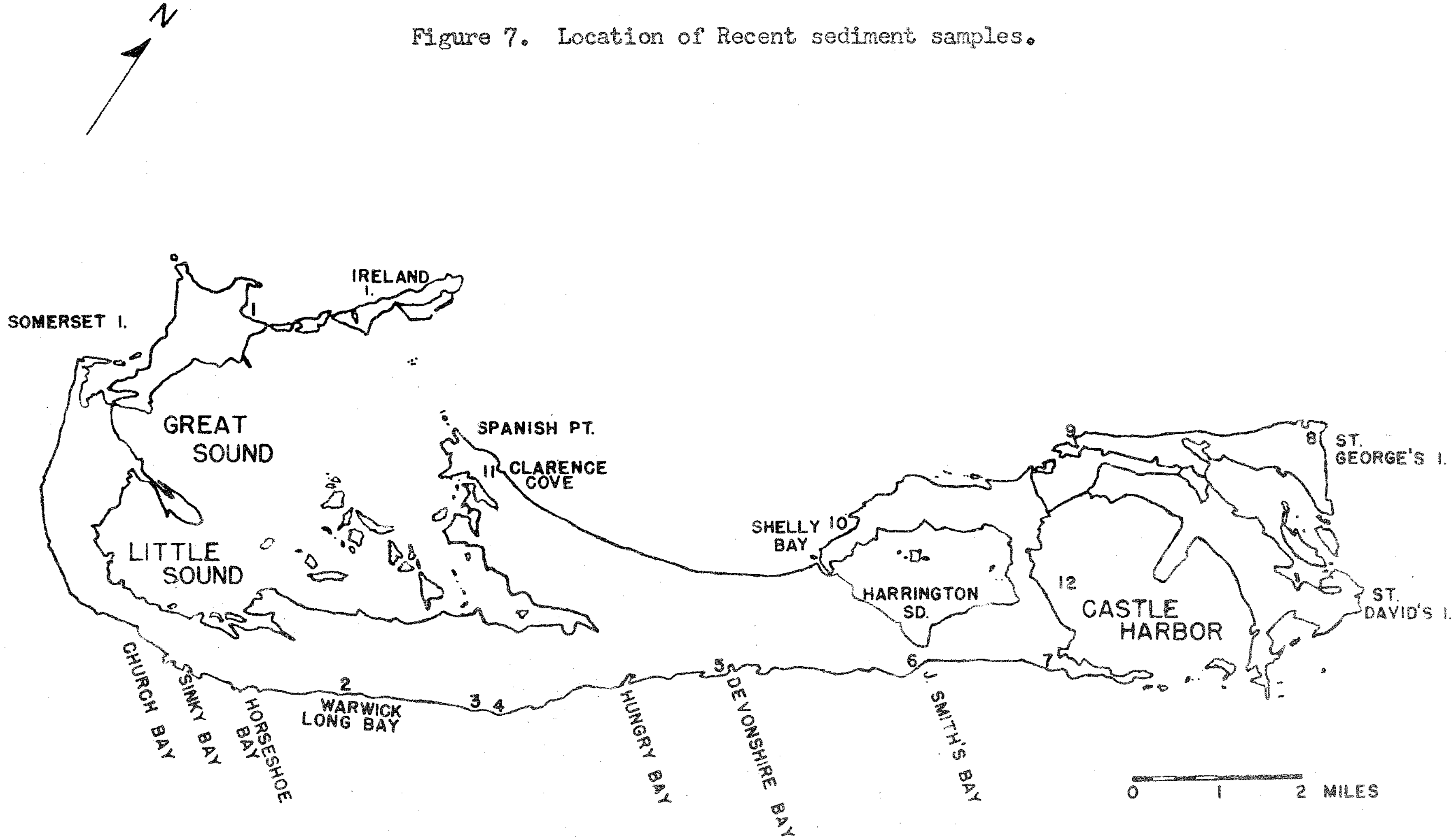
Grain size and sorting of the Recent sediments and Pleistocene Limestones

The Recent sediments which were studied are composed of fine to medium grained carbonate sands. In general the sediments are well sorted. The beach sand from Shelly Bay and samples from Castle Harbor and the lagoonal area were poorly sorted and contained more than 10% silt-sized carbonate particles.

Recent sediment sample localities

1. Mangrove Bay
2. Warwick Long Bay
3. Coral Beach
4. Elbow Bay
5. Devonshire Bay
6. John Smith's Bay
7. Tucker's Town
8. Ft. St. Catherine
9. Whalebone Bay
10. Shelly Bay
11. Clarence Cove
12. Castle Harbor (GCH-4)

Figure 7. Location of Recent sediment samples.



Although sieve analyses could not be made of the Pleistocene limestones, they also are generally composed of fine to medium sand-sized particles which appear to be well sorted.

Distribution of the Recent sediments

Studies of the shallow water sediments around the Bermuda Islands were made by Bigelow (1905) and Todd (1939). Bigelow divided the sediments into three different types, "blue muds," white marls, and shell sands.

The "blue muds" are described by Bigelow (1905, p. 582) as "Chiefly of terrigenous origin, being the fine detritus washed down by the rains from the surrounding calcareous hills, together with some vegetable remains." These muds were found chiefly in small, more or less landlocked, basins with poor circulation of sea water, such as Mullet Bay on St. George's Island.

White calcareous marls which are essentially pure $CaCO_3$ (Renard and Murray, 1891, p. 48) are reported from many areas over the lagoon, especially in the deep basins. In many localities these marls are mixed with varying amounts of shell sands.

Bigelow and Todd found that the shell sand is the predominant sediment in the vicinity of the islands and reefs. These sediments are generally well sorted, although poorly sorted sediments were found in Castle Harbor and in the lagoonal area (Todd, 1939).

Bigelow and Verrill (1905) showed that mollusc fragments and foraminifera are the dominant constituent in the coarse fraction of the Recent marine sediments. Agassiz (1895) and Bigelow thought that the silt sized material was derived primarily from the erosion of the Pleistocene limestones on the islands. Verrill thought that this material was largely derived from the fragmentation of the skeletal fragments which form the coarse fraction. He believed that organisms played a major role in breaking up these materials.

Foreman (1951) studied the insoluble residues of the Pleistocene limestones and concluded that the insoluble minerals were derived from the volcanics. Moore and Moore (1946) published faunal lists of marine limestones dredged from Castle Harbor and concluded that the limestones were deposited in a pre-glacial time or during a period of rising sea level in Pleistocene time. Officer _et al._ (1952) have objected to this interpretation. They feel that the limestones are probably of Pleistocene age.

Recent Sediments

South Shore sediments

Sediments from the beaches and recently active dunes along the South Shore are fairly uniform in composition (Table 2). Mollusc fragments are generally the most abundant constituents. Lithothamnoid algae and foraminifera are both major contributors, and normally they are

TABLE 2. Composition of constituent grains in beach sands and dune sands, South Shore, Bermuda.

	J. Smith Bay	Warwick Long Bay	Devonshire Bay	Elbow Bay Dune	Tuckers Town Dune
ALGAE					
Halimeda-					
Preserved	6.9%	8.2%	2.0%	9.6%	7.7%
Mold	0	0	0	0	0
Cast	0	0.6	0	0	0
Lithothamnoid algae	20.4	17.6	25.4	16.6	21.0
Amphiroa	0	4.4	0	0.4	3.3
FORAMINIFERA					
High-Mg	15.9	27.8	18.7	11.3	18.6
Low-Mg	1.1	0	0.3	0	0.3
COELENTERATA					
Coral					
Preserved	4.8	5.3	8.0	3.5	10.6
Mold	0	0	0	0	0
Cast	0	0	0	0	0
BRYOZOA	0	0	0	0.4	0.6
ECHINODERMATA					
Echinoid	1.6	1.1	8.0	0.8	1.8
MOLLUSCA					
Preserved	34.6	20.0	29.8	35.4	26.0
Mold	0	0	0	0	0
Cast	0	0.2	1.0	0.4	0
MISCELLANEOUS			0.7		0.3
UNKNOWN	13.3	11.0	9.7	7.3	7.1
CRUSTACEAN	1.6	1.1	1.7	1.2	2.7
LIMESTONE FRAGMENTS	0	2.9	0	0	0
NON-CARBONATE (?)	0	0	0	13.1	0

present in roughly equal amounts. Among the foraminifera, the red, sessile foraminifera *Homotrema rubrum* is the most abundant and conspicuous form. In many sediments it is present in large enough quantities to color the sediment a light pink color. Scleractinian corals and *Halimeda* are minor contributors in all the sediments. Locally echinoids and *Amphiroa* are abundant but their distribution is somewhat erratic.

In general the rough water sediments from the South Shore contain an abundance of fragments derived from organisms which live in rough water: lithothamnoid algae, *Homotrema rubrum*, and coral. Some of the constituent grains in these beach sands may be derived from erosion of the poorly consolidated Pleistocene limestones along the coast.

Lagoonal sediments

Samples from the lagoonal area in the vicinity of North Rock and from Castle Harbor were analyzed to determine their composition. Table 3 shows that they have a different composition from the South Shore sediments. In the lagoonal sediments *Halimeda* fragments constitute up to 50% of the sediment. Molluscs fragments are the other major constituent; lithothamnoid algae and foraminifera are minor or accessory contributors. The foraminifera in these sediments belong to the genus *Archaias*; *Homotrema rubrum* is rare or absent except in the sediments near the reefs.

TABLE 3. Composition of constituent grains in beach sands and marine sediments from the lagoonal area.

	Shelly Bay	Mangrove Bay	Ft. St. Catherine	LNR-16	GCH-4	Clarence Cove
ALGAE						
Halimeda-						
Preserved	29.3%	9.8%	28.7%	46.8%	57.5%	20.3%
Mold	0	0	0	0	0	0
Cast	0.7	0	0	0	0	0
Lithothamnoid algae	3.0	15.8	15.8	1.4	1.2	11.3
Amphiroa	1.6	0	1.9	0.7	0	0
FORAMINIFERA						
High-Mg	6.1	28.1	22.0	5.9	9.9	9.7
Low-Mg	0	0	0	0	0	0
COELENTERATA						
Coral						
Preserved	0.5	6.0	2.1	0.2	0	0.5
Mold	0	0	0	0	0	0
Cast	0	0	0	0	0	0
BRYOZOA	0	0	0	0	0	0
ECHINODERMATA						
Echinoid						
Test	0.4	0.8	1.0	0.2	0	0
Spines				1.2	0	0
MOLLUSCA						
Preserved	38.5	20.9	18.3	35.4	23.6	30.6
Mold	0	0	0	0	0	0
Cast	0.2	0.3	0.2	0	0	0.2
MISCELLANEOUS	0	0	0	0	0	0.5
UNKNOWN	17.6	10.3	8.7	8.6	7.8	21.5
CRUSTACEAN	0.2	0.5	0.6	0	0	0.2
LIMESTONE FRAGMENTS	1.8	1.8	0	0	0	5.3
ALCYONARIAN SPICULES	0	0	0	0.5	0	0
POROSITY	41.3%	42.6%	33.2%	35.9%	34.2%	36.9%

The samples from Castle Harbor (GCH-4) and from the vicinity of North Rock (LNR-16) are the only Recent sediments analyzed which contain appreciable amounts of silt sized material (more than 5%). It is impossible to identify grains whose size is below 30 microns (see Appendix 4). In all cases these fine silt grains have been included in the unknown fraction. This problem is not encountered in the beach sands, which are generally well sorted and composed of fine to medium sands.

North Shore Sediments

The sediments collected from beaches along the North Shore display a wide range of composition (Table 3). The Shelly Bay beach sand is most similar to the lagoonal sediments in that it contains a large proportion of Halimeda although mollusc fragments are somewhat more abundant than in the lagoonal sediments. The relative proportions of the other constituents are essentially the same as in the lagoonal sediments.

Beach sands from Clarence Cove, Mangrove Bay and Fort St. Catherine are more or less intermediate between the lagoonal and rough water sediments. Mollusc fragments are the dominant constituent and Halimeda fragments are the next most abundant. These sediments contain substantial amounts of the characteristic constituents of the rough water sediments; lithothamnoid algae and Homotrema rubrum.

Living Homotrema are not common in Clarence Cove (H. A. Lowenstam, personal communication) so it is assumed that the Homotrema fragments are derived from the Pleistocene limestones.

Reworking of Pleistocene limestone fragments in Recent sediments

Some of the carbonate material now incorporated in the beach and near shore deposits appears to be reworked Pleistocene limestone fragments derived from the poorly consolidated limestones along the coast. Along the North Shore there appears to be a great deal of reworked carbonate material in the beach sands, especially at Clarence Cove and Ft. St. Catherine. The exact amount of reworked sediment is impossible to determine because there is no reliable criterion to distinguish the reworked grains. Often the Pleistocene limestones disintegrate into the constituent grains, many of which retain no cement. These grains cannot be distinguished from fragments of modern sediment contributing organisms. Erosion of the Pleistocene limestones along the coasts may account for the presence in the beach sands of fragments of sediment contributing organisms from rough water environments mixed with fragments more characteristic of quiet water environments.

Sample localities for Pleistocene limestones

1. St. George's
2. Stoke's Point
3. Esso Tank Farm
4. Shell Tank Farm
5. Whalebone Bay
6. Wilkinson's Quarry
7. Buern's Quarry
8. Government Quarry
9. Crystal Cave
10. Cable Bay
11. McGall's Bay
12. Hungry Bay
13. Grape Bay
14. Motyer Estate
15. Rockwell Estate Quarry
16. Seymour's Quarry
17. Butterfield Quarry

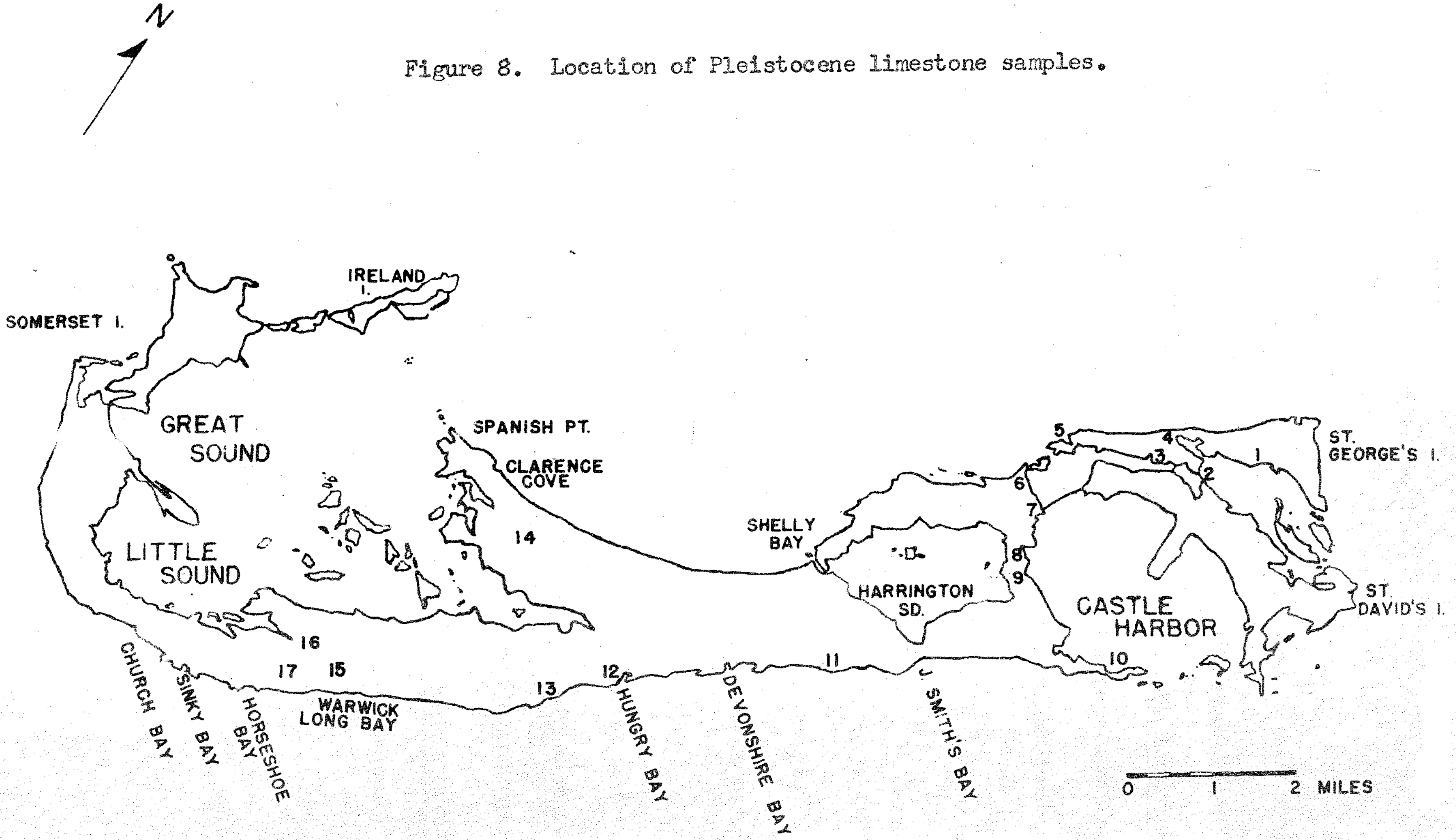


Figure 8. Location of Pleistocene limestone samples.

Pleistocene limestones

Walsingham formation

The composition of the Walsingham formation (Table 4) is different from that of the Recent sediments, in that foraminifera are the dominant constituent. The most abundant foraminifera is a species of the *Amphistegina* which is unusually thick walled. In thin section these foraminifera appear quite similar to thin sections made of the Miocene foraminifera *Amphistegina angulata* which was recovered from borings in Castle Harbor (Newman, 1958). Other foraminifera in the limestone are *Homotrema rubrum*, *Archaias sp.* and *Gypsina sp.* Mollusc fragments are the next most abundant constituent, followed in abundance by fragments of lithothamnoid algae. Other constituents are present as minor or accessory contributors.

In general the composition of the formation is quite similar to the present rough water sediments except for the preponderance of *Amphistegina sp.* The abundance of fragments of this foraminifera is difficult to explain unless they represent reworked fragments from *Amphistegina* sand similar to that penetrated in the Castle Harbor borings (Newman, 1959).

TABLE 4. Composition of constituent grains in the Walsingham formation.

	Wilkinson's Quarry	Crystal Cove	Gov't. Quarry	Buern's Quarry
ALGAE				
Halimeda-Preserved	0%	0%	0.3(?)%	0%
Mold	0	0	0	0
Recrystallized	0	0.2(?)	0.3	0.6(?)
Lithothamnoid algae	4.6	7.2	9.6	5.9
<u>Amphiroa</u>	0.8	0.6	0.2	0.2
FORAMINIFERA-High-Mg	11.9	17.6	12.0	13.3
Low-Mg	14.1	11.1	17.1	22.2
COELENTERATA				
Coral Preserved	0	0	0	0
Mold	0	0	0	0
Recrystallized	2.8(?)	0	0.6(?)	1.3(?)
BRYOZOA	0	0	0.2	0
ECHINODERMATA				
Echinoid Test } Spines }	1.0	1.2	0.7	0.4
MOLLUSCA-Preserved	3.9	3.3	4.4	0
Mold	0	0	0	0
Recrystallized	8.4	6.0	7.2	6.5
MISCELLANEOUS	0.1	0	0	0
UNKNOWN	11.1	1.1	11.1	11.1
VOLCANIC(?)GRAINS	0.	0.6	1.1	0
CALCITE CEMENT	40.7	44.4	35.8	36.9
POROSITY	18.2%	7.4%	6.1%	15.7%

Belmont formation

The Belmont formation can be divided into two distinct lithologies on the basis of its appearance in outcrop and its state of alteration. On St. George's Island the formation is a highly altered crystalline limestone containing conspicuous calcite veins and small caves. Abundant volcanic minerals are found (Table 5) in the limestones on St. George's Island. The Belmont limestone at Stoke's Point is perhaps the most highly altered limestone on the island. Its composition is also unique. Foraminifera are the most abundant constituent and fragments of the *Amphistegina sp.*, usually found only in the Walsingham formation, constitute almost half of the foraminifera. Mollusc fragments are the only other constituent present in any quantity and they constitute only 5% of the rock.

Samples of the Belmont limestone from the Esso Tank Farm and Whalebone Bay are similar in composition to the Recent sediments from the South Shore beaches (Table 5). Lithothamnoid algae, molluscs and foraminifera are the most abundant constituents. The sample from Whalebone Bay contains an appreciable number of recognizable reworked pebbles of the Walsingham formation and fragments of *Amphistegina sp.* from the Walsingham sediments are present among the foraminifera.

TABLE 5. Constituent composition of the Belmont formation.

		Hungry Bay	Grape Bay	Seymour's Quarry
ALGAE				
Halimeda-	Preserved	0.7%	2.4 %	2.0%
	Mold	0	0	1.4
	Cast	0	0	2.0
Lithothamnoid algae		18.1	9.3	52.8
Amphiroa		2.7	1.6	0.6
FORAMINIFERA				
	High-Mg	34.8	39.5	1.8
	Low-Mg	0	0	0
COELENTERATA				
Coral-	Preserved	14.1	0.4	1.7
	Mold	0	0	0
	Cast	0	0	2.3(?)
BRYOZOA		0	0	0
ALCYONARIAN SPICULES		0	0.2	0
ECHINODERMATA				
Echinoid		1.3	0.7	0.6
MOLLUSCA-	Preserved	16.8	2.3	3.5
	Replaced	0	0	2.6
	Cast	0	0	6.7
MISCELLANEOUS		0	0.2	0
UNKNOWN		7.3	7.8	6.1
CEMENT		0	25.6	16.1
POROSITY		56.6	6.4	30.7

TABLE 5. (continued)

	Esso Tank Farm	Whalebone Bay	Stoke's Point
ALGAE			
Halimeda-Preserved	0%	0%	0%
Mold	5.1	1.1	0
Cast	0	0	0
Lithothamnoid algae	25.1	20.2	0
Amphiroa	0.7	0	0
FORAMINIFERA			
High-Mg	8.6	8.9	2.2
Low-Mg	0	1.3	16.8
COELENTERATA			
Coral- Preserved	0	0	0
Mold	0	0	0
Cast	0.7(?)	2.1(?)	0
BRYOZOA	0	0.4	0
CRUSTACEA	0	0.2	0
ECHINODERMATA			
Echinoid - Test	0.5	0	0.4
Spines	0.5	0.7	
MOLLUSCA			
Pelecypoda-Preserved	5.3	4.7	0.4
Replaced	2.6	3.2	0
Cast	16.3	15.9	
Mold	5.3	0	4.9
Gastropoda-Preserved	0	0	0
Mold	0	0	0
Cast	0.2	0	0
MISCELLANEOUS	0	0	0
UNKNOWN	6.3	10.3	3.28
CEMENT	26.2	29.2	42.5
REWORKED WALSINGHAM LIMESTONE FRAGMENTS	2.4	1.3(?)	0
POROSITY	(9.3)	(12.8)	(6.6)

The samples of Belmont limestone taken from Hungry Bay and Grape Bay are much less altered and more poorly consolidated. These limestones are predominantly made of fragments of lithothamnoid algae, molluscs and high-Mg foraminifera. The relative amounts of these constituents vary among the various outcrops. These rocks lack the reworked grains of the Walsingham formation and the volcanic material which occurred in the Belmont formation on St. George's Island.

Devonshire formation

Only one analysis (Table 6) was made of the Devonshire formation. This sample contains molluscs, lithothamnoid algae and foraminifera, an assemblage is characteristic of the rough water environment.

TABLE 6. Constituent composition of the Devonshire formation.

		Grape Bay
ALGAE		
Halimeda-	Preserved	4.4%
	Mold	0
	Cast	0
Lithothamnoid algae		20.4
Amphiroa		0.3
FORAMINIFERA		
	High-Mg	17.7
	Low-Mg	0
COELENTERATA		
Coral-	Preserved	0
	Mold	0
	Cast	0
BRYOZOA		1.0
ECHINODERMATA		
Echinoid		0
MOLLUSCA-	Preserved	26.2
	Mold	0
	Cast	0
MISCELLANEOUS		
UNKNOWN		21.8
CEMENT		8.1
POROSITY		(17.2)

Eolianites

The eolianites show a considerable variation in composition (Table 7). In general, the same four constituents which make up most of the Recent sediments also are the dominant constituents in the eolianites. The differences in composition are mainly changes in the relative amounts of these four contributors. Foraminifera, primarily Homotrema, molluscs and algal fragments are the most abundant constituents in the eolianites which were studied.

TABLE 7. Constituent composition of the younger eolianites.

	Pembroke Eolianite St. George's	Somerset Eolianite McGill's Bay	Eolianite Rockwell Estate	Eolianite Motger Estate
ALGAE				
Halimeda				
Preserved	8.8	10.7	4.8	7.2(?)
Mold	0	0	0	0
Cast	0	0	0	0
Lithothamnoid algae	24.2	7.5	4.0	13.3
Amphiroa	2.6	0.5	0.7	0
FORAMINIFERA				
High-Mg	19.5	38.8	12.5	19.5
Low-Mg	0	0.3	0	0
COELENTERATA	0	0		
Coral				
Preserved	5.4	5.9	1.8	0
Mold	0	0	0	0
Cast	0	0	0	0
BRYOZOA	0	0	0	0
ECHINODERMATA				
Echinoid				
Test	0.6	0.8	2.6	1.8
Spines				
MOLLUSCA				
Preserved	10.9	17.9	32.8	4.9
Mold	0	0	0	0
Cast	0	0	0	11.6
MISCELLANEOUS	0	0.5	0	0
UNKNOWN	15.8	12.1	27.6	8.7
CEMENT	12.3	4.9	13.3	14.1
POROSITY	43.6	46.6	27.4	38.5

Plantagenet Bank

Cuttings from limestones on Plantagenet Bank, approximately 35 miles southeast of Bermuda, were collected during drilling operations on the bank. The boring was made in 192 feet of water and penetrated approximately 60 feet of limestones. The hole was uncased and the cuttings were removed by circulating aerated sea water. The samples were collected from cuttings which settled out in the trough that returned the aerated water to the ocean. Because of the uncased hole and the crude method of collecting samples, the cuttings collected at any given time could have come from any point in the boring down to the depth reached at that time. The age of the limestones penetrated by the boring is unknown.

Samples of the cuttings were analyzed and the data are presented in Table 8.

Samples of the cuttings collected from the boring while drilling to a depth of 44' contain fragments of lithothamnoid algae, Homotrema, molluscs, coral and Amphistegina sp., listed here in order of abundance. This assemblage is similar to the assemblage of skeletal fragments found in the rough water sediments collected from Recent beach sands along the South Shore of Bermuda. Below 44 feet the limestone is highly altered and distinctly different from the shallower samples. Lithothamnoid algae make up approximately 50% of the limestone. These algal fragments are still recognizable despite the highly altered state of the limestone. Amphistegina sp. (?) and Gypsina sp. (?) and a single individual of the Miliolidae were recognized in the cuttings. Apparently this highly altered limestone was originally a coarse, angular carbonate sediment composed largely of algal fragments.

TABLE 8. Constituent composition of composite samples from Plantagenet Bank.

		0-24'	0-44'
ALGAE			
Halimeda-	Preserved	0.9%	3.7
	Mold	0	0
Lithothamnoid algae		26.0	23.1
Amphiroa		1.2	0.3
FORAMINIFERA			
	High-Mg	14.2	17.1
	Low-Mg	4.0	4.0
COELENTERATA			
Coral-	Preserved	9.3	5.8
	Mold	0	0
	Cast	0	0
BRYOZOA		0.6	0.9
ECHINODERMATA			
Echinoid-	Test	1.6	0.3
	Spines	0.3	0.6
MOLLUSCA-	Preserved	11.1	14.7
	Mold	0	0
	Cast	0.3	0
MISCELLANEOUS		0.3	0
UNKNOWN		27.8	25.8
CRUSTACEA		0.3	0.9
ALCYONARIAN SPICULES		0.3	0.3
QUARTZ		0.6	0
VOLCANIC MATERIAL		0.9	2.5

Discussion

The examination of the thin sections of the Recent sediments and the Pleistocene limestones has shown that the majority of the constituent grains are derived from the skeletal carbonates secreted by marine organisms. Many of the grains which were included among the unknown fraction are also probably derived from skeletal carbonates of marine organisms but their petrographic features were not diagnostic of any specific organism. No evidence was found in the thin sections for the presence of oolites or for the formation of aragonite cemented beach rock on Bermuda. All of the non-skeletal carbonate in the Pleistocene limestones is present as calcite cement or as secondary calcite filling molds (see the following section and Appendix 4).

The analyses of the Recent sediments and Pleistocene limestones have shown that mollusc fragments, lithothamnoid algae, forminifera and Halimeda are the major sediment contributing organisms. The beach sands from the South Shore and the Belmont and Devonshire formations lack the abundance of Halimeda fragments which characterize the lagoonal sediments, some of the North Shore beaches and some of the "younger eolianites." The Walsingham formation was shown to be composed dominantly of foraminifera, primarily Amphistegina , which are rare or absent in the overlying Pleistocene limestones and the Recent sediments.

Despite the poor quality of the samples from Plantagenet Bank it was determined that these sediments are also derived from skeletal carbonates of marine organisms. In the poorly preserved, dolomitized portion of the section, fragments of lithothamnoid algae were found to make up a major fraction of the limestone.

The similarity in the types of constituent grains making up the post-Walsingham limestones and the Recent sediments lends support to the hypothesis advanced by Sayles (1931) and Bretz (1960) that these carbonates were originally deposited during interglacial times when sea level was near its present level.

The distinctive composition of the Walsingham formation has some important implications for the geologic history of the islands. This was briefly discussed in the Introduction and the possibility was advanced that these may be reworked Miocene foraminifera.

Conclusions

1. The Recent sediments examined are fine to medium sands composed of the skeletal fragments of marine organisms now living in the area. The sediments are generally well sorted, although poorly sorted sands were found in the lagoonal area near North Rock, in Castle Harbor and at Shelly Bay.

2. Fragments of mollusc, lithothamnoid algae, foraminifera and Halimeda are the major constituents in the Recent sediments. No evidence of marine inorganic carbonate precipitation was found on Bermuda.

3. The beach sands from the South Shore are characterized by an abundance of lithothamnoid algae, mollusc fragments, and the red, sessile foraminifera Homotrema rubrum. In general, the post-Walsingham limestones are made up of a similar assemblage of sediment contributing organisms.

4. Recent marine sediments from the lagoonal area and Castle Harbor contain an abundance of Halimeda, mollusc fragments, and the foraminifera of the genus Archaias.

5. The beach sands from the North Shore contain a mixture of constituent grains from the lagoonal and rough water sedimentary assemblages. Part of this mixed character may be caused by reworking of Pleistocene limestone fragments which cannot be distinguished from Recent carbonate skeletal fragments in the thin section.

6. The foraminifera which are the dominant constituent in the Walsingham formation are rare or absent in the overlying limestones and in the Recent sediments.

7. In general, the post-Walsingham Pleistocene limestones and Recent sediments are very similar in type and relative proportion of fragments of the sediment contributing organisms.

8. Analysis of the cuttings from operations on Plantagenet Bank showed that these sediments and limestones were composed of constituent grains derived from the same sediment contributing organisms that occur in the Recent sediments in Bermuda. <u>Amphistegina</u> is more abundant in these limestones than in the Recent sediments of Bermuda.

EFFECTS OF DIAGENETIC ALTERATION ON THE PETROGRAPHY OF THE PLEISTOCENE LIMESTONES

Approximately 80 thin sections of the Pleistocene limestones were examined and compared with 40 thin sections of the Recent sediments and more than 50 thin sections of skeletal carbonates from sediment contributing organisms. This section is intended to summarize the results of the petrographic examination of the limestones and to indicate those changes observed in the limestones which can be shown to be the result of diagenetic processes.

Preparation of the thin sections and a general evaluation of the petrographic techniques are discussed in Appendix 4.

Alteration of internal structures of constituent grains

Comparison of the constituent grains in the Pleistocene limestones with thin sections made from the skeletons of living sediment contributing organisms indicates that some alteration of the internal structures of the constituent grains has occurred. Fragments of both aragonitic and calcitic organisms appear to be affected.

Unaltered mollusc fragments are usually very lightly colored when seen in thin section and the internal structure of the fragments is visible. When viewed under crossed nicols, the fragments show the typical birefriengence of calcite or aragonite, and the layered internal structure is accentuated.

In the Pleistocene limestones and in some of the Recent sediments which appear to contain reworked Pleistocene limestone fragments, the mollusc shell fragments show progressive alteration, the final result of which is the almost complete obliteration of the internal structure. The first indication of this alteration in thin section is the change of color in the fragment to a light brownish or brownish yellow color. Under crossed nicols, the same fragments display lower bi-refringence and the internal structure is not as distinct as in the unaltered shell fragments. Further alteration causes the fragment to become a darker brown color and the structure becomes increasingly obscure. Finally the fragment appears almost brown and is essentially isotropic when viewed under crossed nicols.

It appears that no changes in mineralogy are involved in the disintegration of the original structure. Mollusc fragments showing this type of alteration are stained by Feigl solution, indicating that they are still aragonite. Also a computation of the amount of aragonite in Recent beach sands, assuming that these fragments were still aragonite, checked closely with the results obtained by X-ray diffraction methods (see Table A-3).

Similar types of structural disintegration are observed in fragments of calcitic sediment contributing organisms. The alteration of the fragments of Homotrema is especially obvious. Thin sections made from the skeletons of living foraminifera very clearly show the characteristic red color and the radial internal structure of the cell walls. In the Pleistocene limestones and some of the Recent sediments, the Homotrema fragments are a very light pink, and in thin sections the birefringence of the cell walls is much lower than in the fresh specimens. In the most altered limestones the thin (approximately 0.02 mm) inner chamber walls are very difficult to distinguish because they have altered to essentially structureless, cryptocrystalline calcite. The thicker (0.1 to 0.2 mm) outer walls of the foraminifera are less altered but the original radial structure is partially obliterated.

Structural alteration of a different type is observed in specimens of the foraminifera Amphistegina and Eponides. The original radial internal structure of these tests is accentuated by diagenetic alterations. The original crystals which make up the chamber walls recrystallize so that the boundaries between original crystal elements are eliminated and wedge-shaped crystals are formed which penetrate into the internal cavities of the test. In a few limestone samples, these wedge-shaped crystals include the prismatic cement which was originally deposited on the outside of the test. Thus portions of the test and the overlying cement now form optically continuous crystals.

The internal structure of the Archaias fragments is poorly defined in skeletons of living specimens. Diagenetic alteration does not result in any obvious changes in the internal structure.

In the Pleistocene limestones the cells of the fragments of lithothamnoid algae and Amphiroa are filled with cryptocrystalline calcite(?). In the limestones from the Walsingham formation and portions of the Belmont formation the algal fragments retain only very blurred outlines of the original cell structure. In some of these limestones, the cell structure is so poorly preserved that identification is based on the presence of the conceptacles (spore cases) which are filled with secondary calcite and thus retain their original outlines. On the other hand, algal fragments from the limestone at Seymour's Quarry display easily recognizable cell outlines. In general, the cell outlines in fragments of Amphiroa are distinguishable in the Pleistocene limestones. The process by which the cell outlines are obliterated is not known.

Removal of aragonite from the Pleistocene limestones

Removal of aragonitic skeletal carbonates (see Table 10) by solution is common in the Pleistocene limestones. The aragonite is completely removed, usually leaving a void which preserves the external form of the original fragment. In the eolianites where the grains are not completely surrounded by cement, the external form of the fragment is often preserved by a thin line of brownish carbonate (?) material. If the mold which results from the removal of the aragonite is later filled by secondary calcite, this brownish material outlines the shape of the original fragment.

Two sets of samples were collected from the working faces of active quarries to see if the solution of aragonite was controlled by distance from the ground surface. The Butterfield Quarry is located in moderately friable eolianite, and the Rockwell Estate Quarry is located in poorly consolidated eolianite.

The data (Table 9) show that there is no simple relation between the amount of solution of aragonite and the distance from the ground surface. The samples from these two quarries show that solution can occur at any level below the surface. In addition, deposition of secondary calcite as cement or as a filling for molds left by solution can occur at any depth. There appear to be no intervals in which only solution or only deposition of secondary calcite occurs.

None of the limestones showed any removal of originally calcitic fragments by solution as was observed in the aragonitic fragments.

Deposition of secondary calcite

Deposition of secondary calcite within the Pleistocene limestones is a conspicuous diagenetic change. Secondary calcite may be deposited

TABLE 9. Composition of constituent grains in eolianites.

	Rockwell Estate Quarry			Butterfield Quarry		
Depth below surface	0'	7'	17'	0'	12'	35'
CALCAREOUS ALGAE						
<u>Halimeda</u>						
Preserved	4.8%	8.4%	3.3%	9.9%	16.8%	9.0%
Mold	0	2.4	4.4	4.4	0.6	0
Cast	0	0	0	9.9	0.6	1.5
LITHOTHAMNOID ALGAE	4.0	18.9	11.1	8.4	8.7	11.5
<u>Amphiroa</u>	0.7	1.6	2.3	0	3.5	0.5
FORAMINIFERA						
High-Mg	12.5	23.0	18.1	30.7	30.1	26.0
Low-Mg	0	0	0	0	0	0
MOLLUSCA						
Preserved	32.8	15.0	19.2	9.4	22.7	12.5
Replaced	0	0	0	1.0	0	4.0
Mold	0	1.2	2.0	0.5	0	0
Cast	0	2.9	8.4	3.5	0	6.5
CORAL						
Preserved	1.8	1.2	0.7	0	0	0
Mold	0	2.8(?)	5.7(?)	1.5(?)	0	0
Cast	0	0	0	0	0	0
ALCYONARIAN SPICULES	0	1.2	0	0	0	1.0
ECHINOIDS	2.6	1.2	0.7	2.0	2.9	1.0
BRYOZOA	0	1.2	0.7	0	0	0
MISCELLANEOUS	0	0	0	0	0	0
UNKNOWN	27.6	14.9	17.8	10.9	10.4	16.5
CEMENT	12.9	4.0	5.7	6.4	1.7	10.0
PORES	27.4	36.8	39.0	42.7	39.6	33.3

in the following ways: as cement between the original carbonate grains which formed the sediment; within the internal cavities of the skeletal fragments; or within the voids resulting from the solution of aragonite from the sediment.

In all these cases the calcite crystals grow from the cavity wall into the empty space. Thus they display many of the features which Bathurst (1958) has shown to be characteristic of such conditions:

1. Preferred orientation of the longest crystal dimensions perpendicular to the original wall.
2. Increase in crystal size away from the wall.
3. Plane boundaries between crystals in the mosaic.

The mosaic of crystals which results from the filling of the molds by secondary calcite has been termed drusy mosaic by Bathurst.

Cementation

On the basis of appearance, two types of cement can be differentiated in the Pleistocene limestones:

1. Prismatic cement
2. Anhedral cement (or granular cement)

The cement in both cases appears to be calcite. This is determined by staining with Feigl's solution and comparison of the indices with the indices of the mounting medium (see Appendix 4). Calcite cement has been observed growing on aragonitic grains.

The prismatic type of cement is formed of calcite prisms arranged perpendicular to the surface on which they are growing (Fig. 9) (Appendix 6). The prisms range in size from less than 30 microns long to around 0.1 mm. In general this type of cementation does not completely fill the intergranular pores but in parts of the Walsingham formation and the lower portion of the "younger eolianites" the calcite prisms have essentially filled the pores. In these cases the individual crystals extend from the edge of the pore to the center where the crystals meet (Fig. 9) (Appendix 6). This type of cementation appears to form initially at the points of grain contact.

The Belmont and Devonshire formations often have prismatic cement which is slightly different from that described above. In these limestones, the cement often forms a uniform coating on the pore walls of very small calcite prisms, less than 100 microns long (Fig. 12) (Appendix 6). The thickness of the calcite cement does not appear to be affected by the points of grain contact.

The second type of cementation is most common in parts of the Walsingham formation and the Belmont formation on St. George's Island. In this type of cementation the pores are commonly filled with anhedral calcite crystals (Fig. 11, Appendix 6). Along the margins of the pore the small calcite prisms are oriented perpendicular to the grain wall on which they are situated. The grain size increases toward the center of the pore. In these respects, this type of cementation appears to be the same as that which Bathurst (1958) called granular cementation.

Both types of cement may be present in the same limestone.

Calcite overgrowths on echinoid fragments

Echinoid fragments in portions of the Walsingham and Belmont limestones were found to have overgrowths of optically continuous calcite. In most cases the overgrowths appear to be replacing an earlier calcite cement. In several instances, portions of the original prismatic calcite cement were still present (Fig. 10, Appendix 6). No cases were observed in which the overgrowth appeared to be replacing an original constituent grain. In all cases the original reticulate or stellate pore structure of the echinoid fragment was preserved. These original pores appear to be filled with cryptocrystalline calcite which was not recrystallized when the overgrowth formed.

Drusy mosaic

After the original shell material has been dissolved, the mold is filled by secondary calcite. The portion of the mosaic along the shell wall is formed of small crystals oriented perpendicular to the wall. The crystal size becomes larger toward the center of the cavity (Figs. 11 and 12, Appendix 6).

Among the recrystallized skeletal fragments in the Pleistocene limestones, the drusy mosaic is the most common form of alteration. In the most altered limestones approximately 75% of the recrystallized fragments display the typical drusy mosaic.

Replacement mosaic

Approximately 25% of the recrystallized skeletal fragments from the Walsingham and Belmont formations exhibit a distinctly different fabric from the drusy mosaic just described. This type of fabric is called a replacement fabric and displays the following features:

1. No change in crystal size near the margins of the mosaic
2. Few, relatively large calcite crystals with plane boundaries between crystals
3. No change in orientation of crystals near the boundary of the mosaic
4. The orientation of the crystals or ghost structures within the mosaic often preserve the gross features of the original internal layered structures of the fragment.

Figure 13 (Appendix 6) shows a case of the replacement mosaic which preserves some features of the original pelecypod shell structure. This particular fragment also shows that typical drusy mosaic has developed on the right hand corner of the fragment.

The initial stages in the development of this type of mosaic were observed in pelecypod shells in the limestones dredged from Town Cut Channel, St. George's Harbor. Figure 14 (Appendix 6) illustrates one case in which the irregular margin of the replacing calcite crystal can be seen next to the unreplaced aragonite.

It is postulated that this type of mosaic forms by essentially simultaneous solution of the original aragonite shell material and deposition of calcite. As Figure 13 (Appendix 6) illustrates, there can be a combination of this replacement mechanism and solution of the shell so that both types of mosaic may be present in the same shell fragment.

Discussion

Petrographic analyses of the Pleistocene limestones indicate that solution of aragonite and deposition of secondary calcite are important diagenetic effects. The removal of aragonite by solution provides sufficient carbonate to account for the secondary calcite which is deposited as cement or as drusy calcite to fill the solution voids. If secondary calcite is deposited in place of the original aragonite and if all the intergranular pores are filled by cement, a Recent beach sand would be changed into a limestone composed of approximately 2/3 secondary calcite.

The process leading to the replacement mosaic also has an effect on the composition of the total rock, as it removes aragonite from the limestone and replaces it with calcite. The replacement process seems to affect only a small percentage of the mollusc fragments in the samples studied.

The process of structural alteration which occurs in the skeletal carbonates does not appear to have any effect on the mineralogy of these fragments. However, this disintegration may be important as a preliminary stage in the solution of aragonitic skeletal fragments.

The quarry analyses show that removal of aragonite and deposition of secondary calcite can take place throughout the vertical interval which has been sampled.

Conclusions

1. Removal of aragonite, apparently by solution, is common in the diagenetic alteration of the Pleistocene limestones in Bermuda. There is no evidence that originally calcitic constituent grains are removed from the limestones.

2. Alteration of the original internal structure is observed in both aragonitic and calcitic constituent grains.

3. Deposition of secondary calcite in the Pleistocene limestones as cement, filling molds left by the removal of aragonite, and as echinoid overgrowths appears to be an important diagenetic process.

4. Aragonite may be removed from the constituent grains by a replacement process resulting in a mosaic which preserves some of the original shell structure.

MINERALOGY AND Sr AND Mg CONTENT OF THE SEDIMENT CONTRIBUTING ORGANISMS, RECENT SEDIMENTS AND PLEISTOCENE LIMESTONES IN BERMUDA

Introduction

The mineralogy and Sr and Mg content of the skeletal carbonate from Recent sediment contributing organisms is discussed and compared with the data on the mineralogy and Sr and Mg content of the Recent sediments. The mineralogy and Sr and Mg content of the Pleistocene limestones is compared with the data for the Recent sediments to show how much effect diagenesis has had in changing the original composition.

As can be seen from Table 10, most of the organisms secrete either calcite or aragonite. Only molluscs secrete both. From the thin section analyses (see Appendix 4) it is possible to calculate how much calcite or aragonite is contributed to the sediments by any organism. Using this technique it can be shown that *Halimeda* and molluscs are the major aragonite contributing organisms. The calcite in the Recent sediments is derived primarily from lithothamnoid algae and benthonic foraminifera.

To determine the amount of calcite and aragonite which the

TABLE 10. Mineralogy of the skeletal carbonates of the sediment contributing organisms in Bermuda.

	Calcite	Aragonite
Calcareous marine algae		
***Halimeda		X
***Lithothamnoid algae	X	
Amphiroa	X	
***Benthonic foraminifera	X	
Coelenterata		
Alcyonarian spicules	X	
*Scleractinian corals		X
Bryozoa	X	
Echinodermata		
Echinoids	X	
***Mollusca	X	X
Arthropoda		
Decapoda	X	(Phosphate)

***	Major sediment contributors (normally constitute more than 10% of the sediment)
**	Minor sediment contributors (normally constitute 3-10% of the sediment)
*	Accessory sediment contributors (normally constitute less than 3% of the sediment)

molluscs contribute to the Recent sediments, recognizable pelecypod and gastropod fragments were separated from the coarse fraction (>2 mm) of beach sands from Coral Beach, Shelly Bay and Mangrove Bay. These composite samples were analyzed by X-ray diffraction (see Appendix 2) to determine their aragonite content. It was assumed that these samples were representative of the carbonate contributed to the Recent sediments by the molluscs. The results of these analyses are as follows:

	Weight % calcite	
Locality	Pelecypods	Gastropods
Coral Beach	13%	12%
Mangrove Bay	2%	4%
Shelly Bay	3%	1%
Average	6%	6%

From these data it can be seen that pelecypods and gastropods contribute similar amounts of aragonite and calcite, so that no error is introduced by grouping them together as molluscs. The data also show that the molluscs are not a major contributor of calcite to the Recent sediments in Bermuda.

$MgCO_3$ and $SrCO_3$ content of carbonates from sediment contributing organisms

$MgCO_3$ is present in solid solution in the calcite derived from sediment contributing organisms in Bermuda. Figure 15 indicates that

Table 11

MgCO$_3$ Content of Calcite from Sediment Contributors in Bermuda (determined by X-ray diffraction)

	MgCO$_3$ (mol %) Avg.	Range
Calcareous marine algae		
Lithothamnoid algae		
"Boiler rock," Bermuda	$15._4$	$14._9$-$15._8$
Lithothamnoid nodule		
Challanger Bank	$14._6$	
Goniolithon sp. (Ellis Flats)	$16._7$	$16._3$-$17._3$
Amphiroa sp.		
Admiralty House	$15._5$	
Lagoonal area (Nr-3)	$15._9$	
Foraminifera		
Homotrema rubrum		
Lagoonal area (R-14)	$12._5$	$12._3$-$12._7$
South Shore beach sands	$11._3$	$11._0$-$11._4$
Archaias compressus (NR-13)	$12._8$	
Archaias angulatus (NR-13)	$13._8$	$13._5$-$14._7$
Triloculina sp. (NR-13)	$11._8$	$11._6$-$11._9$
Quinqueloculina sp. (NR-13)	$13._3$	
Valvulina sp. (NR-13)	$11._3$	
Amphistegina lessonii (NR-13)	$2._5$	$2._4$- $2._7$
Eponides repanda (R-13)	$11._9$	
Gypsina sp. (R-13)	$11._7$	
Mollusca		
Pelecypoda		
Ostrea frons		
Shelly Bay	<0.6	
Harrington Sound	<0.6	
Pinctada radiata		
Mullet Bay	$1._7$	
Pecten ziczac		
Great Bay	<0.7	

Table 11 (continued)

		Mg CO$_3$ Avg.	(mol %) Range
Fragments from sediments			
Coral Beach		$2._1$	
Shelly Bay		$2._1$	
Gastropoda			
Littorina ziczac			
Harrington Sound		$1._7$	
Fragments from sediments			
Coral Beach		$<0._7$	
Shelly Bay		$<0._7$	
Mangrove Bay		$1._0$	
Bryozoa			
	R-13	$9._5$	$9._3$-$9._8$
Echinoidea			
Spines	R-13	$6._1$	
	NR-3	$6._5$	$5._4$-$7._4$
Tests			
	Coopers Island	$16._0$	
Crustacea			
Decapoda			
Claw fragment		$13._9$	
Carapace fragment		$14._7$	
	Castle Harbor		
Claw fragment		$11._7$	
	Lagoon		

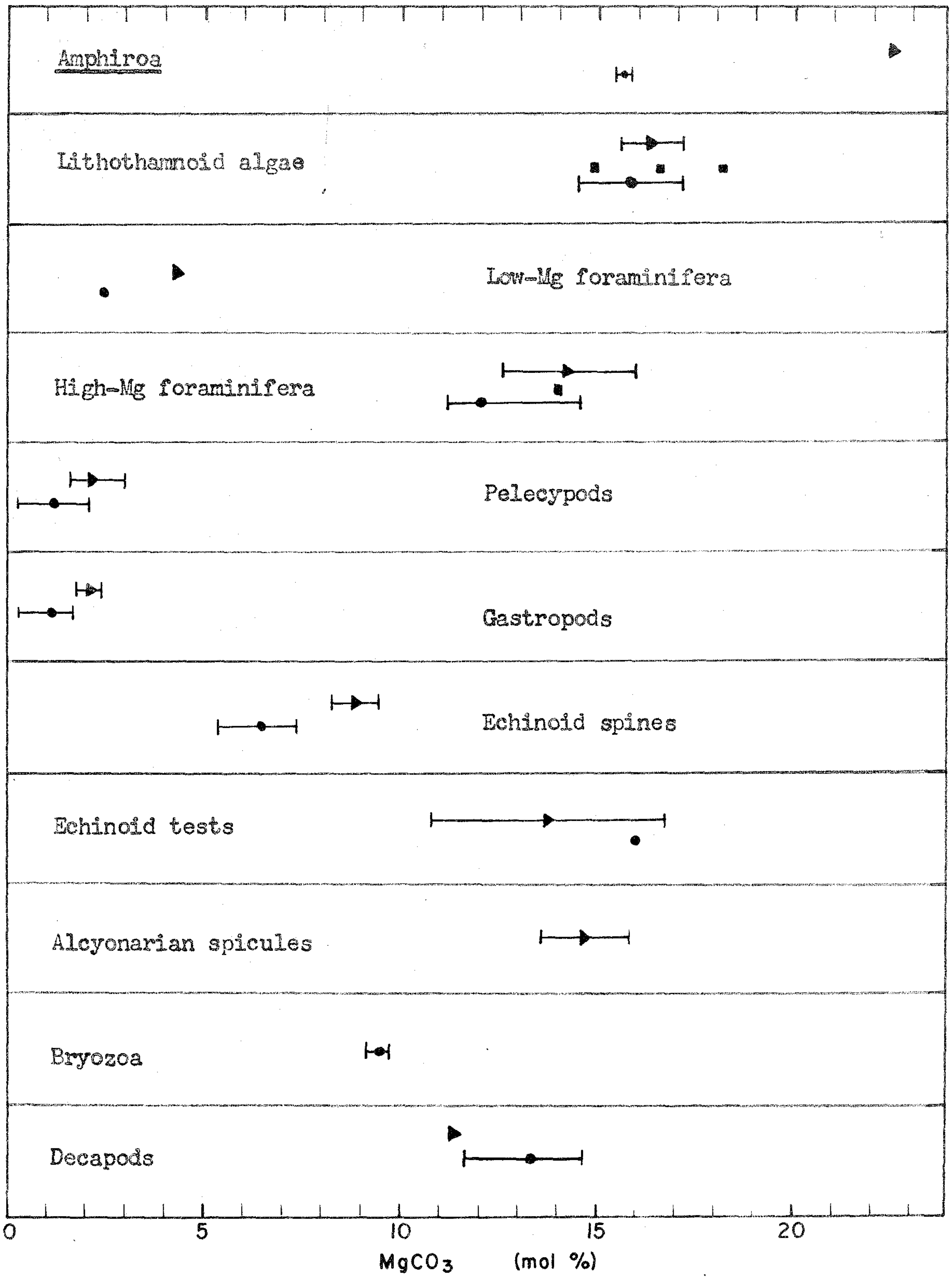


Figure 15. $MgCO_3$ content of calcites from sediment contributing organisms. (▲ Chave, 1954a; ■ Goldsmith et al, 1955; ● Present study)

TABLE 12. $SrCO_3$ and $MgCO_3$ of the skeletal carbonates of sedimentary contributing organisms (Analyst E.G.)

	$MgCO_3$ (mol %)	$SrCO_3$ (mol %)
Foraminifera		
Amphistegina lessonii		
EB-3	3.7	0.2_0
NR-13	4.5	0.2_5
Archaias angulatus		
NR-13	12.9	0.2_5
A. compressus		
NR-13	14.5	0.2_4
Calcareous marine algae		
Halimeda sp. Shelly Bay	1.0	1.0_9
Halimeda sp. Shelly Bay	0.8	1.1_5
Lithothamnoid algae West Reef	17.6	0.3_0
Lithothamnoid algal nodule Whalebone Bay	12.8	0.3_2

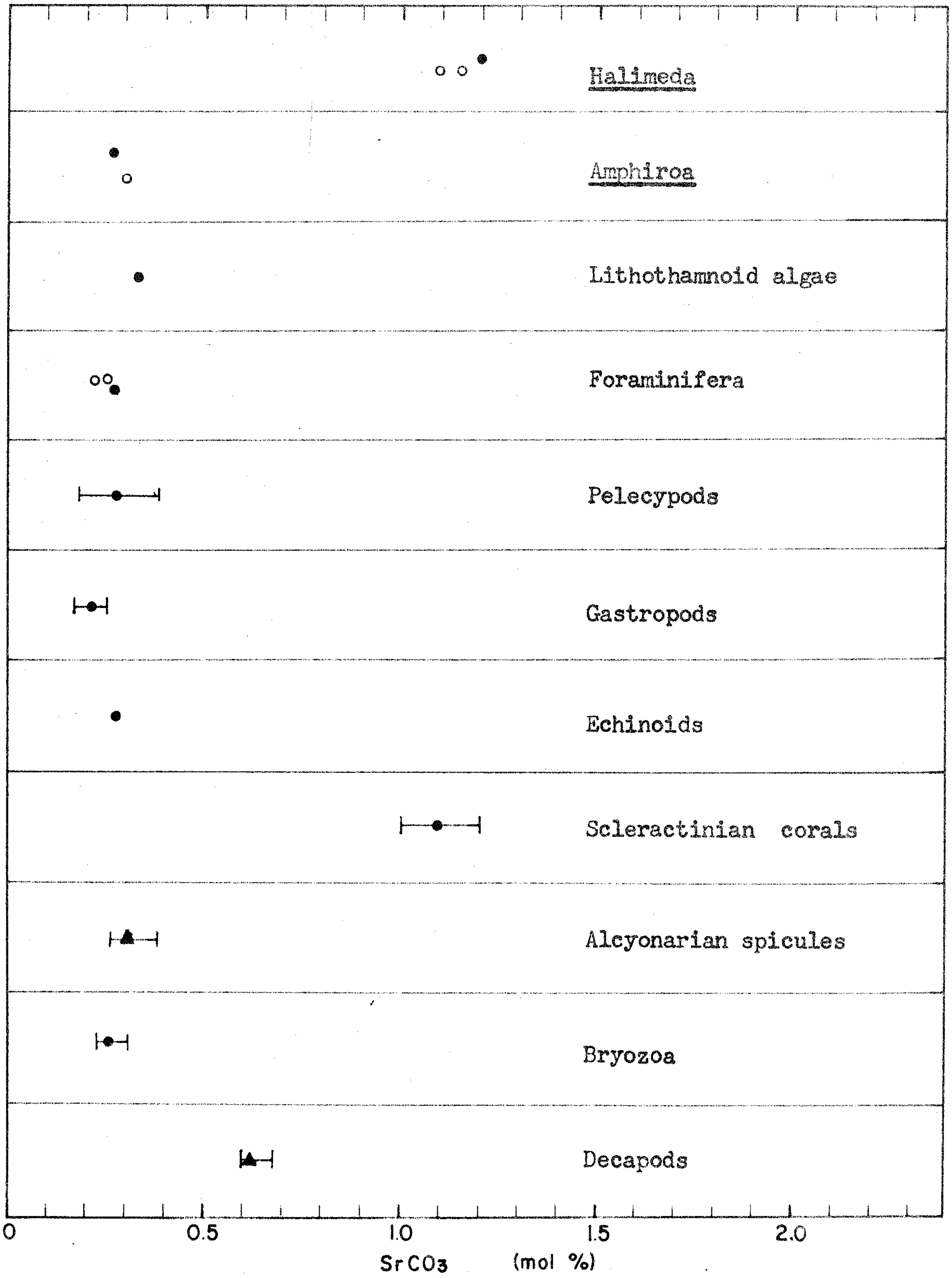


Figure 16. $SrCO_3$ content of carbonate skeletons of sediment contributing organisms in Bermuda. (▲ Thompson and Chow, 1955; ● Lowenstam, 1961; ○ Present study).

the major contributors of calcite in Bermuda (lithothamnoid algae and foraminifera) contain between 10 and 17 mole % $MgCO_3$ in solid solution. Calcite containing less than 4 mol % $MgCO_3$ in solid solution is found in fragments from molluscs and Amphistegina (the low-Mg foraminifera). Calcites containing between 5 and 10 mol % $MgCO_3$ are found only in echinoid spines and bryozoa, neither of which is a significant contributor to the sediments. Therefore, the calcite in the Recent sediments which is derived from the sediment contributing organisms should contain two Mg-calcite phases, a large amount of a high-Mg calcite (more than 10 mol % $MgCO_3$) and a small amount of low-Mg calcite (less than 5 mol % $MgCO_3$).

Small amounts of Mg are found in aragonite secreted by Halimeda and the molluscs (Clarke and Wheeler, 1922; Chave, 1954a). In all cases these contain less than 1 mol % $MgCO_3$ so that they do not contribute a major amount of Mg to the sediments. No analyses of the $MgCO_3$ content of aragonitic materials were made in this study.

There is significant variation in the Sr content of aragonites (see Fig. 16) secreted by various organisms (Thompson and Chow, 1955; Odum, 1957; Lowenstam, 1961). Pelecypods and gastropods secrete aragonite containing less than 0.4 mol % $SrCO_3$ in solid solution (Thompson and Chow, 1955; Odum, 1957; Lowenstam, 1961). Aragonite secreted by scleractinian corals and Halimeda contains around 1.0 to

1.2 mol % $SrCO_3$ in solid solution. Although Sr is preferentially accommodated in the aragonite lattice, organic calcites do contain $SrCO_3$. Figure 16 shows that calcite from sediment contributing organisms contains 0.4 mol % $SrCO_3$ or less.

Amount and $MgCO_3$ content of calcite in the Recent sediments

Selected samples of Recent sediments were analyzed by X-ray diffraction techniques (see Appendix 2) to determine the amount and $MgCO_3$ content of the calcite. These data (Table 13) are shown diagrammatically in Figures 17 and 18. The amount of calcite is indicated by the figure at the bottom of each block. For example, the dune sand from Elbow Bay contains 53 wt % calcite while the beach sand from Shelly Bay contains 30 wt % calcite. The $MgCO_3$ content of the calcite is shown by the height of the block; for example, the sediment from GNR-15 contains calcite which has an apparent $MgCO_3$ content of between 13 and 14 mol % $MgCO_3$. Where the blocks have a step, this indicates that calcites with different $MgCO_3$ contents are found in the sediment. The amount of each type of calcite is indicated by the width of the step. Thus, the dune sand from Elbow Bay contains calcite of which approximately 70% contains 13.9 mol % $MgCO_3$ in solid solution and 30% contains 3 mol % $MgCO_3$. Similarly the Devonshire Bay beach sand contains calcite of which 10% has 13.8 mol % $MgCO_3$ in solid solution and 90% contains 2.9 mol % $MgCO_3$ in solid solution.

TABLE 13. Amount and $MgCO_3$ content of calcite in Recent sediments.

	Calcite (wt %)	$MgCO_3$ (mol %)	Amount of each calcite phase
Elbow Bay dune sand	53%	13.9	(70%)
		3.0	(30%)
Tucker's Town dune sand	65%	13.9	(90%)
		4.0	(10%)
Warwick Long Bay beach sand	65%	13.9	(85%)
		3.5	(15%)
Devonshire Bay beach sand	55%	13.9	(10%)
		2.9	(90%)
John Smith's Bay beach sand	65%	14.6	(90%)
		4.7	(10%)
Mangrove Bay beach sand	50%	12.0	(40%)
		3.0	(60%)
Shelly Bay beach sand	30%	16.3	(70%)
		6.7	(30%)
Whalebone Bay beach sand	60%	12.6	(40%)
		1.6	(60%)
Ft. St. Catherine beach sand	40%	12.9	(70%)
		3.0	(30%)
Clarence Cove beach sand	45%	14.5	(15%)
		3.2	(85%)
GNR-11 (between North Rock and Three Hill Shoal)			
<2 mm, > 1 mm fraction	30%	14.2	(90%)
		3.4	(10%)
< 60 microns fraction	60%	13.6	(90%)
		3.2	(10%)
GNR-15 (outside the reef north of North Rock)			
<2 mm, > 1 mm fraction	60%	13.8	
< 60 microns fraction	70%	13.2	

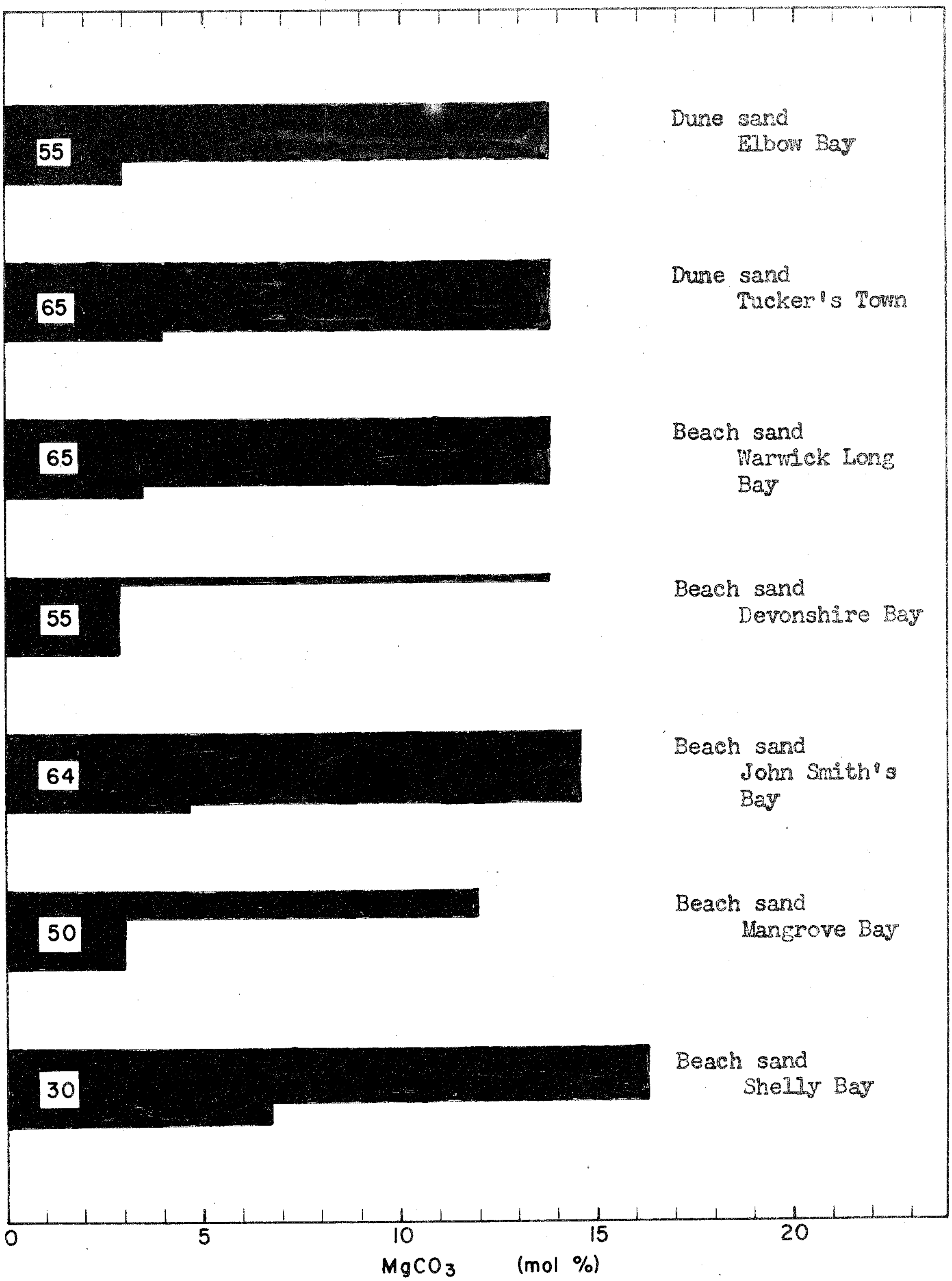


Figure 17. Amount and $MgCO_3$ content of calcite in Recent sediments in the Bermuda Islands.

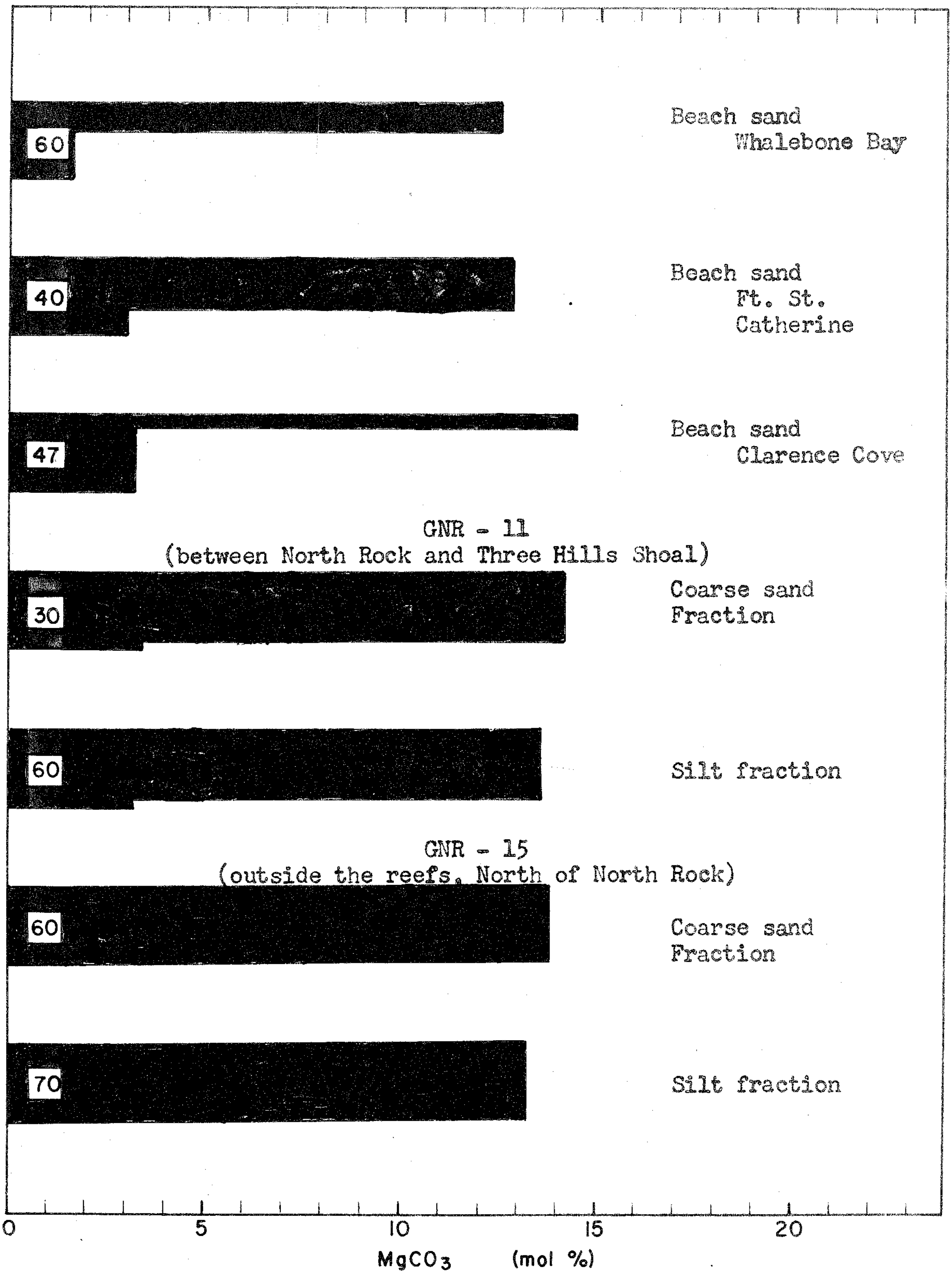


Figure 18. Amount and $MgCO_3$ content of calcite in Recent sediments in the Bermuda Islands.

Discussion

If the Recent sediments consisted entirely of skeletal fragments of organisms now living in Bermuda, the calcite in the sediments would contain approximately 15 mol % of $MgCO_3$. The sediments from the vicinity of North Rock do contain calcites of this composition. Beach sands from John's Smith Bay and Warwick Long Bay approach this composition but they appear to be the exception rather than the rule. Sediments which contain substantial amounts of calcites with $MgCO_3$ contents of less than 5 mol % $MgCO_3$ (Clarence Cove, Shelly Bay, Mangrove Bay, Whalebone Bay) are in locations where there is an appreciable amount of reworking of the Pleistocene limestones. Also the thin section analyses of these sediments indicate that limestone fragments are incorporated in the sediments. As previously shown, there are no major sediment contributors which would account for this large amount of calcite containing an intermediate or low $MgCO_3$ content.

The most likely source for this low-Mg calcite phase is the Pleistocene limestones. The marine sediments from the Three Hills Shoal and north of North Rock, which are least likely to contain large amounts of reworked Pleistocene limestones, also contain little or none of the low-Mg calcite phase. In the following section it will be shown that the $MgCO_3$ content of the low-Mg calcite phase is similar to the $MgCO_3$ content of the calcites in many of the Pleistocene limestones.

The $MgCO_3$ content of the calcite in the silt sized fraction of the Recent sediments from the North Rock - Three Hills Shoal area is essentially the same as the calcite in the coarse sand sized fraction of these sediments. By examination of thin sections, the coarse sand sized fraction can be shown to be derived from the major sediment contributing organisms. The similarity of their $MgCO_3$ contents suggests that the silt sized material is also derived from fragmentation of these same organisms, rather than from the erosion of the Pleistocene limestones as suggested by Agassiz (1895) and Bigelow (1905).

$SrCO_3$ and $MgCO_3$ content of bulk samples of Recent sediments

$SrCO_3$ and $MgCO_3$ concentrations in representative bulk samples of selected Recent sediments were determined by emission spectrographic analyses (see Appendix 3). The sediments were selected to provide a sample of major sedimentary environments on the Bermuda Banks and to indicate the range in Mg and Sr concentrations which occur in the Recent sediments. The data are presented in Table 4.

$SrCO_3$ contents of the Recent sediments vary from 0.3 to 0.7 mol %, and most sediments contain between 0.5 and 0.6 mol % $SrCO_3$. The highest $SrCO_3$ contents occur in sediments containing large amounts of aragonite. Mixtures of aragonite from corals or Halimeda, both of which contain from 1.0 to 1.2 mol % $SrCO_3$, and calcites, which contain 0.2 to 0.3 mol % $SrCO_3$, would be expected to give the range of

TABLE 14. $MgCO_3$ and $SrCO_3$ concentrations in Recent sediments.

	$MgCO_3$ (mol %)	$SrCO_3$ (mol %)	Analyst
GNR-11 between Three Hills Shoals and North Rock			
Fraction <2 mm>1 mm	3.1_0	0.6_0	EG
Fraction <60 microns	6.1_0	0.5_5	EG
GNR-15 north of North Rock			
Fraction <2 mm >1 mm	8.1_0	0.6_0	EG
Fraction < 60 microns	7.2_0	0.5_5	EG
Beach sands			
Shelly Bay	4.1	0.7_0	MGG
Elbow Bay	6.9	0.3_0	MGG
John Smith's Bay	8.7	0.6_0	EG
Warwick Long Bay	7.4	0.5_4	EG
Clarence Cove	2.3	0.6_7	EG
Ft. St. Catherine	5.0	0.5_1	EG

$SrCO_3$ contents observed.

The $MgCO_3$ concentrations of the Recent sediments vary from 2.3 to 8.7 mol %. Most of the sediments contain more than 5 mol % $MgCO_3$. Analyses of bulk samples do not permit a distinction to be made between dilution of the Mg content by aragonite or low-Mg calcite, and depletion of Mg from the constituent grains without any dilution. For example, the samples from Shelly Bay and the coarse fraction from GNR-11 contain less than 5 mol % $MgCO_3$, because the sediments in each case contain approximately 70% aragonite. The sample from Clarence Cove, which has the lowest $MgCO_3$ content (2.3 mol %), contains only 50% aragonite but most of the calcite has a low $MgCO_3$ content (Figure 18).

Conclusions

1. *Halimeda* and molluscs are the major contributors of aragonite to the Recent sediments. Lithothamnoid algae and benthonic foraminifera are the major sources of calcite. The Recent sediments contain from 30 to 70% aragonite, and the remainder of the sediment is calcite.

2. With the exception of the small amount of low-Mg calcite contributed by the molluscs, the calcite from the sediment contributing organisms contains 11 to 17 mol % $MgCO_3$. The skeletal fragments of

calcitic organisms and the molluscs contain 0.2 to 0.4 mol % $SrCO_3$. Only Halimeda and scleractinian coral fragments contain more than 1 mol % $SrCO_3$.

3. The calcite in the sediments consists of a mixture of high-Mg calcite (more than 10 mol % $MgCO_3$) and low-Mg calcite (less than 4 mol % $MgCO_3$). The amount of low-Mg calcite is highest in the beach sands which contain the greatest amount of eroded Pleistocene limestone fragments. Low-Mg calcite is missing in the North Rock sediment. This may be caused by the reef which shields the depositional site from most of the Pleistocene limestone fragments.

4. Silt-sized carbonates from the lagoonal sediments in the vicinity of North Rock appear to be derived from the same type of organic calcite which makes up the coarse-sand fraction. It appears that little of the silt-sized material in this part of the lagoon comes from the erosion of the Pleistocene limestones.

5. $SrCO_3$ contents of the Recent sediments range from 0.3 to 0.7 mol %. The highest Sr contents are found in the sediments containing the greatest amount of Halimeda fragments.

6. The $MgCO_3$ contents vary from 2.3 to 8.7 mol % $MgCO_3$. The low $MgCO_3$ contents result from an abundance of aragonite in the sediment or the reworking of low-Mg calcite, the latter presumably derived from the Pleistocene limestones.

MINERALOGY AND $SrCO_3$ AND $MgCO_3$ CONTENT OF THE PLEISTOCENE LIMESTONES

The data for the Recent sediments have shown that the aragonite content and the $SrCO_3$ and $MgCO_3$ contents of the sediments are controlled by the composition of the constituent grains. Thus, the mineralogy and the $SrCO_3$ and $MgCO_3$ contents of the Pleistocene limestones are controlled by their original composition and by the diagenetic processes which have altered the limestones.

Epstein and Lowenstam (1953) have shown that the ocean temperatures in Bermuda during interglacial times were essentially the same as they are today. It is thought that the "younger eolianites" as well as the interglacial marine deposits were formed from skeletal fragments of organisms which lived on the banks during interglacial times (Sayles, 1931; Bretz, 1960).

The organisms whose carbonate skeletons now form the Pleistocene limestones grew at temperatures similar to today, and probably in sea water of the same chemistry as the present ocean. Therefore, the skeletal carbonates from these organisms probably contained $SrCO_3$ and $MgCO_3$ contents which were similar to the organisms now living in the area. Thus, the original $SrCO_3$ and $MgCO_3$ content of the Pleistocene limestones was probably similar to the Recent sediments.

Consequently, a comparison of the mineralogy and $MgCO_3$ and $SrCO_3$ contents of the Pleistocene limestones and the Recent sediments should indicate the changes caused by diagenesis.

Amount and $MgCO_3$ content of calcite in the Pleistocene limestones

Samples of the Pleistocene limestones were collected from outcrops from different parts of the islands (Fig. 8). In collecting the samples an effort was made to include different lithologies and the various states of consolidation which are found in the Pleistocene formations. X-ray diffraction techniques (Appendix 2) were used for all the analyses and the data are summarized by formation in Table 15.

The diagrams showing the amount and composition of the calcites are the same as the diagrams used in the discussion of the Recent sediments. The amount of calcite in the total sediment is indicated by the number given at the bottom of the block. The amount of $MgCO_3$ contained in the calcites is indicated by the height of the bar, and the relative amount of each calcite phase is indicated by the thickness of the bar.

Discussion

Samples from the Walsingham formation, the Belmont formation on St. George's Island and the uncorrelated marine limestones contain calcites whose $MgCO_3$ content is between 0.6 mol % and 2.6 mol %. The

TABLE 15. Amount and MgCO$_3$ content of calcites in the Pleistocene limestones.

	Calcite (wt %)	MgCO$_3$ (mol %)	Amount of each calcite phase in mixture
Walsingham limestone			
Government Quarry			
Be 19 (well consolidated)	100%	1.2	
Wilkinson Quarry WQ-1B (well consolidated)	100%	<0.6	
Crystal Cove Be-1 (well consolidated)	100%	2.6	
Belmont limestone			
Stoke's Point Be 17 (well consolidated)	100%	1.0	
Esso Tank Farm, Ferry Reach Road			
Be 16 (well consolidated)	100%	2.2	
ETF-20 (well consolidated)	100%	2.1	
Hungry Bay			
HB-13 (unconsolidated)	60%	13.3	(70%)
		3.5	(30%)
HB-12 (poorly consolidated)	60%	13.3	(65%)
		3.0	(35%)
HB-10 (poorly consolidated)	50%	13.3	(75%)
		3.3	(25%)
Cable Bay			
CB-1 (poorly consolidated)			
(fresh surface)	65%	10.5	(25%)
		8.6	(75%)
(weathered surface)	75%	11.2	(20%)
		2.3	(80%)
Grape Bay			
Be-7 (well consolidated)	60%	14.0	(75%)
		3.5	(25%)

TABLE 15. (continued)

	Calcite (wt %)	MgCO$_3$ (mol %)	Amount of each calcite phase in mixture
Devonshire limestone			
Grape Bay			
GB-1 (poorly consolidated)	65%	13.5	(75%)
		4.0	(25%)
GB-2 (unconsolidated)	60%	14.3	(75%)
		3.5	(25%)
Marine limestones, unknown correlation			
Marine limestone			
Government Quarry	80%	3.1	
GQ-53(well consolidated)			
Marine limestone			
Seymour's Quarry	95%	2.0	
SQ-1 (well consolidated)			
Marine limestone			
Shell Tank Farm Be-3			
Ferry Reach Road	80%	1.7	
(well consolidated)			
Younger eolianites			
Pembroke eolianite			
McGall's Bay	55%	12.6	(50%)
MG-7 (fresh surface)		2.0	(50%)
St. George's	60%	12.2	(35%)
SG-7 (fresh surface)		1.6	(65%)
Warwick eolianite			
St. George's			
SG-1 (fresh surface)	55%	11.9	(30%)
		2.3	(70%)
Be-11 (weathered surface)	35%	3.5	
Somerset eolianite			
McGall's Bay			
MG-5a (fresh surface)	50%	11.9	(25%)
		2.7	(75%)
Mg-5b (weathered surface)	40%	3.0	
St. George's			
SG-4 (weathered surface)	65%	2.3	

TABLE 15. (continued)

	Calcite (wt %)	$MgCO_3$ (mol %)	Amount of each calcite phase in mixture
Rockwell Estate Quarry			
(fresh surfaces)			
0 feet below ground surface	65%	12.3 2.3	(15%) (85%)
1 " " " "	75%	2.3	
5 " " " "	75%	2.0	
7 " " " "	80%	2.3	
10 " " " "	65%	12.3 3.3	(10%) (90%)
13 " " " "	70%	3.5	
17 " " " "	90%	2.4	
Butterfield Quarry			
(fresh surfaces)			
0 feet below ground surface	90%	3.0	
3 " " " "	80%	2.6	
9 " " " "	85%	3.3	
12 " " " "	65%	3.3	
20 " " " "	80%	2.3	
25 " " " "	85%	3.0	
30 " " " "	75%	3.8	
35 " " " "	90%	1.6	

X-ray diffraction patterns from these samples indicated the presence of only one Mg-calcite phase.

No aragonite was detected in the samples from the Walsingham formation or the Belmont formation on St. George's Island. The samples from the uncorrelated marine units were found to contain between 5 and 20% aragonite. Examinations of the thin sections of the marine limestones showed that all of them contained constituent grains of organisms which now contribute high-Mg calcite to the Recent sediments. For example the sample from Seymour's Quarry (SQ-1) is composed dominantly of fragments of lithothamnoid algae. As discussed previously, these algal fragments were deposited during interglacial periods and most likely contained more than 10 mol % $MgCO_3$ in solid solution when deposited. Therefore it can be concluded that the calcites in these limestones have been greatly depleted in $MgCO_3$, whereas the aragonitic grains are present in these limestones.

No dolomite or other Mg-containing carbonate phase was found in samples of the most altered portions of the Walsingham and Belmont formations.

The analyses of samples of the Devonshire formation and the Belmont formation outcrops along the South Shore indicated that two Mg-calcite phases are present in these limestones. Between 20 and 80% of the calcite in these rocks contains from 2.3 to 3.2 mol % $MgCO_3$

in solid solution. The remainder of the calcite in the limestones contains between 10.5 and 14.0 mol % $MgCO_3$ in solid solution. The amount and $MgCO_3$ content of these two calcite phases are similar to those found in the Recent beach sands. Variations in the degree of consolidation of these limestones appear to have little effect on the amount of calcite in the limestones or the amount of $MgCO_3$ retained in the calcite.

Aragonite was detected in the samples from the Devonshire and the Belmont formations from the South Shore. The amount of aragonite in these limestones varies between 25 and 50%.

X-ray diffraction analyses were made of fresh and weathered samples of "younger eolianites" from McGall's Bay and St. George's (Fig. 19). In both of these areas, Sayles (1931) recognized a complete sequence of the post-Walsingham eolianites (Table 1). The terminology of Sayles has been used to indicate the superposition of the formations (<u>i.e.</u>, Pembroke eolianite is the oldest and Somerset eolianite is the youngest) but no time equivalence between the two sections is implied by the use of this terminology.

The fresh samples from these eolianites contain 50 to 60% of calcite, which consists of two Mg-calcite phases. The high-Mg calcite in these limestones contains between 11.8 and 12.6 mol % $MgCO_3$. The low-Mg calcite phase contains 1.6 to 2.5 mol % $MgCO_3$.

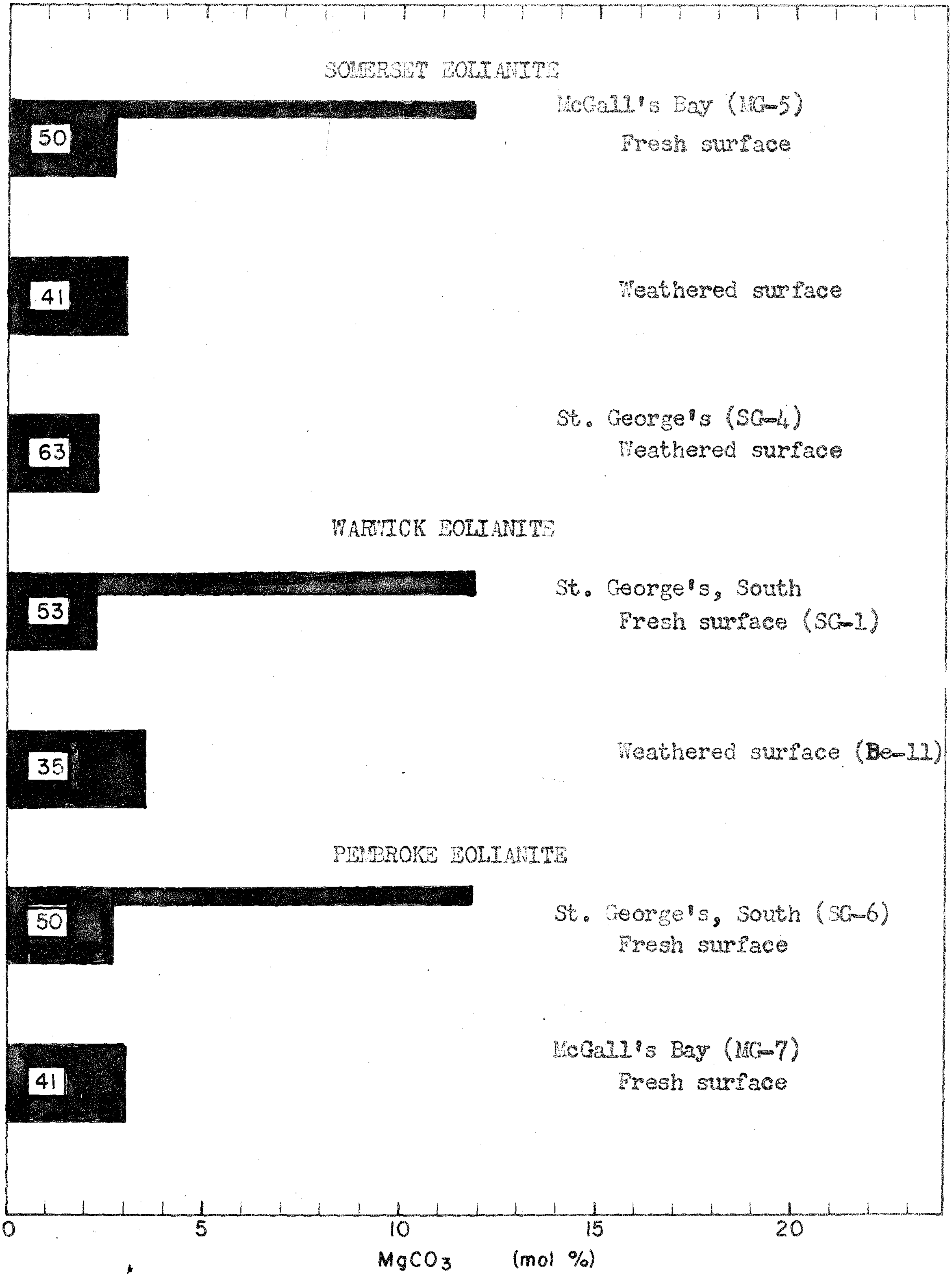


Figure 19. Amount and $MgCO_3$ content of calcite in the "younger eolianites".

Samples from the weathered outcrop surface of the Warwick and Somerset eolianite consist of 35 to 65% calcite, which contains between 3.6 and 3.0 mol % $MgCO_3$. None of these weathered outcrop samples displays the two phase composition of the calcite which is found in all of the fresh samples.

Each of these eolianite sections contains interbedded paleosols (Sayles, 1931, pp. 397, 406), which indicates that the deposition of the formations was separated by time intervals of unknown length. The data (Fig. 19) suggest that the time involved in the deposition and post-depositional history is not as important in determining the $MgCO_3$ content of the calcites as is the relationship of the sample to local alteration caused by weathering on the outcrop surface.

The "younger eolianites" taken from the working faces of the Butterfield Quarry and the Rockwell Estate Quarry (see Figs. 20 and 21) were found to contain from 65 to 90% calcite. With the exception of two samples from the Rockwell Estate Quarry (RWEQ-0, 10) these calcites consisted of a low-Mg calcite phase containing between 3.8 and 1.6 mol % $MgCO_3$ in solid solution. Samples from the ground surface and 10 feet below the ground surface in the Rockwell Estate Quarry contain calcites of which 10 to 15% have $MgCO_3$ contents of 12.3 mol %. The lowest $MgCO_3$ content in the calcites (1.6 mol % $MgCO_3$) from these quarry samples occurs in the sample taken from 35 feet below

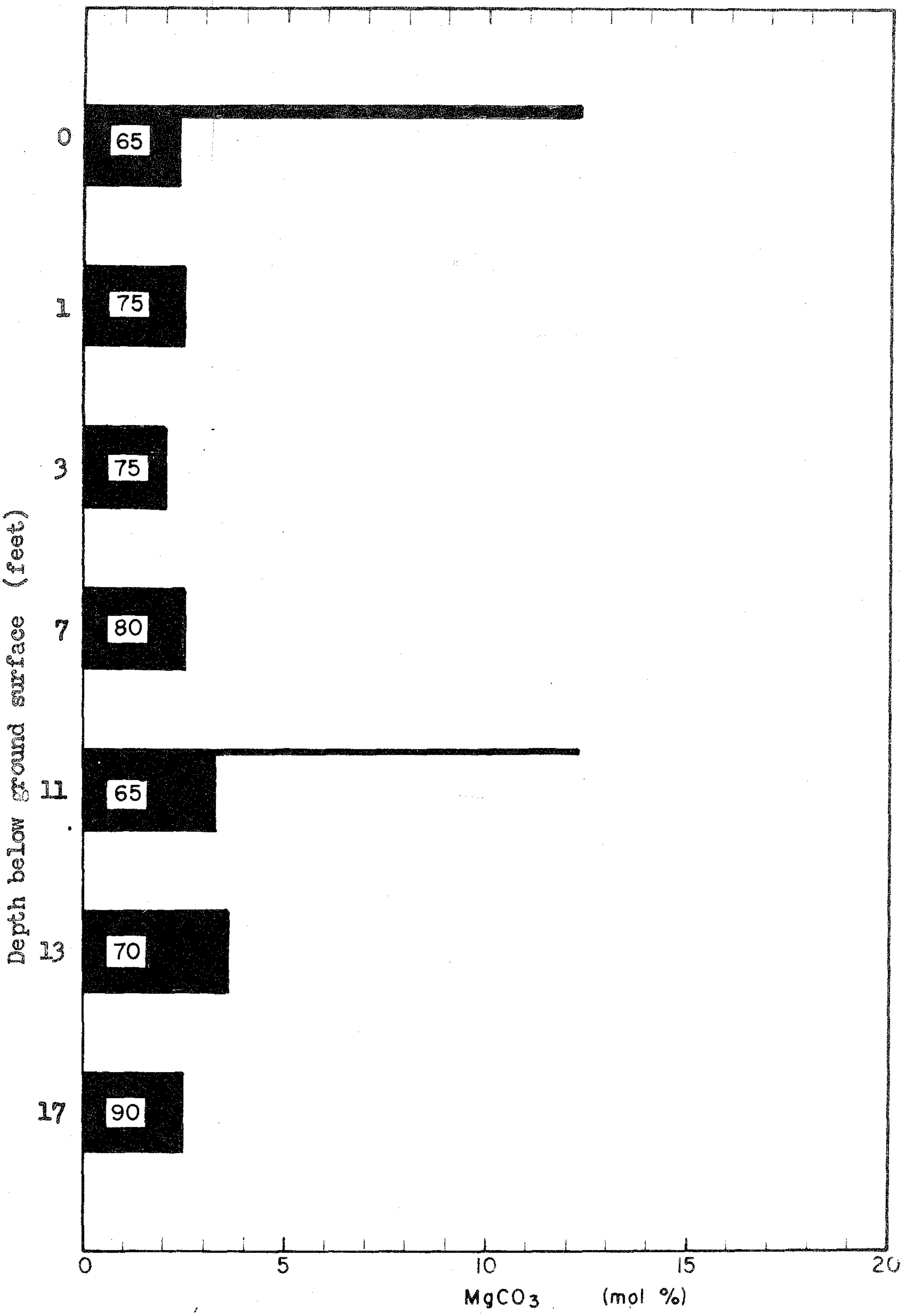


Figure 20. Amount and $MgCO_3$ content of calcite in eolianites from the Rockwell Estate Quarry.

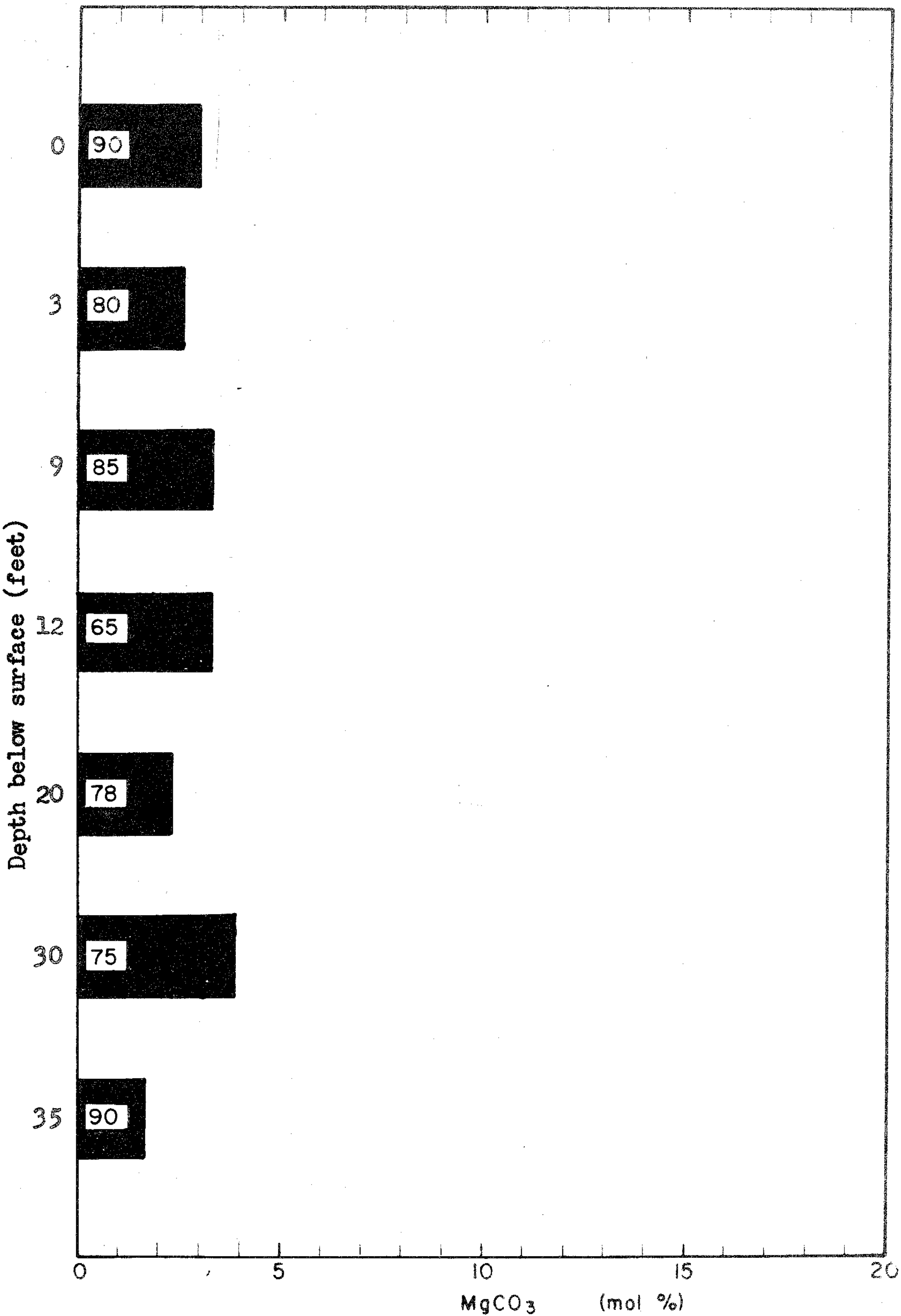


Figure 21. Amount and MgCO$_3$ content of calcite in eolianites from the Butterfield Quarry.

the ground surface. The data do not indicate any systematic trends in the calcite content of the total rock samples with increasing depth in the quarry.

It has been shown by analysis of the thin sections of the Pleistocene limestones that all of the post-Walsingham Pleistocene limestones contain fragments of organisms which precipitate high-Mg calcites. Therefore the absence of a high-Mg calcite phase in these limestones at present indicates that Mg has been depleted from the originally high-Mg calcites. Since X-ray diffraction analyses of the limestones did not reveal any dolomite or other Mg-containing phase, it must be concluded that the Mg has been removed from the rocks.

TABLE 16. $SrCO_3$ and $MgCO_3$ contents of the Pleistocene limestones.

	$MgCO_3$ (mol %)	$SrCO_3$ (mol %)	Analyst
Walsingham formation			
Government Quarry (Be-1)	2.40	0.04	EG
Buern's Quarry (BQ-3)	2.10	0.004	EG
Wilkinson's Quarry (WQ-1B)	0.67	0.08	EG
Marine limestone			
Seymour's Quarry (SQ-1)	2.34	0.19	EG
Belmont formation			
Esso Tank Farm (Be-16)	2.30	0.06	EG
Esso Tank Farm (ETF-20a)	2.00	0.03	EG
Stoke's Point (Be-17)	0.82	0.04	EG
Eolianites			
Somerset eolianite (SG-4)	3.10	0.40	MGG
St. George's			
Butterfield Quarry (BFQ)			
(3' below surface)	2.30	0.20	MGG
20' below surface	3.30	0.20	MGG
35' below surface	3.30	0.15	MGG
Rockwell Estate Quarry (RWE)			
1 foot below surface	1.90	0.37	EG
7 feet below surface	2.90	0.25	EG
13 feet below surface	2.88	0.37	EG
17 feet below surface	2.60	0.26	EG

TABLE 17. $SrCO_3$ and $MgCO_3$ contents of fresh water carbonates and secondary calcites from the Pleistocene limestones.

	$MgCO_3$ (mol %)	$SrCO_3$ (mol %)	Analyst
Stalactites			
Cave, St. David's Island	2.31	0.05	EG
Crystal Cave (CC-2)	0.5	0.01	MGG
Cave, Gov't Quarry (GQ-30)	1.1	tr.	EG
Fissure filling calcite (Wilkinson's Quarry (WQ-1A)	tr.	0.02	MGG
Secondary calcites from Pleistocene limestones			
Cement			
Gov't. Quarry (GQ-56)	2.50	tr.	EG
Cement (ETF-20d)	1.20	tr.	EG
Sparry calcite filling pelecypod mold (ETF-20de)	1.70	0.02	EG
Sparry calcite lining pelecypod mold (ETF-20b)	0.70	tr.	EG
Calcite vein (GQ-3)	1.0	0.03	EG
Sparry calcite coating fissure walls (GQ-5c)	1.2	0.01	EG

tr. - trace

$SrCO_3$ and $MgCO_3$ contents of bulk samples of Pleistocene limestones, fresh water carbonates and secondary calcites

The $SrCO_3$ and $MgCO_3$ contents of bulk samples of the Pleistocene limestones were determined by emission spectrographic techniques (see Appendix 3). The samples from the Belmont and Walsingham formations are representative of the highly altered portions of these formations. The quarry samples of eolianite and the sample of the Somerset eolianite were discussed previously (see Tables 7 and 9). In addition, stalactites and samples of the cement, veins and sparry calcite cavity fillings from the Pleistocene limestones were analyzed. The data are shown in Tables 16 and 17.

Discussion

The samples from the Walsingham, Belmont and uncorrelated marine limestones contain from 2.4 to 0.8 mol % $MgCO_3$ which corresponds to the range of $MgCO_3$ contents of the stalactites and secondary calcites (2.5 to approximately 0 mol % $MgCO_3$). Examination of thin sections of these limestones shows that they contain constituent grains whose original $MgCO_3$ content was probably equivalent to similar fragments in the Recent sediments. Thus the similarity of $MgCO_3$ contents in limestones and the stalactites and fresh water carbonates is due to diagenetic alteration rather than original composition. As discussed previously the original $MgCO_3$ content of the Walsingham limestone is not known.

The eolianite samples from the Rockwell Estate and the Butterfield Quarry contain from 3.3 to 1.9 mol % $MgCO_3$. These $MgCO_3$ contents are slightly higher than the highly altered samples from the Belmont and Walsingham formations, but definitely lower than Belmont sediments which have similar constituent grain compositions.

The close correspondence between the total $MgCO_3$ content of the limestones shown in Table 16 and the $MgCO_3$ content of the calcites in these limestones (Table 15), shows that all the Mg in the highly altered, calcitic limestones is in solid solution in the calcites. None of the Mg removed from the Mg-calcites has been stabilized in the highly altered limestones. The $MgCO_3$ contents of the eolianites, which still contain some aragonite, do not indicate any Mg-rich phases in these rocks.

The $SrCO_3$ contents of the Walsingham, Belmont, and marine limestones (0.2 to 0.03 mol % $SrCO_3$) are below the range of $SrCO_3$ contents in Recent sediments or sediment contributing organisms (see Figure 16, Table 14). This could be explained as dilution of the original $SrCO_3$ content of the constituent grains by the deposition of secondary calcite which has a very low $SrCO_3$ content. Examination of the thin sections of these limestones indicates that there is not enough secondary calcite in the most altered limestones to account for a dilution to 1/10 of the original $SrCO_3$ content. Therefore, the most likely explanation is that the constituent grains in the most altered limestones have been depleted in $SrCO_3$ during the diagenetic alteration.

The $SrCO_3$ content of the eolianites is roughly in the range of the $SrCO_3$ contents of Recent organic calcites (0.1-0.4 mol % $SrCO_3$), but somewhat below the range of $SrCO_3$ contents for the Recent sediments (0.3-0.7 mol % $SrCO_3$). This slightly lower $SrCO_3$ in the eolianites may be the result of deposition of secondary calcite containing between 0.01 and 0.05 mol % $SrCO_3$, or the depletion of Sr from the constituent grains.

$SrCO_3$ and $MgCO_3$ contents of aragonitic skeletal carbonates from the Pleistocene limestones

It has been shown previously that much of the Sr in the Recent sediments is contained in aragonitic fragments of Halimeda and coral. The removal of aragonite from the sediments by solution necessarily results in the removal of Sr, but there is also the possibility that Sr may be removed from high Sr aragonites without altering the mineralogy. To check this possibility, a large coral fragment and Halimeda segments were separated from the poorly consolidated portions of Pleistocene limestones from Town Cut Channel and deposits in Queen's Face Cave, St. George's Island . The Sr and Mg contents of these fragments were determined by emission spectroscopy and the results are as follows:

	$MgCO_3$ (mol %)	$SrCO_3$ (mol %)	Analyst
Coral fragment Town Cut Channel	1.0	1.15	EG
Halimeda sp. Queen's Face Cave	0.35	1.15	EG

The analyses show no difference in the $SrCO_3$ content of these aragonites and argonite from living organisms (Figure 16). The $MgCO_3$ contents of the *Halimeda* segments are lower than the $MgCO_3$ contents of segments from living plants (Table 12). This lower $MgCO_3$ content may be due to depletion of Mg from the aragonite.

$SrCO_3$ and $MgCO_3$ contents of calcites in individual fragments of sediment contributing organisms

The preceding sections have shown the ranges of $SrCO_3$ and $MgCO_3$ contents in the bulk samples from various Pleistocene limestones. To gain a better understanding of the $SrCO_3$ and $MgCO_3$ content of the calcitic fragments of the sediment contributing organisms, individual constituent grains were separated from poorly consolidated or unconsolidated Pleistocene limestones. These grains were individually analyzed by X-ray diffraction techniques and emission spectroscopy (Appendix 3) so that the data can be compared with the data obtained for the bulk samples of the Pleistocene limestones.

The data are shown in Table 18. In addition, the $SrCO_3$ content and the average range of $MgCO_3$ contents of the calcite in constituent grains from the same organisms in the Recent sediments are tabulated.

Discussion

With the exception of the fragments of Homotrema rubrum, the data show that these constituent grains contain either a single low-Mg calcite phase or a mixture of low-Mg calcite and high-Mg calcite phases. The low-Mg calcite phase contains 6 mol % $MgCO_3$ or less, and the high-Mg calcite phase contains more than 10 mol % $MgCO_3$. Only the specimen of Archaias sp from the Devonshire formation at Grape Bay contains a single high-Mg calcite phase.

With one exception, the high-Mg calcite phase contains less $MgCO_3$ than do the same organisms now living in the Bermuda area. The one exception is the echinoid test fragment from the Devonshire formation at Grape Bay. In this sample, the high-Mg calcite phase contained as much $MgCO_3$ as any of the Recent echinoid tests which have been analyzed.

The four samples of Homotrema fragments from these same Pleistocene limestones contained a single phase Mg-calcite. The $MgCO_3$ contents of these calcites ranged between 7.5 and 10.5 mol % $MgCO_3$. These $MgCO_3$ contents are all lower than Homotrema fragments from the Recent sediments.

TABLE 18. $SrCO_3$ and $MgCO_3$ content of calcite fragments of sediment contributing organisms in the Pleistocene limestones.

	$MgCO_3$ (mol %)	Amount of each Mg-calcite phase	$SrCO_3$ (mol %)
Lithothamnoid algae	14.6-17.2		
Living organisms	(Avg 15.9)		0.30
Devonshire fm. (GB-2)	13.2	(90%)	
Grape Bay (2 phases)	2.0	(10%)	0.35
Belmont fm. (CB-1)	2.0		0.12
Cable Bay			
(?) fm. (SQ-1)	1.8		0.08
Seymour's Quarry			
Foraminifera			
Archaias sp.	12.8-14.7		0.25
Living organisms	(Avg 13.8)		
Devonshire fm. (GB-2)	11.5		0.25
Grape Bay			
Belmont fm. (CB-1)	11.0	(30%)	0.17
Cable Bay (2 phases)	1.8	(70%)	
Homotrema rubrum	11.0-12.7		0.35
Living organisms	(Avg 11.5)		
(?) fm (TC-1)	10.5		
Town Cut Channel			
St. George's Island			
Eolianite			
Warwick Long Bay	9.6		
Devonshire fm. (GB-2)	9.0		0.27
Grape Bay			
Belmont fm. (HB-13)	7.5		0.25
Hungry Bay			
Echinoid Test Fragments	10.8-16.8		0.35
Living organisms	(Avg 13.8)		
Devonshire fm. (GB-2)	16.0	(35%)	
Grape Bay (2 phases)	6.0	(65%)	

TABLE 18. (continued)

	MgCO$_3$ (mol %)	Amount of each Mg-calcite phase	SrCO$_3$ (mol %)
Belmont fm.	3.0		
(?) fm. (TC-1) Town Cut Channel St. George's Island	2.4		

The samples from the Belmont limestone contain the lowest $MgCO_3$ content. Samples from the Devonshire formation and the "younger eolianites" contain higher $MgCO_3$ contents. This strongly suggests that Mg has been removed from the calcites in the constituent grains, and the greatest amount of $MgCO_3$ has been removed from the oldest samples. The samples from Seymour's Quarry and Town Cut Channel have not been correlated with the rest of the Pleistocene section on Bermuda; therefore no time significance can be attached to the data from these two limestones.

The data suggest that two different mechanisms are involved in the removal of Mg from the calcite lattice. One mechanism results in in the removal of a major portion of the Mg from the lattice in essentially a single step. Mg-calcites in which the Mg has not been completely removed thus contain a mixture of high-Mg calcite and low-Mg calcite. There appear to be no intermediate $MgCO_3$ contents involved in this process.

The second process appears to remove the Mg gradually from the calcite lattice. Thus analyses of _Homotrema_ fragments from which the Mg has not been completely removed contain an intermediate amount of $MgCO_3$, _i.e._, between 5 and 10 mol % $MgCO_3$.

As stated in the previous section, the X-ray diffraction analysis of the Pleistocene limestones gave no indication of calcites containing between 5 and 10 mol % $MgCO_3$. As discussed in Appendix 2, X-ray diffraction techniques used in this study cannot distinguish Mg-calcite phases whose $MgCO_3$ contents differ by less than 5 mol % $MgCO_3$. Thus, if appreciable amounts of calcite containing between 5 and 10 mol % $MgCO_3$ were present in the limestones, it would be included in either the high-Mg or low-Mg calcite phase. The apparent $MgCO_3$ content of the Mg-calcite phase would be an average of the $MgCO_3$ contents of the various Mg-calcites involved. For example, if a limestone consists of 50% of high-Mg calcite (13 mol % $MgCO_3$), 25% low-Mg calcite (2 mol % $MgCO_3$) and 25% calcite which contained 7 mol % $MgCO_3$, an X-ray diffraction analysis would indicate two Mg-calcite phases. The high-Mg calcite phase would have an apparent $MgCO_3$ content of 13 mol % $MgCO_3$, and the low-Mg calcite phase would have an apparent $MgCO_3$ content of around 4.5 mol %. Mixtures of low-Mg calcites and calcites with $MgCO_3$ contents between 5 and 10 mol % may account for the apparent variable composition of the low-Mg calcite phase found in the X-ray diffraction analyses of the Pleistocene limestones (see Figs. 19, 20, and 21).

The Sr contents of the calcite grains are shown to vary in the same way as the Mg contents. In the calcites which appear to retain most of their original $MgCO_3$ content, the $SrCO_3$ content is similar to that found in living organisms. In constituent grains where the Mg has apparently been depleted, the $SrCO_3$ values are much lower than the values for similar organisms now living in the area. Thus it appears that Sr as well as Mg is depleted from the constituent grains during diagenesis.

$MgCO_3$ content of limestones and dolomites from Plantagenet Bank

Samples of the cuttings collected from the boring on Platangenet Bank were analyzed by X-ray diffraction techniques. X-ray diffraction analysis indicated that the cuttings from less than 24 feet below the sediment interface contained calcite (40%) and aragonite (60%). The cuttings from 24' to 44 feet contained calcite, aragonite and some dolomite. The calcite from both samples consists of mixtures of two different Mg-calcite phases. Approximately 30% of the calcite is a low-Mg phase (3 mol % $MgCO_3$); the remaining 70% of the calcite is a high-Mg phase (13.5 mol % $MgCO_3$).

The cuttings from below 44 feet contained only dolomite. X-ray diffraction analyses of the dolomites indicate an excess of $CaCO_3$ (57 mol %), and poor ordering in the crystal structure is indicated by the weakness of the (015) reflection (Goldsmith and Graf, 1958).

A chemical analysis (Dr. A. D. Maynes, analyst) of the dolomite indicated the following composition.

$MgCO_3$	43.5 mol %
$CaCO_3$	56.5

These findings confirm the X-ray diffraction analyses.

Discussion

The Plantagenet Bank samples contain the only dolomite found in the Bermuda area. The chemical composition, as determined from the analysis and from the lattice dimensions, indicates an excess of $CaCO_3$. This excess of $CaCO_3$ and the poor ordering of the lattice as shown by the weakness of the (015) reflection are typical of Tertiary dolomites from the Pacific atolls and other sedimentary dolomites (Goldsmith and Graf, 1958b).

So little is known about the geologic history of Plantagenet Bank that nothing can be said about the environment in which the dolomitication occurred.

Conclusions

1. The calcite in the Pleistocene limestones on Bermuda is either low-Mg calcite (less than 4 mol % $MgCO_3$) or a mixture of Mg-calcite phases, a low-Mg calcite and a high-Mg calcite (greater than 10 mol % $MgCO_3$). No calcites with $MgCO_3$ contents between 5

and 10 mol % were found in the limestones.

2. Limestones containing only low-Mg calcite are present in the Walsingham formation, the Belmont formation on St. George's Island, the uncorrelated marine limestones, and in the weathered outcrop surfaces of the "younger eolianites" at McGall's Bay and St. George's. Most of the fresh samples of eolianite from the quarries also contained low-Mg calcite.

3. Limestones of the Belmont and Devonshire formations along the South Shore, unweathered samples of "younger eolianite" from St. George's and McGall's Bay, and some of the quarry samples contained calcites which were a mixture of low-Mg and high-Mg calcite phases.

4. Analyses of the quarry samples suggest that there is no simple relationship between the $MgCO_3$ content of the calcites and the position of the sample with respect to the ground surface.

5. Limestones with low-Mg calcites still contain appreciable amounts of aragonite.

6. The $SrCO_3$ content of the younger eolianites is within the range of $SrCO_3$ concentrations of calcite from sediment contributing organisms. The limestones from the Walsingham formations and portions of the Belmont formation have low $SrCO_3$ contents. (less than 0.1 mol % $SrCO_3$), which suggests that the constituent grains have been depleted in $SrCO_3$.

7. Unaltered aragonite fragments of a coral and a Halimeda segment were found to retain their original $SrCO_3$ contents.

8. Individual constituent grains of calcitic sediment contributing organisms from the Pleistocene limestones were found to be depleted in $MgCO_3$ and $SrCO_3$. In fragments of lithothamnoid algae, Archaias and echinoids, the $MgCO_3$ was present as a high-Mg calcite phase (more than 10 mol % $MgCO_3$) or a low-Mg calcite phase (less than 6 mol % $MgCO_3$) or a combination of the two Mg-calcite phases. Calcites with a single Mg-calcite phase containing between 6 and 10 mol % $MgCO_3$ were found only in fragments of Homotrema. The grains from the older limestones were found to be more depleted in Mg than the grains from the younger limestones. The grains which had lost most of their original Mg content were found to have $SrCO_3$ contents which were lower than in the skeletal carbonates from living organisms.

9. Stalactites and secondary calcites from the Pleistocene limestones were found to contain from 0.7 to 2.5 mol % $MgCO_3$ and 0.01 to 0.05 mol % $SrCO_3$.

10. No dolomite was found in the Pleistocene limestones on Bermuda, which suggests that Mg depleted from the Mg-calcites has been completely removed from the rocks analysed.

11. Dolomite, containing an excess of $CaCO_3$ (57 mol %) occurs in the lower portion of the limestone on Plantagenet Bank. The age of

the dolomitized limestone and the environment in which dolomitization occurred are not known.

O^{18}/O^{16} and C^{13}/C^{12} ratios of the carbonate sediments and Pleistocene limestones

Introduction

The O^{18}/O^{16} and C^{13}/C^{12} ratios of the carbonates in the Recent sediments and the Pleistocene limestones were studied to determine how these quantities were affected by diagenesis. As in the previous sections, the basis approach is a comparison of the isotopic composition of the sediment contributing organisms and the Recent sediments, with the isotopic composition of the carbonates from the Pleistocene limestones. From the comparison of these data it is possible to discuss the changes which result from diagenesis.

O^{18}/O^{16} and C^{13}/C^{12} ratios of skeletal carbonates from sediment contributing organisms

Relatively few data are available concerning the isotopic composition of the oxygen and carbon in the marine carbonates of Bermuda. Some data on the isotopic composition of the oxygen for Recent and Pleistocene invertebrates were published by Epstein and Lowenstam

(1953) in their study of the temperatures of shell deposition in Bermuda. There were no carbon isotope data published for these forms.

Selected specimens of major sediment contributing organisms and bulk samples of the Recent sediments in Bermuda were analyzed to determine the O^{18}/O^{16} and C^{13}/C^{12} ratios of the carbonates. The results are shown in Tables 19 and 20 and Figures 22 and 23.

Discussion

The analyses of the carbonates from sediment contributing organisms show that the foraminifera, molluscs, lithothamnoid algae and the spines of echinoids fall within the range of δO^{18} (+0.5 to -0.9 ‰) and δO^{13} (0.0 to +3.5 ‰) values. Of the major sediment contributing organisms, only Halimeda fragments have an isotopic composition which differs materially from the range of other major sediment contributing organisms. The analysis of a terrestrial gastropod indicates that if these were abundant in a limestone, they would cause an appreciable change in the C^{13} content of the sample. These gastropods usually occur in the sediments as unbroken individuals and are easily recognized and avoided in the preparation of the samples.

With the exception of the beach sand from Clarence Cove (No. 54), the Recent sediments, regardless of grain size, are within the range of δO^{18} and δC^{13} values of the skeletal fragments of the sediment contributing organisms. This is especially interesting in the case of the

TABLE 19. O^{18}/O^{16} and C^{13}/C^{12} ratios of skeletal carbonates from sediment contributing organisms. in Bermuda.

Sample no.	Calcareous marine algae	δO^{18} (o/oo)	δC^{13} (o/oo)
27	Lithothamnoid algae "West Reef," Bermuda	$+0.0_8$	$+1.2_9$
55	Lithothamnoid algal nodule Challenger Bank	-0.1_8	$+1.0_0$
31	Amphiroa sp Clarence Cove	-3.7_0	-1.6_6
32	Halimeda sp. Shelly Bay	-3.3_9	$+0.7_9$
36	Halimeda sp.- Shelly Bay	-2.5_6	$+4.6_9$
	Foraminifera Forminifera		
29	Amphistegina lessonii EB-3	$+0.0_1$	$+0.2_4$
26	Archaias compressus NR-13	-0.6_2	$+3.4_9$
28	Homotrema rubrum R-13	-0.5_4	$+2.3_1$
	Mollusca		
34	Pelecypod fragments >2 mm. Beach sand, Coral Beach	$+0.0_7$	$+0.6_6$
33	Gastropod fragments >1 mm. Beach sand, Coral Beach	$+0.2_9$	$+1.3_0$
37	Strombus gigas Lagoonal area, Bermuda	-0.7_3	$+0.2_4$
38	Poecilozonites sp (terrestrial gastropod) Eolianite, Hamilton Harbor	-0.0_8	-9.7_1
	Echinodermata - echinoids		
	Boring echinoid Cooper's Island		
81	Test	-0.8_1	-7.4_6
80	Spines	0.0_0	$+0.9_4$

TABLE 19. (continued)

Sample no.		δO^{18} (o/oo)	δC^{13} o/oo)
	<u>Lytechinus sp.</u> Ferry Reach		
90	Test	$+0.3_0$	-2.0_2
89	Spines	$+0.0_3$	$+1.2_2$

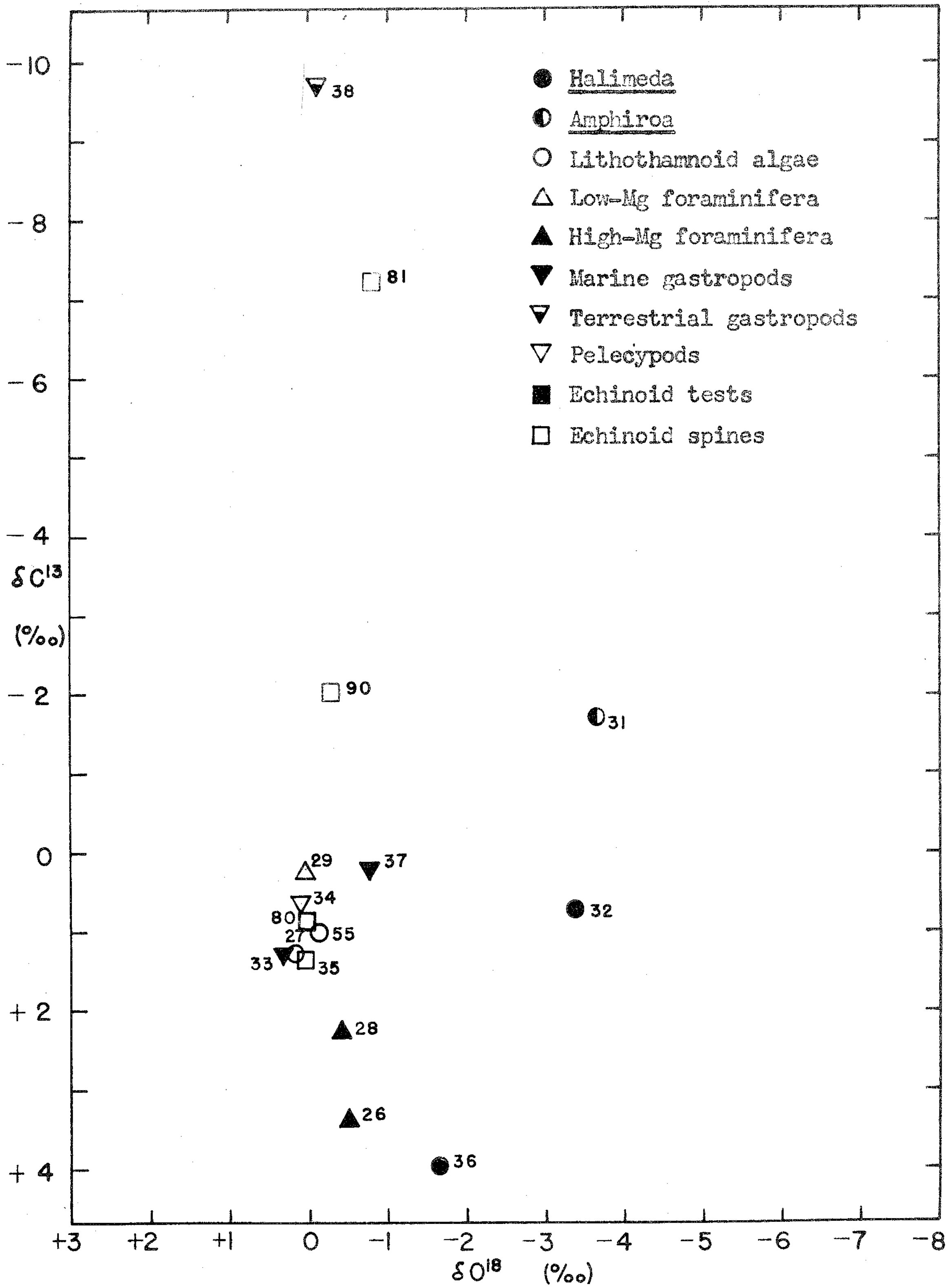


Figure 22. O^{18}/O^{16} and C^{13}/C^{12} ratios of the skeletal carbonates of sediment contributing organisms in the Bermuda Islands.

TABLE 20. O^{18}/O^{16} and C^{13}/C^{12} ratios of Recent sediments in Bermuda

Sample number			δO^{18} (‰)	δC^{13} (‰)
	Beach Sand			
25	" "	Warwick Long Bay	-0.6_4	$+1.5_9$
52	" "	Shelly Bay	-0.2_0	$+2.5_9$
54	" "	Clarence Cove	-3.1_2	-0.3_3
60	" "	Ft. St. Catherine	-0.2_1	$+1.3_7$
117	" "	John Smith's Bay	-0.0_3	$+1.8_7$
116	Dune sand,	Elbow Bay	-0.2_3	$+1.3_2$
	Recent sediments			
GNR-11	Sediments between Three Hills Shoal and North Rock			
84		fraction < 2 mm. > 1 mm.	-0.1_6	$+3.2_2$
85		fraction < 60 microns	-0.9_3	$+2.0_3$
GNR-15	Sediments from north of North Rock			
83		fraction < 2 mm. > 1 mm.	-0.4_7	$+2.0_2$
82		fraction < 60 microns	-0.7_6	$+1.5_6$

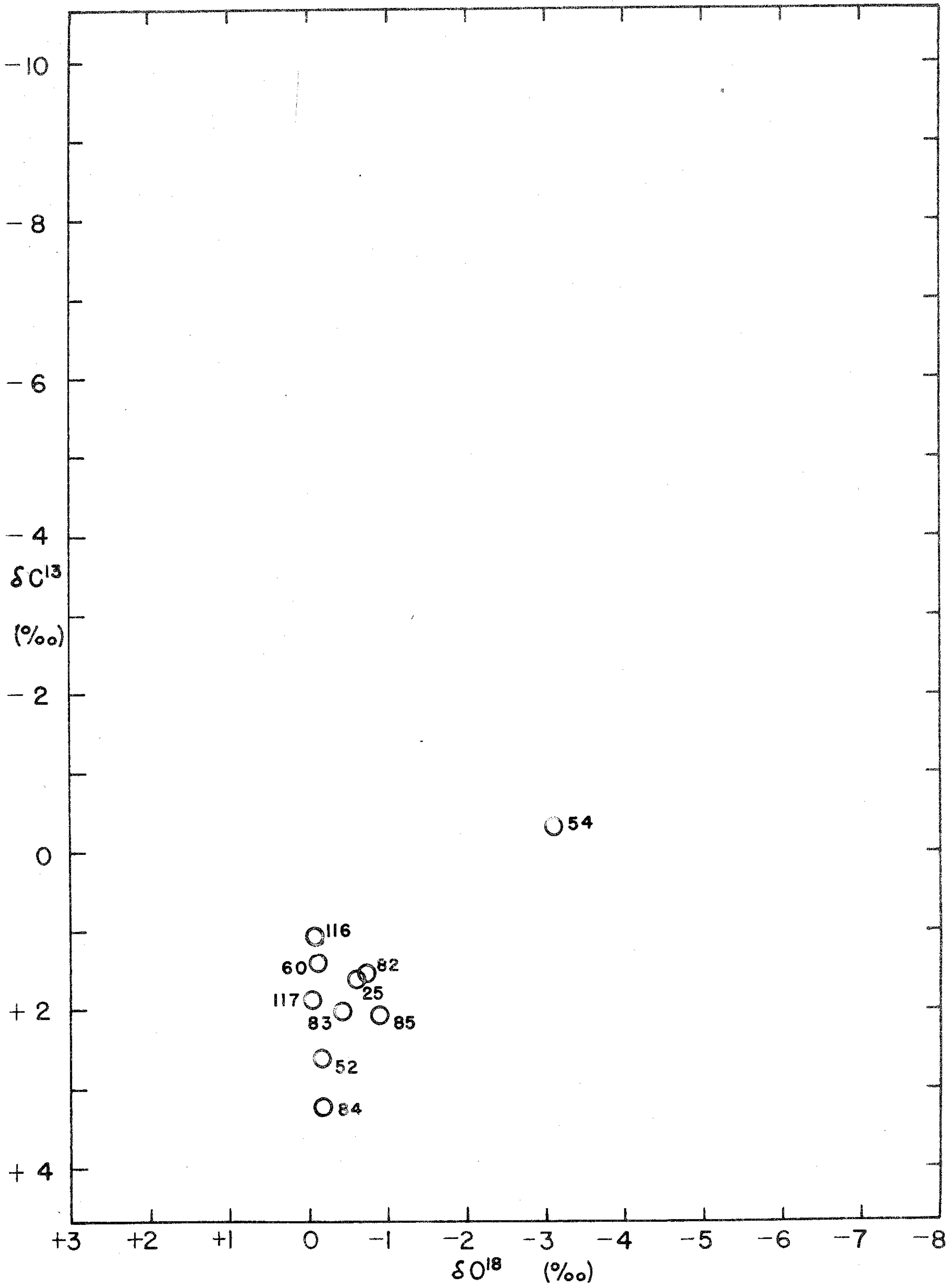


Figure 23. O^{18}/O^{16} and C^{13}/C^{12} ratios of the Recent carbonate sediments in the Bermuda Islands.

Recent marine sediments from North Rock because it suggests that both the coarse and silt sized fractions are derived from skeletal fragments of calcareous organisms.

The beach sand from Clarence Cove is distinctly different from the other Recent sediments. The δO^{18} value of the sample cannot be explained as a mixture of fragments from sediment contributing organisms. An abundance of carbonate derived from the Pleistocene limestones is the most probable explanation for the isotopic composition.

O^{18}/O^{16} and C^{13}/C^{12} ratios of the Pleistocene limestones

Thirty-five samples of Pleistocene limestones were analyzed to determine the δO^{18} and δC^{13} values, and to determine the effect of consolidation and weathering on the isotopic ratios. The data in Table 21 are plotted in Figure 24.

Discussion

The δO^{18} and δC^{13} values of the Pleistocene limestones show a wide variation. In general the poorly consolidated limestones and those which appear least altered in hand specimens have δO^{18} and δC^{13} values close to the range of δO^{18} and δC^{13} values observed in the Recent sediments (δO^{18} = -1 to 0‰, δC^{13} = 0 to -4‰). The most altered limestones and the limestones of the Walsingham formation have δO^{18} and δC^{13} values of around -3.5 and -6.0% respectively.

TABLE 21. O^{18}/O^{16} and C^{13}/C^{12} ratios of Pleistocene limestones

Sample number		δO^{18} (‰)	δC^{13} (‰)
	Walsingham formation		
8	Wilkinson's Quarry (WQ-1)	-3.1_0	-6.0_0
120	Buern's Quarry (BQ-3)	-3.0_8	-5.6_5
9	Government Quarry (Be-1)	-3.4_3	-4.5_6
119	(GQ-2)	-3.0_8	-4.2_6
	Belmont formation		
14	Stoke's Point (Be-17)	-3.7_0	-2.4_3
13	Esso Tank farm, Ferry Reach Road (Be-16)	-2.0_2	-2.8_5
22	(ETF-20a)	-3.2_8	-3.9_5
6	Grape Bay (Be-7)	-1.0_8	$+1.5_6$
7	McGall's Bay (Be-22)	-1.0_8	-2.9_6
	Hungry Bay		
47	Unconsolidated (HB-13)	$+0.1_5$	$+2.4_4$
46	Consolidated (HB-12)	-0.3_7	$+0.9_6$
23	" (HB-10)	-0.0_5	-2.5_6
	Cable Bay		
42	Fresh surface (CB-1)	-1.4_9	-0.8_4
41	Weathered surface (CB-1)	-1.7_4	-3.0_7
	Devonshire formation		
115	Grape Bay (GB-1)	$+0.2_1$	-1.5_2
	Marine limestones correlations uncertain		
121	Shell Tank Farm, Ferry Reach Rd. (Be-3)	-1.1_4	-2.9_3
62	Government Quarry (GQ-53)	-1.9_7	-5.9_7
63	Seymour's Quarry (SQ-1)	-2.0_5	-5.8_1

TABLE 21. (continued)

Sample number		δO^{18} (‰)	δC^{13} (‰)
Eolianites			
	Somerset eolianite, McGall's Bay		
42	Fresh surface (MG-5a)	-0.9_2	-0.7_2
43	Weathered surface (MG-5b)	-1.0_7	-0.7_2
122	Eolianite, St. George's	-1.0_3	-1.3_1
	Eolianite, Laffan Road, Hamilton		
58	Porous bed (ME-1)	-2.7_4	-4.9_2
57	Crystalline limestone (ME-2)	-2.6_0	-5.9_1
45	Eolianite, Devonshire Marsh	-2.9_4	-6.6_6
	Eolianite, Sinky Bay		
	10 feet below ground surface		
94	Unconsolidated (SB-10-2)	$+0.4_8$	$+1.8_8$
93	Consolidated (SB-10-1)	-1.1_8	-2.5_5
	30 feet below ground surface		
91	Unconsolidated (SB-2-30a)	-0.7_0	-0.4_0
92	Consolidated (SB-2-30c)	-1.2_1	-1.6_0
	Eolianite, Rockwell Estate Quarry		
12	Ground surface (RWE-0)	-1.9_9	-2.3_7
87	5' below ground surface (RWE-5)	-2.1_9	-3.4_5
88	10' " " " (RWE-10)	-1.8_4	-2.9_0
11	17' " " " (RWE-17)	-2.5_9	-5.4_6
	Eolianite, Butterfield Quarry		
112	Ground surface (BFQ-0)	-2.6_8	-6.1_2
113	12' below ground surface (BFQ-12)	-2.7_7	-2.7_5
114	35' " " " (BFQ-35)	-2.2_2	-6.6_2

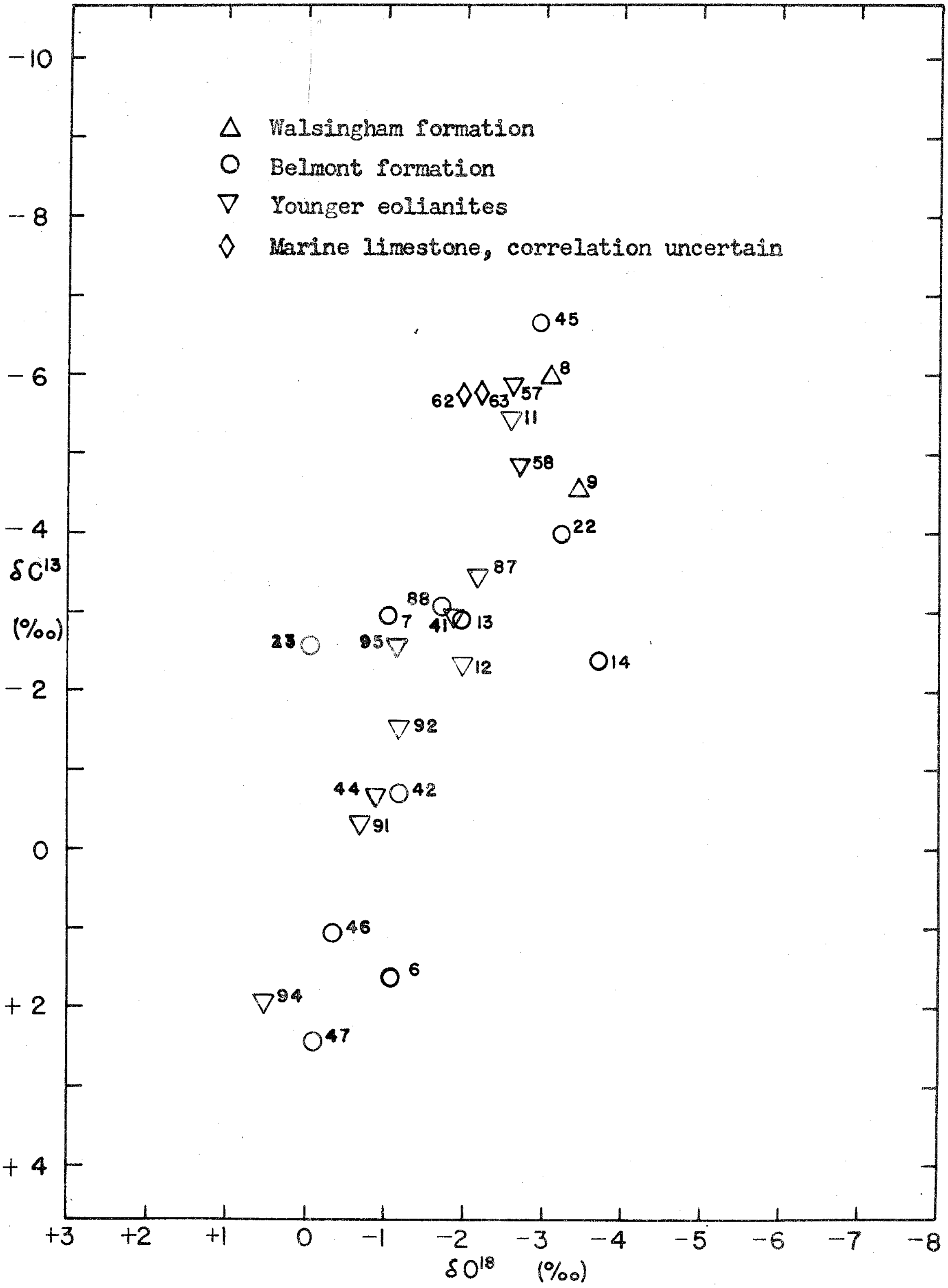


Figure 24. O^{18}/O^{16} and C^{13}/C^{12} ratios of the Pleistocene limestones in the Bermuda Islands.

All the other limestones have δO^{18} and δC^{13} values which fall between these two extremes.

In all cases where sets of consolidated and unconsolidated limestones from the same bed were analyzed, it was found that the consolidated portion had more negative values of δO^{18} and δC^{13}. Essentially the same relation was observed between analyses of samples taken from weathered and unweathered portions of the outcrops of the same limestones. In each case the weathered limestone sample showed a more negative value for δO^{18} and δC^{13} than did the unweathered sample.

Comparison of the results of the isotopic analyses and the thin section analyses for the quarry series from the Rockwell Estate and Butterfield quarries show that the isotopic ratios, especially the C^{13}/C^{12} ratio, are strongly influenced by the amount of secondary calcite in the sample. For example, in the Butterfield Quarry, the samples from the ground surface and from 35 feet below the ground surface show similar δO^{18} values (-2.7 and -2.2‰ respectively) and similar δC^{13} values (-6.1 and -6.6‰ respectively). The thin section analyses of these samples (Table 9) showed that both contained more than 20% secondary calcite (i.e., cement and casts). The sample from 12 feet below the ground surface had only 2% secondary calcite, and its isotopic composition (δO^{18} = -2.7‰ δC^{13} = -2.7 ‰) was quite different from the samples above and below.

These analyses indicate a consistent relationship in the changes of the δO^{18} and δC^{13} values of the limestones, regardless of whether the alteration was superficial weathering on the outcrop surface or consolidation within the rock body 80 feet below the ground surface. In both cases, these changes in the δ values appear to be related to the deposition of secondary calcite. It will be shown later than these δ values can be explained by the deposition of the secondary calcites from fresh water in which the carbon has been derived from biological processes.

O^{18}/O^{16} and C^{13}/C^{12} ratios of stalactites, "soil bases," and secondary calcites from the Pleistocene limestones

Stalactites from Crystal Cave and caves on St. David's Island and at Government Quarry, as well as samples of "soil bases," were analyzed. These "soil bases" are bands of stained, highly altered limestone which occur between the soils and the underlying limestones (Sayles, 1931; Bretz, 1960). In addition, samples of secondary calcite forming cement, veins and sparry calcite mold fillings were ground from freshly polished surfaces of Walsingham and Belmont limestones. It is estimated that less than 10% contamination from adjacent carbonate grains occurred during the drilling process.

The O^{18}/O^{16} and C^{13}/C^{12} ratios of the stalactites, "soil bases" and secondary calcites shown in Table 22 are plotted in Figure 25.

TABLE 22. O^{18}/O^{16} and C^{13}/C^{12} ratios of stalactites, "soil bases," and secondary calcites from the Pleistocene limestones.

Sample number		δO^{18}(‰)	δC^{13}(‰)
Stalactites			
1	Crystal Cave (CC-1)	-2.7_5	-8.0_1
24	" " (CC-2)	-1.1_8	-3.4_3
2	Cave- Government Quarry	-3.0_4	-7.3_8
53	Cave - St. David's Island	-1.6_2	-3.9_9
"Soil Bases"			
5	McGall's Bay (underlying St. George's soil) developed on eolianite	-2.5_7	-7.3_6
10	Government Quarry developed on Walsingham formation	-3.4_5	-5.9_0
18	Soil base "matrix"	-3.9_0	-6.6_6
Calcite Vein			
3	Esso Tank farm	-3.4_3	-7.9_6
Calcite vein			
4	Wilkinson's Quarry	-2.9_7	-9.0_1
15	Sparry calcite vein (GQ-3a)	-3.9_5	-7.8_6
21	Calcite coating fissure wall (GQ-5c)	-4.5_8	-8.6_4
16.	Sparry calcite cement (ETF-20d)	-3.3_1	-5.9_2
19	Pelecypod cast, sparry calcite (ETF-20c)	-3.2_0	-5.2_0
20	Sparry calcite crystals lining pelecypod mold (ETF-20b)	-2.6_8	-8.1_0

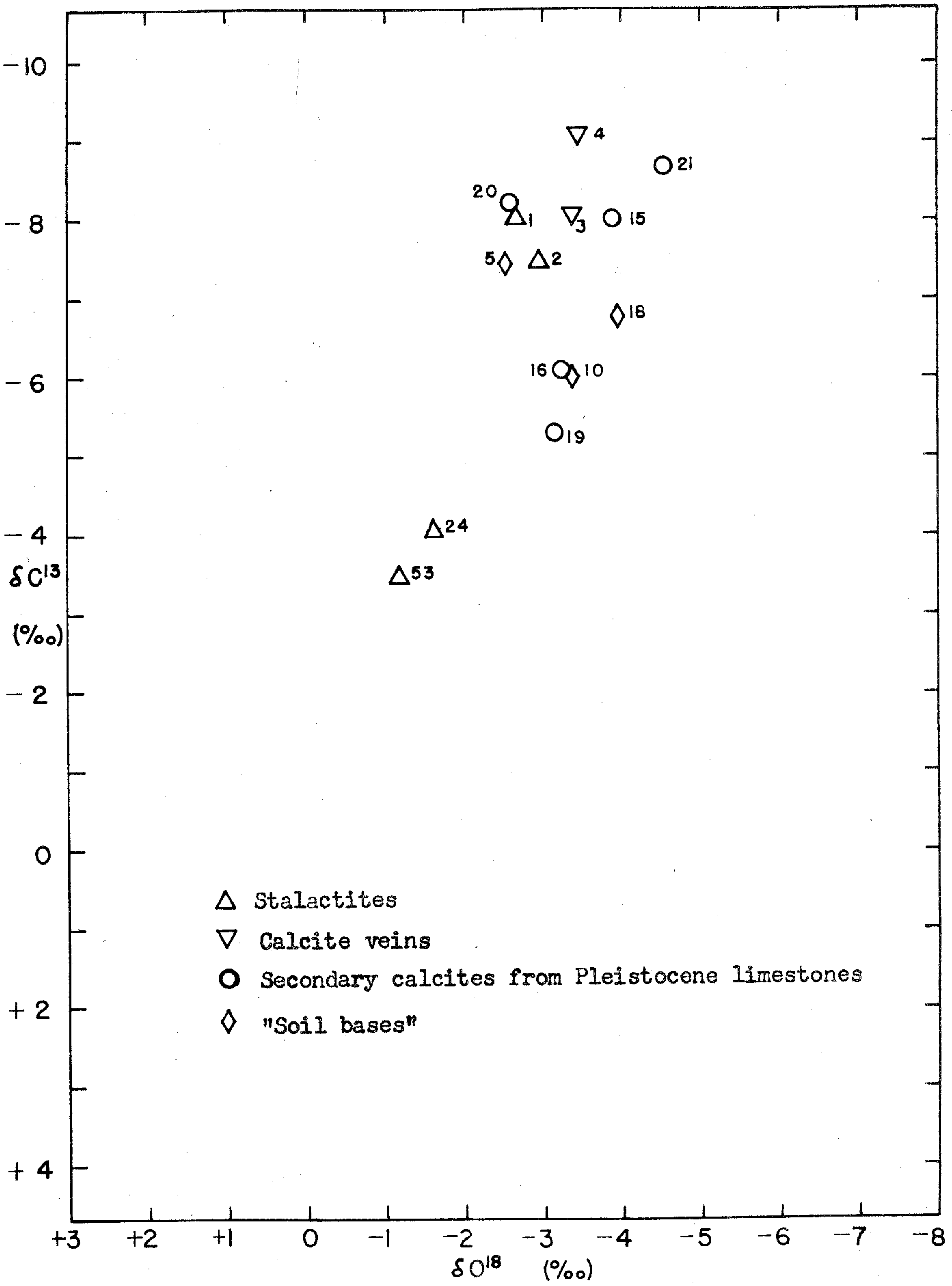


Figure 25. O^{18}/O^{16} and C^{13}/C^{12} ratios of fresh water carbonates, "soil bases" and secondary calcites from the Pleistocene limestones.

Discussion

The stalactites were analyzed to obtain data on the O^{18}/O^{16} and C^{13}/C^{12} ratios of carbonate unquestionably formed in fresh water. These stalactites occur in caves which were formed by the action of fresh water (Bretz, 1960). The stalactites from the caves at Government Quarry and on St. David's Island were collected in place by the writer. The Crystal Cave stalactites were collected by diving and were furnished by Dr. H. A. Lowenstam.

As indicated in Figure 25, the analyses of the stalactites fall into two widely separated groups. The stalactite from the Government Quarry and one of the Crystal Cave stalactites (CC-1) have δO^{18} values of -3.0 and -2.7 ‰ and δC^{13} values of -7.4 and -8.0‰ respectively. The other stalactite from Crystal Cave (CC-2) and the stalactite from St. David's Island have δO^{18} values of -1.2 and -1.6‰ and δC^{13} values of -3.4 and -3.9‰ respectively. The close correspondence of the δ values indicates that the stalactites of each group formed under similar conditions.

The cave on St. David's Island is small and occurs on a cliff overlooking the ocean. The air circulation within the cave appears to be fairly good because the cave has at least two openings. It is assumed that the stalactite from Crystal Cave with the similar isotopic composition formed under similar conditions with good air circulation. The conditions under which the other group of stalactites formed will be discussed with the formation of the veins.

The δO^{18} values of the "soil bases" ranged between -2.5 and -3.9‰ and the δC^{13} values were between -5.9 and -7.3‰. The "soil bases" are usually found associated with a soil at the base of the paleosols (Sayles, 1931; Bretz, 1960). They are interpreted to have been formed by the soil forming processes. Thus, the "soil bases" must have formed in a fresh water environment.

With the exception of the stalactites, the δO^{18} values of the samples fall between -2.5 and -4.5‰. The average δO^{18} value for the group is approximately 3.5‰. The two stalactites (24, 53) discussed previously have δO^{18} values around 1.5‰.

The δO^{13} values show a much wider range. The δC^{13} values of most of the samples range from -9 to -5.2‰; two of the stalactites have δC^{13} values of -3.4 and -4.0‰. The δC^{13} values of each of the types of carbonate tend to group together and the averages of the groups suggest a trend in δC^{13} values. These averages are:

	δC^{13}
Calcite veins	-8.3‰
Stalactites (1, 2)	-7.8
"Soil bases"	-6.6
Cements and sparry calcite filling molds	-6.4
Stalactites (24, 53)	-3.7

It is thought that this progression in δC^{13} values is caused by differences in the amount of CO_2 which is derived from the atmosphere and from the soil zone. The secondary calcites deposited in the Pleistocene limestones and in caves with restricted circulation of air have more negative δC^{13} values because most of the carbon was derived from the soil zone and was produced by biologic processes. In caves with good circulation of air much of the carbon in the carbonates probably came from the atmosphere, so that the δC^{13} values are less negative (Vogel, 1959). In addition, the δO^{18} values in these stalactites are less negative than in the secondary calcites. This may be caused by evaporation of water during the deposition of the stalactites which changes the isotopic composition of the water.

As the data (Figure 25) indicate, the range of δO^{18} and δO^{13} values of the fresh water carbonates from stalactites and the "soil bases" is almost identical to the range of δO^{18} and δC^{13} values observed in the secondary calcites from the Pleistocene limestones. The correspondence appears too close to be entirely fortuitous and suggests that the secondary calcites and the fresh water carbonates are formed under similar conditions.

O^{18}/O^{16} and C^{13}/C^{12} ratios of limestones and dolomites from Plantagenet Bank

Cuttings of the carbonate sediments and limestones from the drilling operation on Plantagenet Bank were analyzed to determine the

O^{18}/O^{16} and C^{13}/C^{12} ratios. The results of these analyses are as follows:

Sample number		Depth	δO^{18} (‰)	δC^{13} (‰)
61	Carbonate sands, calcite and aragonite	0-24'	$+1.1_2$	$+2.0_4$
59	Dolomite	44-60'	$+4.4_5$	$+3.0_0$

Discussion

The limestone in the cuttings from the shallow portions of the boring had a δC^{13} content ($\delta C^{13} = +2.0‰$) which is within the range of δC^{13} values found in the Recent sediments from Bermuda. The δO^{18} value of this sample ($\delta O^{18} = +1.1‰$) is distinctly different from the Recent sediments of Bermuda and indicates either lower temperatures at the time of deposition or changes in the δO^{18} values of the water from which it formed. Possibly both mechanisms were involved.

The dolomite from the boring shows a distinctly different δO^{18} value ($\delta O^{18} = +4.4‰$) from those found in any of the limestones on Bermuda while the δC^{13} ($\delta C^{13} = +3.0‰$) value is within the range of δC^{13} values found in the Recent sediments of Bermuda.

Conclusions

1. The major sediment contributing organisms, with the exception of Halimeda, have δO^{18} values from +0.3 to -0.9‰ and δC^{13} values from +0.2 to +3.5‰. Fragments of the Halimeda and Amphiroa have δO^{18} values from -2.5 to -3.7‰ and δC^{13} values from +4.7 to +1.7‰. Echinoid tests and terrestrial gastropods have δO^{18} values of 0 to -0.8 and δC^{13} values from -2.0 to 9.6‰.

2. All but one of the Recent sediments analyzed had δO^{18} values of 0 to -1‰ and δC^{13} values of +1 to +3.2‰. This range of δO^{18} and δC^{13} values corresponds to the range observed for the carbonate skeletons of the major sediment contributing organisms. Only the beach sand from Clarence Cove, which appears to contain appreciable amounts of reworked Pleistocene limestone, has δ values which cannot be explained as a mixture of the skeleton carbonates from sediment contributing organisms.

3. The δO^{18} and δO^{13} values of the Pleistocene limestone range from values similar to the Recent sediments to more negative values of δO^{18} and δC^{13}. The highly altered limestones have more negative δ values than the poorly consolidated limestones.

4. Comparison of the δ values and the thin section analyses of eolianite samples from the Butterfield and Rockwell Estate Quarries indicates that the deposition of secondary calcite in the limestones

accounts for the change in the δ values.

5. The same changes in the δ values of limestones were found to be produced by diagenetic alteration within the rock mass and by superficial weathering on the outcrop surface.

6. The δO^{18} and δC^{13} values of stalactites and "soil bases" have the same range as the values of the cements, veins and other secondary calcites from the Pleistocene limestones.

7. The fresh water calcites and the secondary calcites from the Pleistocene limestones exhibit a range of δC^{13} values which appears to be controlled by the amount of CO_2 in the ground water which comes from the atmosphere and the amount which is derived from biological processes taking place in the soil zone.

8. The δO^{18} values of two stalactites (one of them from a cave opening on the coast with good air circulation) suggests that some evaporation may have occurred in the formation of these two stalactites.

9. The δO^{18} and δC^{13} values of a carbonate sediment and a dolomite from Plantagenet Bank are distinctly different from the values for the Bermuda sediments and Pleistocene limestones. Nothing is known about the environment in which these sediments and dolomites formed.

DIAGENESIS OF THE PLEISTOCENE LIMESTONES IN BERMUDA

Introduction

As stated in the Introduction, a discussion of diagenesis must consider the temperature, pressure and chemical composition of the sediments and water. In this section, the temperature, pressure and chemical composition of the water in the Bermuda limestones during the diagenetic processes are considered. The changes in the mineralogy, and chemical composition of the limestones resulting from the diagenetic processes are discussed in terms of the physical and chemical limits of the environment in which diagenesis took place.

It will be shown, on the basis of geologic evidence, that the diagenetic alteration of the Pleistocene limestones in Bermuda probably took place within a fresh water environment. With this background, the various changes in the limestones which were shown to result from diagenetic processes are examined to see which of these changes is diagnostic of fresh water alteration. These criteria can then be applied to limestones in other regions to see if they too were diagenetically altered in a fresh water environment.

Pressure

None of the Pleistocene limestones in Bermuda have been deeply buried. With the exception of the area between Castle Harbor and

Harrington Sound the topography seems to be that of an undissected dune system (Bretz, 1960). The highest point of the island is approximately 260 feet above sea level. From seismic refraction measurements made in the lagoon north of the islands, Officer et al. (1952) found that the average depth to the top of the truncated volcanic cone was about 250 feet. Thus, the deepest burial which any of the limestones has undergone is approximately 500 feet. The maximum depth of burial of the limestones sampled in this study is probably measured in tens or hundreds of feet.

Twelve bird's eggs have been recovered from depths of up to 28 feet below the surface in the Walsingham formation and younger eolianites (Wood, 1923; Verrill, 1904; Nelson, 1840; Agassiz, 1895). Descriptions of the eggs given by Wood indicate that, although the eggs are broken, they have not been crushed. This indicates that little or no compaction has occurred in the sediments following their deposition.

Bermuda's climate during glacial Pleistocene periods

Since the exact time of the diagenetic alteration of the Bermuda limestones is not known, the possible range of temperatures in Bermuda during glacial Pleistocene periods must be considered.

Using temperature gradients calculated on the basis of the known extent of the Pleistocene glaciers, Bryon and Cady (1934) state that the minimum mean monthly temperature for the coldest month in

Bermuda during a glacial stage was between 0°C and 4°C. For the mean monthly temperature for the warmest month of the year, they postulate a minimum temperature of approximately 16°C. This would give 8-10° as the minimum mean annual temperature, approximately 12° colder than at present.

Paleotemperature measurements were made by Emiliani (1958) of a North Atlantic deep sea core (latitude 34°54'N longitude 44°16'W), approximately 1300 miles east of Bermuda. These data provide some means of estimating the temperatures in Bermuda during the glacial Pleistocene. Using the oxygen isotope method for determining the temperature at which certain planktonic foraminifera lived, and using the deduced bathymetric range for these foraminifera, Emiliani determined that during the coldest periods the summer surface temperature was approximately 16°C and the warmest summer surface temperatures were around 25°C.

Additional evidence is available from the analyses of post-Pleistocene and Pleistocene interglacial fauna of Bermuda by the oxygen isotope method (Epstein and Lowenstam, 1954). These data indicate that the temperature during these times was within ±2°C of its present value.

If it is assumed that the temperature of the limestones on Bermuda is controlled simply by the heating of the surface by the sun, it is possible to compute the temperature distribution within the rocks. From the computations based on this model it can be shown that the seasonal temperature variations of the surface (present surface temperature extremes: min. 16.7°C, max. 28.9°C) are damped out within the rock body. At a depth of 20 meters from the interface the temperatures vary less than 1°C from the mean annual temperature.

In the highly permeable limestones on Bermuda, the temperature of rain which flows through the rocks probably has an important effect on the temperature distribution. During 1960 and 1960 the temperatures of rains in Bermuda were measured by Miss Jane Spaeth at the Bermuda Biological Station. The temperature of the rains during the period from August 1960 to March 1961 varies from 23.5°C to 13.5°C. These temperature variations are similar to the monthly air temperatures in Bermuda during the same period (see Fig. 4).

There are no data for the temperature variation within the Bermuda limestones, so that it is impossible to determine the effect of the variation in the temperatures of the rains. Also there is no way to determine the possible temperature variation of the rains during the Pleistocene.

Since it is impossible to determine when the diagenetic alteration of the Bermuda limestones occurred, it is not possible to determine the exact temperature at which the diagenesis occurred. Thus, the temperature of diagenesis of the Bermuda limestones cannot be determined except to say that it was between 0° and 30° C.

Fresh water environment

The fresh water environment is divided into two zones, the saturated fresh water zone (the Ghyben-Herzberg lens) and the unsaturated fresh water zone which lies above the water table. As shown in Appendix 5, about 2/3 of the island is underlain by a fresh water lens. The Walsingham district and the coastal areas are apparently underlain by brackish or marine water.

All of the samples of Pleistocene limestones analyzed in this study were collected from outcrops which are presently in the unsaturated fresh water zone. As shown in Appendix 5, the boundary between the saturated and unsaturated fresh water zone is closely related to sea level. Because of the changes of sea level during Pleistocene time, it is possible that the rocks were also in the saturated fresh water zone during times of high sea levels.

If the present restricted distribution of brackish or marine water underlying the islands is typical of the water distribution during most of the island's Pleistocene history, very few of the samples analyzed in the study were ever in the saturated marine water environment following their deposition. It is possible that the samples of Walsingham limestone contained sea water at one time or another.

O^{18}/O^{16} and C^{13}/C^{12} ratios of secondary carbonates deposited during diagenesis.

Assuming that the secondary calcites deposited in the limestones during diagenesis are precipitated in isotopic equilibrium with the interstitial water, the O^{18}/O^{16} ratios of the carbonates will be controlled by the O^{18}/O^{16} ratio of the water and the temperature at which the deposition took place.

The oxygen isotope fractionation in the $CaCO_3$-water system has been studied in the low temperature region for inorganic materials (McCrea, 1950) and organically precipitated carbonates (Epstein et al. 1951). Both of these studies showed the same fractionation as a function of temperature for equilibrium precipitates, which may be expressed as follows:

$$T(°C) = 16.5 - 4.3\,(\delta - A) - 0.14\,(\delta - A)^2$$

where δ is the δO^{18}(‰) measured for the carbonate and A is the δO^{18}(‰) value for the water from which the carbonate precipitated.

Although the average δO^{18} values have been determined for the rain (-4‰) and the surface marine waters (+0.8‰) in Bermuda at present, there is no way of determining the δO^{18} value of these waters during Pleistocene times. This is especially true for the Bermuda rains, whose δO^{18} values at present have a wide range (see Appendix 5) depending on the type of storm involved.

Assuming that the rain water in Bermuda during the Pleistocene had the same δO^{18} value as it does today and that the surface marine waters had the same δO^{18} value as mean ocean water ($\delta O^{18} = 0‰$), the δO^{18} value of carbonates deposited in the fresh and marine water environments may be computed for the temperature ranging from 0 to 30°C. These values, plotted in Figure 26, show a considerable overlap in the possible δO^{18} values of secondary carbonates deposited from marine and fresh water. Thus, the δO^{18} values of the secondary carbonates do not appear to be useful in distinguishing the fresh water and marine water diagenetic environments because of the uncertainties regarding temperatures and the δO^{18} values of the waters during the Pleistocene epoch.

The δC^{13} values of the secondary carbonates deposited in the diagenetic environment are controlled by the C^{13}/C^{12} ratio of the bicarbonate in the water from which they are deposited. Thus it is necessary to consider the sources of carbon in the marine and fresh water environments.

The C^{13}/C^{12} ratio of oceanic bicarbonate is controlled by an equilibrium with the CO_2 of the atmosphere (Vogel, 1959). The δC^{13} value of oceanic bicarbonate appears to be fairly constant (Craig, 1954) therefore, and the carbonates deposited in isotopic equilibrium with marine waters should have δC^{13} values of around 0‰ (Craig, 1954; Vogel, 1959). The range of δC^{13} values of the carbonate skeletons of

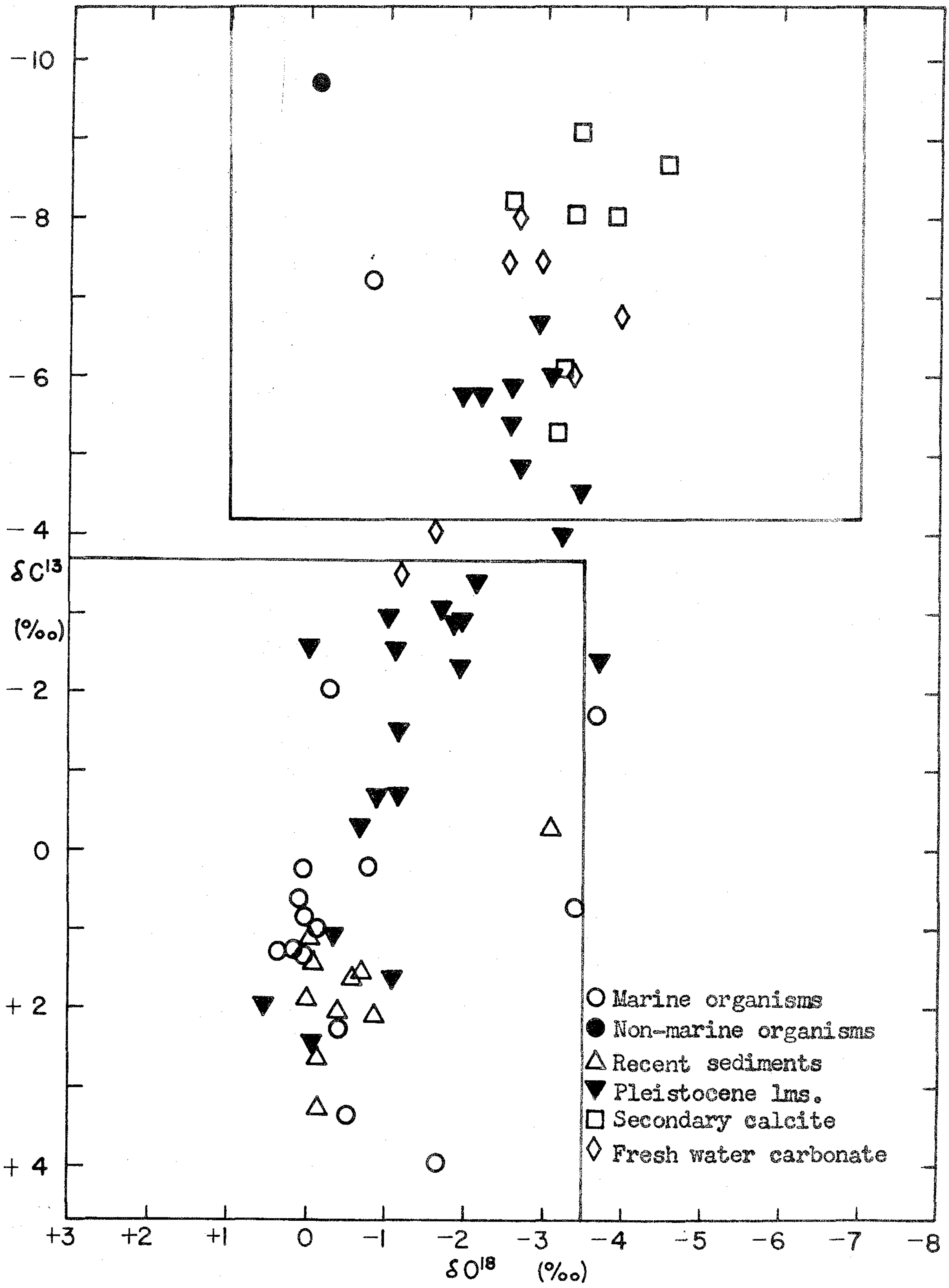


Figure 26. O^{18}/O^{16} and C^{13}/C^{12} ratios of carbonates deposited in equilibrium with marine and fresh water at temperatures of 0° to 30° C. (Values for the sediments and limestones from Bermuda are plotted for comparison)

marine invertebrates (excluding echinoderms) and marine limestones (Craig, 195δ; Baertschi, 1957; Clayton and Degens, 1959) are plotted in Figure 26 to show the range of δC^{13} values of marine carbonates reported by other investigators.

Craig (1953) suggested that the carbon in fresh water carbonates probably is derived from organically produced CO_2. Vogel (1959) pointed out that the soil zone is the most probable source for the large amounts of CO_2 which are dissolved in ground waters. The CO_2 content of the air immediately above the soils is known to be higher than the average value for the atmosphere (Geiger, 1950, p. 125). Russel and Appleyard (1915) showed that the average soil gas contains approximately 10 times the amount of CO_2 that is found in the atmosphere. They point out that the composition of the soil gas varies with the season, type of soil, crops, tillage and biological activity.

Rain water flowing through the well drained soils in Bermuda is continually in contact with the soil gas, since the soil cannot be more than 80% saturated with water (Wycoff and Botset, 1936; Hansen, 1955).

Terrestrial plants contain carbon which has δC^{13} values ranging from -19.9 to -30.1‰ (Wickman, 1952; Craig, 1953). The CO_2 derived from the decomposition of this material should contain carbon with essentially the same range of δC^{13} values. Another source of CO_2 in the soil zone is respiration of CO_2 by plant roots. The carbon in the CO_2 respired by the roots appears to be isotopically lighter than atmospheric CO_2 (Parks and Epstein, 1961) but the exact δC^{13} value is not known. The δC^{13} value of the carbon in the bicarbonate of the ground water is changed by the carbon derived from the solution of calcite or aragonite in the limestones.

Vogel (1959) analyzed the bicarbonate in ground waters from Germany for which he found δC^{13} values ranging from -11.9 to -16.6‰ (average 13.6‰). These δC^{13} values are within the range which would be expected to result from the process discussed above.

The range of δC^{13} values (Craig, 1953; Baertschi, 1957; Vogel, 1959) of fresh water carbonates (excluding tuffas and hot spring deposits) is plotted in Figure 26 to indicate the variation of δC^{13} values found by other investigators.

The changes in the δO^{18} and δC^{13} values of the Pleistocene limestones of Bermuda (Fig. 26) are from δ values more or less characteristic of marine carbonates (i.e., δO^{18} = 0 to -1‰, δC^{13} = 0 to +3‰) to δ values characteristic of fresh water carbonates (i.e., δO^{18} = -3 to -4‰; δC^{13} = -4 to -10‰). As shown previously, this is due in large part to the deposition of secondary calcite. No isotopic analyses were made of individual skeletal fragments from the highly altered Pleistocene limestones, so the possibility cannot be eliminated that some exchange of oxygen and possibly carbon has taken place in the original organic carbonates.

Stability of aragonite

From thermodynamic considerations and experimental work, it is clear that aragonite is metastable with respect to calcite at surface temperatures and pressures (Jamieson, 1953). The exact boundary of the stability field for aragonite is still not certain (Goldsmith, 1959), but enough is known to say that only under very exceptional conditions could aragonite be the stable form of $CaCO_3$ at surface temperatures and pressure.

It was observed in the Pleistocene limestones that aragonitic skeletal fragments were removed by completely dissolving the aragonite. It is clear that the removal of aragonite is not caused by the spontaneous inversion of aragonite to calcite. Several of the older limestones on the island still retain small amounts of aragonite despite the loss of large amounts of Mg from the Mg-calcites and the precipitation of large amounts of secondary calcite.

Diagenetic effects observed in sediments in sea waters

There is no evidence of the inversion of aragonite to calcite during early diagenesis of marine sediments in sea water (Ginsberg, 1957). From previous studies and his own studies of the $MgCO_3$ content of Recent marine sediments, Chave (1954b) concluded that there is no evidence for exchange of Mg between sea water and the sediments. They appear to neither lose nor gain Mg in the marine environment. Krinsley and Bieri (1959) found no difference between aragonitic pteropod shells taken in plankton tows and those recovered from deep sea cores. The Sr content in unaltered coral and aragonitic material from the Bikini boring (Odum, 1957, p. 99) indicates that the Sr/Ca ratio is essentially the same as in living forms. A similar conclusion may be drawn from other data given for calcareous sands of various origins (Odum, 1957, p. 83).

At present there is no evidence for diagenetic alteration of carbonate sediments which have remained in a marine environment since their deposition. However, further work is required before it is possible to say that no diagenetic changes similar to those observed in the fresh water alteration of the Bermuda limestones can occur in a marine environment.

$MgCO_3$ content of calcites at surface temperatures.

The $MgCO_3$ content of Mg-calcites has been determined experimentally for temperatures above 500°C (Graf and Goldsmith, 1955a, 1958; Harker and Tuttle, 1955; Goldsmith and Heard, 1961). The ex-solution curve for the Mg-calcites has been extrapolated visually to the temperatures at which diagenesis took place in Bermuda. Assuming that the experimental data are correct, the extrapolated curve indicates that the calcites formed during diagenesis at surface temperatures should contain 1 mol % $MgCO_3$ or less.

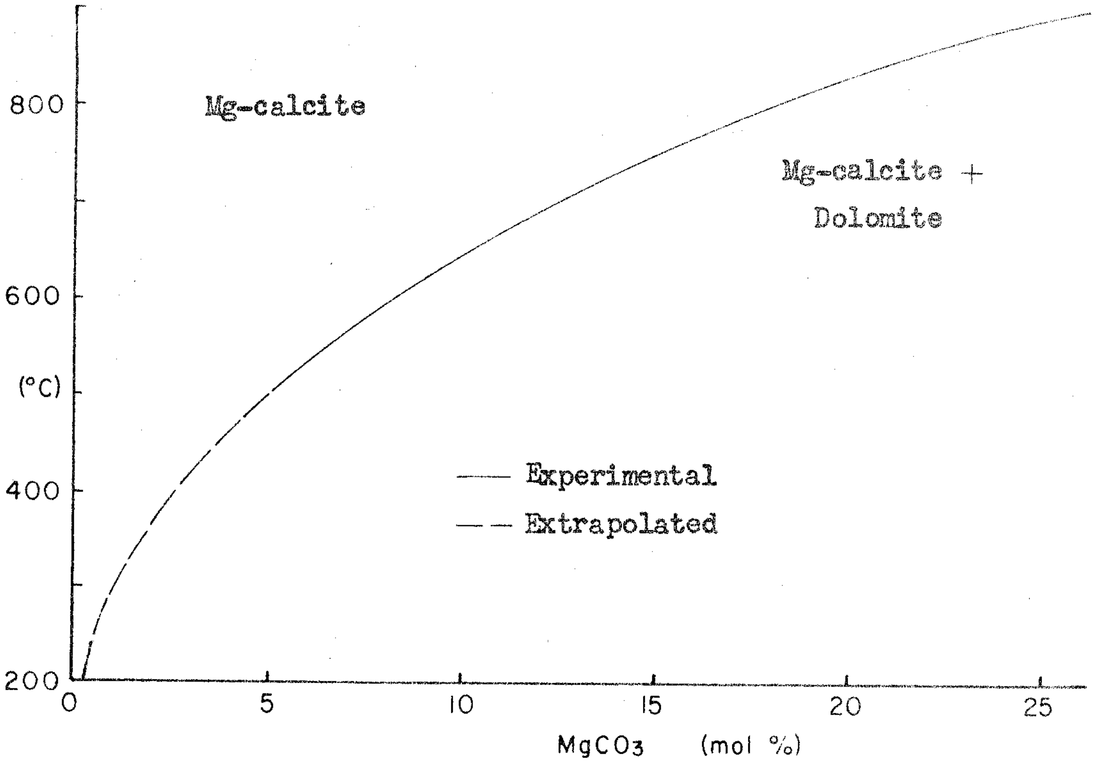


Figure 27. Exsolution curve for Mg-calcites.

As discussed in previous sections, the secondary calcites formed by deposition from solution, and the originally high-Mg calcites from which the Mg has been leached, have between 1 and 3 mol % $MgCO_3$ in solid solution. At first glance the $MgCO_3$ contents of these calcites seem to be the result of two different processes. In the secondary calcites, the $MgCO_3$ content appears to be controlled by the processes of deposition. In the originally high-Mg calcites, the present $MgCO_3$ contents appear to result from a depletion process in which the Mg is removed from the calcite. The data do not show conclusively that two different processes are involved. Goldsmith (1960) has postulated that the removal of Mg from the originally high-Mg calcites probably involves aqueous solution and recrystallization or replacement, so that the process which controls the Mg content may actually be the same for both types of calcites.

The lack of agreement between the extrapolated experimental curve and the observed $MgCO_3$ contents of the calcites formed in the Pleistocene limestones may be explained by one of two possibilities: 1) the experimental curve extrapolated to these temperatures has no significance or 2) the Mg content of the calcites formed during diagenesis is controlled by a non-equilibrium process.

Additional work is required to resolve this problem. It is necessary to know the exact mechanism or mechanisms by which Mg is removed from the Mg-calcites. With a knowledge of the mechanisms involved it would be possible to determine whether different processes do result in Mg-calcites containing more than 1 mol % $MgCO_3$, or if only one mechanism is operative in controlling the Mg content of calcites.

If more than one process is found to form Mg-calcites containing more than 1 mol % $MgCO_3$, then additional experimental work is needed to determine the $MgCO_3$-$CaCO_3$ exsolution curve below 500°C.

Conclusions

1. The diagenetic environment of the Pleistocene limestones on Bermuda was characterized by low pressures with essentially no compaction.

2. The temperature of the environment was between 0 and 30°C.

3. All of the limestones studied are presently within the unsaturated fresh water zone, but they may have been saturated with fresh water during times of higher sea level. If the present distribution of brackish and marine water underlying the island is typical of most of the Pleistocene, only the limestones from the Walsingham district were saturated by sea water during times of higher sea level.

4. Because of possible variations in the temperature and δO^{18} values of the fresh water during Pleistocene times, the O^{18}/O^{16} ratio of the carbonates cannot be used alone to distinguish fresh water

diagenetic alteration from diagenesis in other environments.

5. The secondary calcites and the Pleistocene limestones which have been subjected to diagenetic alteration in a fresh water environment have δC^{13} values of -4 to -10‰. There appears to be no source other than a fresh water environment for carbonates with such δC^{13} values. Thus, the presence of carbonates with such δ values could be used to indicate the existence of fresh water diagenetic alteration in a limestone.

6. The removal of aragonite and the removal of Mg from high-Mg calcites can be interpreted as the elimination of metastable carbonate phases from the sediments. The stable carbonate phase at the temperatures and pressures at which diagenesis occurred in Bermuda appears to be low-Mg calcite (less than 3 mol % $MgCO_3$).

7. Extrapolation of the experimental data on the $MgCO_3$ content of calcites to lower temperatures indicates that the equilibrium $MgCO_3$ contents of calcites formed during diagenesis should be less than 1 mol % $MgCO_3$. The calcites in the diagenetically altered Pleistocene limestones contain from 1 to 3 mol % $MgCO_3$. The reason for this discrepancy is not understood.

APPLICATIONS OF CRITERIA TO OTHER CARBONATE SECTIONS

The results obtained from the study of the Bermuda limestones show that fresh water alteration produces changes in the mineralogy, trace element content and isotopic composition of the altered limestones. Samples from Bikini Atoll, Eniwetok Atoll and the McLish limestone of Oklahoma were analyzed to determine whether the criteria for detecting fresh water alteration in marine carbonates of Bermuda were applicable.

The samples from Bikini Atoll and Eniwetok Atoll come from a geologic setting similar to Bermuda. Therefore the results obtained from the study of these carbonate sections should be directly comparable with those from Bermuda.

The samples analyzed from the McLish formation (mid-Ordovician) of Oklahoma are quite different in age and in geologic setting from the other carbonates studied. These samples were analyzed to see if the diagenetic effects reflected the difference in geologic setting and post depositional history of the limestone.

Bikini Atoll

Core samples from the boring operations on Bikini Atoll were provided by Dr. J. I. Tracey of the U. S. Geological Survey.

The geology of Bikini Atoll and the surrounding atolls has been extensively studied (U. S. Geological Survey Professional Paper 260). Detailed studies of the cores and cuttings from the boring (Emery et al., 1954) have shown that the sediments throughout the entire section are shallow water deposits which formed in a lagoon similar to the present. Thus, the problem of differences resulting from deposition in grossly different environments is eliminated.

It has been postulated that the carbonates from parts of the boring were exposed to fresh water alteration at least twice during their history (Ladd and Tracey, 1957). A 24-foot recrystallized limestone was penetrated at a depth of 1127 feet (Miocene). Moderate to complete recrystallization was found in the section between 294 and 450 feet, and some alteration was present to depths of around 700 feet. The shallow zone of alteration (200 to 800 feet) was thought to have formed during Pleistocene emergence of the atoll. Unaltered shells of terrestrial gastropods were recovered from the cores of the highly altered limestone (Ladd, 1958) at depths of 400 to 1800 feet on Bikini Atoll. From these two lines of evidence it has been postulated that parts of the atoll were subaerially exposed during parts of the Miocene and during the Pleistocene periods. This evidence did not prove, however, that the alteration of the carbonate sediments occurred at the time of emergence.

$SrCO_3$ and $MgCO_3$ contents of the Bikini core samples.

Aragonitic skeletal fragments of pelecypods, Halimeda and Porites from the recrystallized zone above 600 feet and from the portions of the core below the zone of recrystallization were analyzed by emission spectroscopy to determine the $SrCO_3$ and $MgCO_3$ contents. In addition, the $SrCO_3$ and $MgCO_3$ contents of limestones (matrix) were determined. These data are shown in Table 24.

Discussion

The $SrCO_3$ content of the aragonitic fragments of Halimeda and Porites from living organisms and from the core ranged from 1.0 to 1.2 mol % $SrCO_3$. The analyses show no significant difference between the values for living and fossil fragments. The aragonitic pelecypod fragments have a much lower $SrCO_3$ content (0.2 to 0.4 mol % $SrCO_3$) but again the values from the fossil fragments are within the possible range of variation of living organisms in Bermuda (see Fig. 16). No data are available on the Sr content of pelecypod shells from Bikini.

The limestone samples contain between 0.07 and 1.1 mol % $Sr CO_3$. The calcitic limestone sample from 1135 feet in the core contained the lowest $SrCO_3$ content (0.07 mol % $SrCO_3$). The samples containing large amounts of aragonite had at least 10 times this amount of $SrCO_3$ and the sample containing the largest amount of aragonite also

TABLE 23. Mineralogy, $SrCO_3$ and $MgCO_3$ content of Bikini core samples. (Analyst - EG)

Sample	Material	Depth	Calcite (%)	$MgCO_3$ (mol %)	$SrCO_3$ (mol %)
75	Pelecypod shell fragment	15'	tr(?)	0.5	0.4_0
76	" " "	180'	3%	0.0_7	0.2_2
70	" " "	925'	3%	0.1_0	0.2_5
79	" " "	1082'	0	0.0_7	0.3_0
64	*Porites sp.* living	-	tr(?)	0.4_5	1.1_0
74	" "	635'	1%	0.3_0	1.0_2
67	*Halimeda sp.* living	-	2%	0.3_0	1.2_5
66	" "	55'	3%	0.4_5	1.2_5
72	Calcite matrix	1135'	100%	3.0	0.0_7
95	Unaltered matrix	55'	32%	3.8_0	0.7_9
96	" "	195'	40%	1.5_0	0.9_8
97	" "	940'	23%	1.7_5	1.1_0
71	Chalky matrix	125'	64%	1.3_0	0.7_2

had the highest $SrCO_3$ content (1.1 mol % $SrCO_3$). These data indicate that the aragonite has a high-Sr content (1 mol % $SrCO_3$ or more) and is probably derived from coral or Halimeda. As shown previously, the δ values of these limestones indicate that coral is the most likely contributor if the aragonite is derived from the skeletal fragments of sediment contributing organisms.

The $MgCO_3$ contents of the Halimeda and Porites fragments range from 0.3 to 0.4 but again there appears to be no significant difference between fragments of living organisms and fossil fragments. The aragonitic pelecypod fragment from 15 feet in the core has 0.5 mol % $MgCO_3$, which is significantly higher than the fragments from deeper in the core which contain 0.1 mol % $MgCO_3$ or less. It is impossible to say whether this represents original difference in $MgCO_3$ content or loss of Mg resulting from diagenetic processes.

The $MgCO_3$ content of the limestone ("matrix") samples ranged from 1.5 to 3.8 mol % $MgCO_3$. There is no correlation between the amount of calcite and the $MgCO_3$ content of the samples.

As discussed previously, there is no evidence of fresh water alteration of the core below 700 feet with the possible exception of the recrystallized limestones at 1127-1151 feet (Miocene age). These cores offer one of the few carbonate sections where the sediments appear to have been continuously exposed to sea water since their deposition with no chance for fresh water alteration. Thus, they offer a chance to examine the effect of sea water on the $MgCO_3$ content of the limestones.

Bulk analyses of the limestone samples from the core have been published by Emery et al. (1954, pp. 66, 84-87). These analyses from various sections of the core have been grouped together and the average $MgCO_3$ contents from various segments of the core are as follows:

Depth (feet)	Average $MgCO_3$ content(range)(mol %)	Age(ibid., p. 80-84)
0-100	4.2 (1.4 to 9.6) (5 analyses)	Recent
100-700	1.4 (0.8 to 2.4) (5 analyses)	Pleistocene and Pliocene
700 to 2600	2.0 (1.4 to 4.0) (5 analyses)	Pliocene and Miocene

On the basis of the geological evidence and the δO^{18} and δC^{13} values of the secondary calcites, the section of the core from 100 to 700 feet has been shown to have been subjected to fresh water alteration, and has significantly lower $MgCO_3$ contents than the portions of the core above and below it.

The $MgCO_3$ contents of the limestones from the lower portion of the core are also significantly lower than in the Recent sediments in Bikini. This may be caused by the original sediments having little Mg-calcite or it may indicate that Mg is leached from Mg-calcites even in a marine environment. Further work to answer this question requires analyses of fragments of originally high-Mg calcitic organisms from these limestones.

O^{18}/O^{16} and C^{13}/C^{12} ratios of the Bikini core samples.

Samples of unaltered aragonitic skeletal fragments of sediment contributing organisms, secondary calcites from the limestones and limestone samples from the cuttings were analyzed. The mineralogy and δO^{18} and δC^{13} values for these samples are given in Table 24. The δO^{18} and δC^{13} values are plotted in Figure 28.

Discussion

As Figure 28 shows, the δO^{18} and δC^{13} values of the samples analyzed form three fairly distinct groups. The mollusc and Halimeda fragments from various depths in the core form a distinct group characterized by positive δC^{13} values (δC^{13} =+0.4 to +4.0 ‰) and slightly negative δO^{18} values (δO^{18} = -0.3 to -2.2 ‰). This corresponds to the δ values of the carbonates from the sediment contributing organisms in Bermuda except that the δO^{18} values of the mollusc fragments are more negative as expected because of the higher temperatures in Bikini (Emery et al., 1954, p. 18). It is interesting to note, in contrast to Bermuda, that the Halimeda fragments in Bikini have the same δ values as the mollusc fragments.

TABLE 24. O^{18}/O^{16} and C^{13}/C^{12} ratios of core samples, Bikini Atoll

Sample number	Sample description*	Depth (feet)	δO^{18} (‰)	δC^{13} (‰)	Calcite (%)
64	Porites lutea, Boro Island		-5.9_2	-1.8_0	tr
74	Porites sp.	635	-5.4_5	$+0.1_8$	1
67	Halimeda sp., Bikini Lagoon		-1.9_3	$+2.7_4$	2
66	'' ''	55	-1.9_6	$+2.6_9$	3
75	Mollusc shell fragments	15	-1.6_1	$+0.3_6$	tr
76	'' '' ''	180	-1.1_8	$+2.9_0$	3
77	'' '' ''	275	-0.3_6	$+2.0_5$	tr
70	'' '' ''	925	-1.3_4	$+3.9_2$	3
73	'' '' ''	925	-1.3_8	$+3.9_2$	0
78	'' '' ''	1082	-2.1_6	$+2.2_8$	0
79	'' '' ''	1082	-2.0_6	$+2.3_0$	0
95	Limestone (unaltered matrix)	55	-3.9_5	-0.7_2	32
96	'' '' ''	195	-4.5_1	-1.0_7	40
97	'' '' ''	940	-4.1_9	-0.0_8	23
69	Coarsely crystalline calcite	80	-7.4_6	-9.7_2	100
71	Limestone (matrix altered)	125	-5.0_2	-0.4_6	64
68	'' (matrix replaced by calcite)	270	-6.1_7	-7.3_6	94
106	'' '' '' '' ''	312	-6.2_5	-5.7_8	93
107	'' (crystalline calcite)	330	-6.9_5	-2.5_8	95
108	'' (chalky calcite)	445	-4.8_8	-2.6_7	100
65	'' (coarsely crystalline calcite)	635	-6.3_4	-5.1_6	100
72	'' (calcite matrix)	1135	-5.1_2	-0.7_1	100

*Sample descriptions by Dr. J. I. Tracy (personal communication).

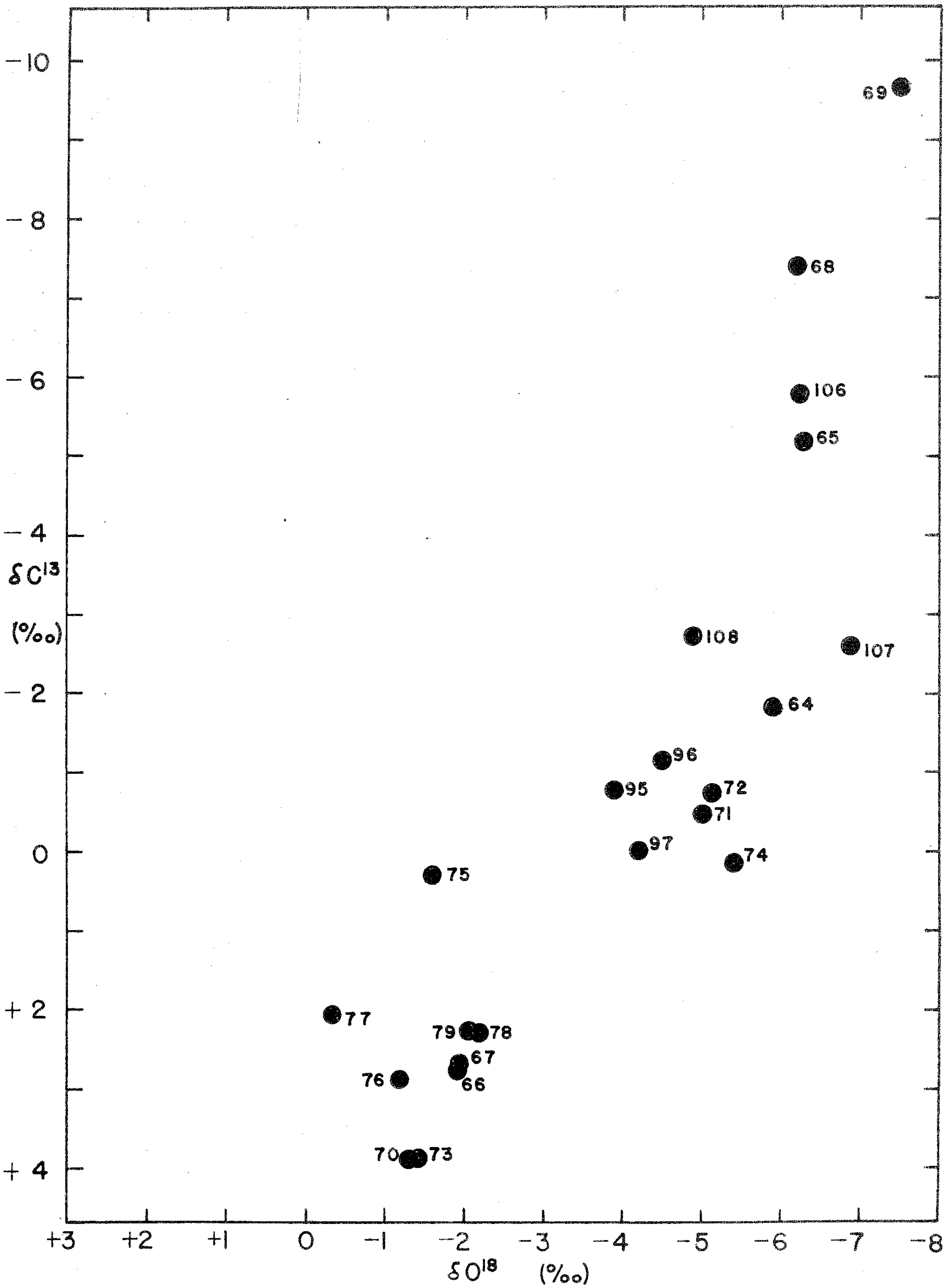


Figure 28. O^{18}/O^{16} and C^{13}/C^{12} ratios of core samples from drilling operations on Bikini Atoll.

The second group of analyses consists of the sparry calcites and crystalline calcites from the depths of 635 feet or less in core. The δO^{18} values of this group of samples ranges from -6.2 to -7.5 ‰ and the δC^{13} values range from -5.2 to -9.6 ‰. The values for this group of samples are very similar to the δO^{18} and δC^{13} values of the fresh water and secondary calcites from Bermuda. In the Bikini core, these samples come from the zone of recrystallization which extends downward in the core to almost 700 feet.

If sea level during the Pleistocene glaciations were 600 feet lower than its present location, these limestones could have been exposed to fresh water alteration. The occurrence of a terrestrial gastropod in cores from depths of 400 feet (Ladd, 1958) supports the hypothesis that these limestones were subaerially exposed during part of Pleistocene time. Thus the geologic evidence lends support to the hypothesis that these limestones were subjected to fresh water alteration during Pleistocene time and that the similarity of the δ values of these calcites and the fresh water calcites in Bermuda shows that the calcites could only have formed from fresh water.

The third group of analyses have δ values intermediate between the two previous groups. These samples which include fragments of coral, and limestones from various depths, have δO^{18} values of -3.9 to -6.9 ‰ and δC^{13} values from 0 to -2.7‰.

Among the limestones in this group of analyses are friable limestones which are described as "matrix" or "paste" because of their appearance in thin section (Emery et al., 1954, pp. 214-259). This material appears as a "tan to light brown carbonate, almost isotropic under crossed nicols" (ibid., p. 235). The origin of the "paste" material is unknown although in one instance a coral fragment is described as decomposing to form "paste" (ibid., p. 257).

The δO^{18} and δC^{13} values of the "matrix" material may be explained by two different processes. The "matrix" samples from depths of around 700 feet in the core may be mixtures of carbonate with δO^{18} and δC^{13} values similar to the values of the mollusc fragments from the core and secondary calcites which formed during subaerial exposure. This mechanism for changing the δO^{18} and δC^{13} values was demonstrated in the Bermuda limestones.

For the matrix samples from below 700 feet, the explanation offered above is not tenable as no secondary calcites have been found. The simplest explanation is that these samples are mixtures of carbonates derived from molluscs and corals. If this is the case, the δO^{18} and δC^{13} values suggest that coral has been a major contributor to the "paste".

The single sample of the recrystallized limestone from 1135 feet in the core (Miocene age) has δO^{18} and δC^{13} values which fall into the intermediate group of analyses. The limestone does not have the isotopic composition which characterizes extensive alteration in a fresh water environment. As discussed previously, this does not rule out alteration in the fresh water zone, but without further analyses, the δ values are indeterminate.

Eniwetok Atoll

Samples from drilling operations on Eniwetok Atoll were made available by Dr. H. S. Ladd and Dr. J. I. Tracey, Jr. of the U. S. Geological Survey. The samples were taken from several different borings, but most of the deeper samples come from F-1 (Ladd and Schlanger, 1960; Ladd, Ingerson, Townsend, Russel and Stephenson, 1953).

Several "leached" and "recrystallized" limestone zones were encountered in the drilling (Ladd and Schlanger, 1960) at depths similar to those in Bikini. A terrestrial gastropod was recovered at a depth of around 800 feet. Pollen was encountered at depths of approximately 1000 feet below sea level (upper Miocene) (Ladd, 1958; Ladd and Tracey, 1957). These data suggest several periods of emergence in the history of Eniwetok.

The δO^{18} and δC^{13} values were determined for unaltered mollusc fragments, sparry calcites from the shallow zone of alteration and altered limestones and a dolomite from the deeper zones of alteration.

The δO^{18} and δC^{13} values and the mineralogy of these samples is presented in Table 25 and figure 29.

Discussion

The unaltered Tridacna fragment from 15 feet and the mollusc fragment from 830 feet have similar δO^{18} (δO^{18} = -0.8 and -1.5 ‰ respectively) and δC^{13} (δC^{13} = +2.8 and +3.1 ‰ respectively) values which correspond to the results obtained from the analyses of mollusc fragments from Bikini and Bermuda. These are probably the original δ values for the skeletal fragments.

The limestone and sparry calcite sample from the shallow zone of alteration (less than 700 feet) have almost identical δO^{18} and δC^{13} values (δO^{18} = -6.0‰, δC^{13} = -6.9 ‰). These δ values correspond to the values obtained from the fresh water carbonates and secondary calcites on Bermuda and the limestones from similar depths in Bikini. These values are interpreted as indicating a fresh water origin for these carbonates during a time of lower sea level during glacial Pleistocene times.

The dolomite sample has a distinctively different isotopic composition (δO^{18} = + 1.9‰ δC^{13} = + 1.1 ‰) from the δ values observed in the limestone samples.

TABLE 25. O^{18} and C^{13} content of core samples, Eniwetok Atoll.

Sample number	Sample Description	Depth (feet)	δO^{18} (‰)	δC^{13} (‰)	Calcite (%)
103	*Tridacna* fragment, unaltered	13-24	-0.8_6	$+2.8_5$	0
102	Mollusc fragments, unaltered	830-840	-1.5_3	$+3.1_9$	tr
105	Altered limestone	254-259	-5.9_0	-6.9_0	100
99	Sparry calcite	600-625	-6.0_0	-6.8_8	95
100	Highly altered calcitic limestone	1232-1248	-2.6_6	-1.6_8	100
101	" " " "	1232-1248	-1.9_4	-0.2_4	100
98	" " " "	2650-2675	-0.7_6	-1.7_9	100
104	Dolomite	4316-4341	$+1.9_0$	$+1.1_0$	tr

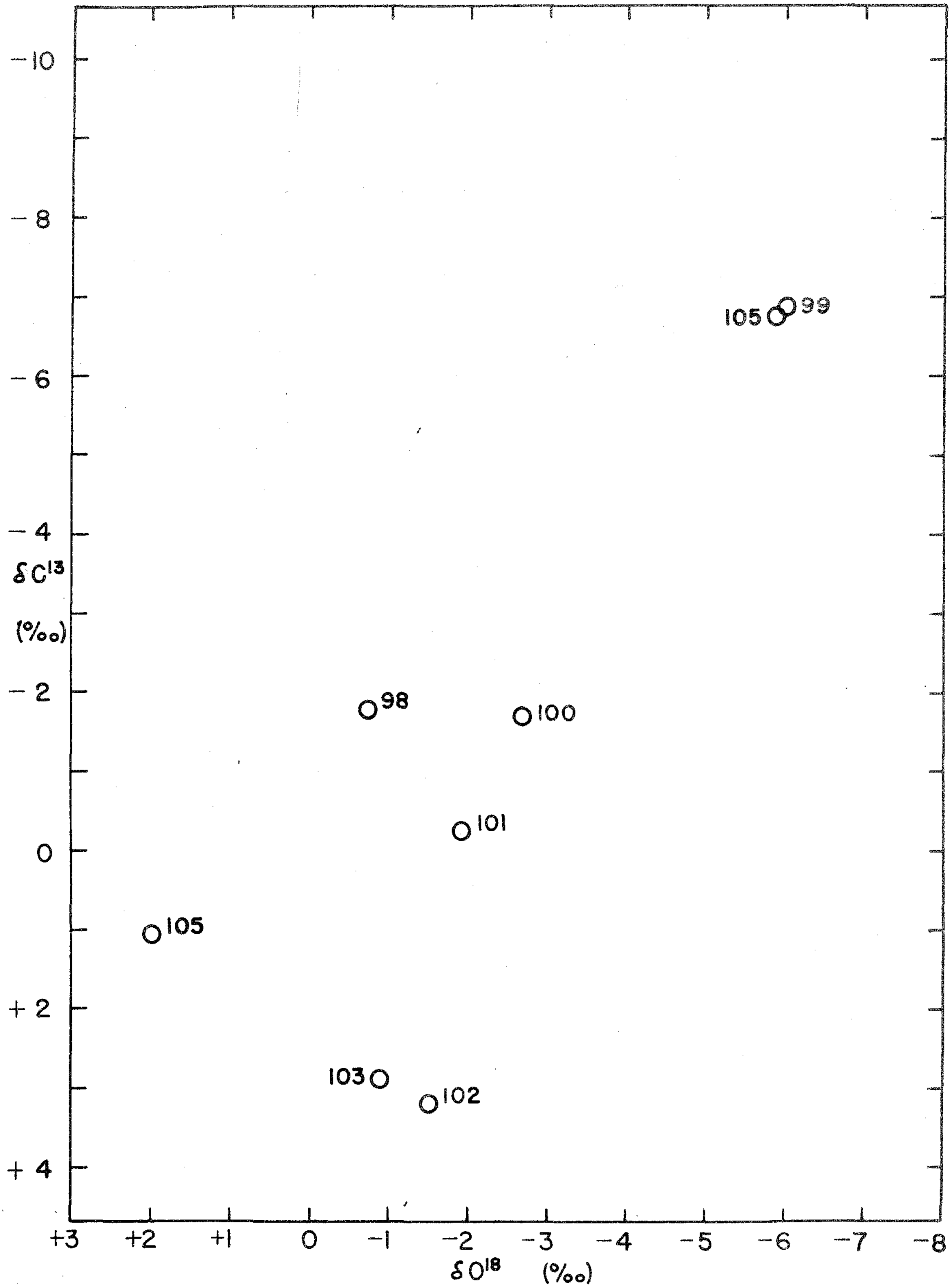


Figure 29. O^{18}/O^{16} and C^{13}/C^{12} ratios of core samples from drilling operations on Eniwetok Atoll.

The samples of altered limestones from 1240 and 2660 feet (Miocene) have δ values (δO^{18} = -0.7 to -2.6 ‰, δC^{13} = -0.2 to -1.7 ‰) intermediate between those found in the unaltered skeletal fragments and the presumably fresh water carbonates from the shallow portions of the hole. These 3 values may be explained by one of several different possibilities. These limestones may consist of mixtures of sediment contributing organisms which would give these results. The limestones may have been subjected to fresh water alteration during Miocene time and their present isotopic composition may result from a mixture of unaltered skeletal fragments and secondary calcites. A third possibility is that the dolomitization which occurred in the limestones may have affected these limestones, resulting in their present isotopic composition.

McLish Limestone, Oklahoma

The McLish formation is a part of the Simpson Group of mid-Ordovician age (Chazyan) (Twenhofel et al., 1954). The Simpson Group is widespread in southern Oklahoma, cropping out in the Arbuckle Mountains and recognized in the subsurface of the Anadarko Basin (Decker, 1939). The speciment from the Townsend Quarry, T 1. N, R 6E, Pontotoc County, Oklahoma, was furnished by Dr. W. E. Ham of the Oklahoma Geological Survey.

Examination of a polished surface of the McLish limestone showed a yellowish gray, very fine grained limestone with a slightly porcellaneous appearance. Within the fine grained limestone are recrystallized shells of orthocerid cephalopods and gastropods (*Maclurites*). Fragments of algae (*Girvanella* and *Hedstromia*) are locally abundant (W. E. Ham, personal communication). The presence of these fossils indicates a marine origin for the limestone.

Many irregularly connected stringers of brownish gray sparry calcite are distributed throughout the specimen. Locally this same type of calcite forms crystalline areas up to 2 cm. long. Gray sparry calcite veins cut both the porcellaneous limestone and the brownish sparry calcite areas. The calcite veins are thought to be of Pennsylvanian age (W. E. Ham, personal communication). This age assignment is based on an assumed relationship between the formation of the vein and the time of extensive faulting throughout the whole region (W. E. Ham, personal communication).

Using a dentist drill, samples for the analyses were ground from the polished surface from the limestone (without the calcite stringers), the sparry calcite area and the gray calcite veins.

$MgCO_3$ and $SrCO_3$ content of the calcites.

Analyses were made of the different generations of calcites in the McLish limestone. The results are as follows:

	$MgCO_3$ (mol %)	$SrCO_3$ (mol %)
Limestone	2.3_0	0.0_4
Sparry calcite	1.6_5	tr
Veins	1.1_0	tr

The $SrCO_3$ content is 0.04 mol % or less while the $MgCO_3$ content varies from 1.1 to 2.3 mol % $MgCO_3$. The $MgCO_3$ content of the limestone (2.3 mol % $MgCO_3$) is greater than the $MgCO_3$ content (1.6 and 1.1 mol % $MgCO_3$) of either of the two generations of secondary calcite. The $MgCO_3$ and $SrCO_3$ contents of the calcites in the McLish limestone are quite similar to those of the secondary calcites and Pleistocene limestones from the Walsingham and parts of the Belmont formations on Bermuda.

O^{18}/O^{16} and C^{13}/C^{12} ratios of the different generations of calcite.

Samples of the three different types of calcite were sampled and the δO^{18} and δC^{13} values determined for each of the different generations of calcite.

		δO^{18} (‰)	δC^{13} (‰)
48	Limestone	-5.5_1	$+0.4_0$
49	Brownish sparry calcite	-4.5_1	$+0.4_2$
50	Grayish sparry calcite veins	-2.8_6	-0.1_7

The δC^{13} values for all three calcites are between +0.4 and -0.2 ‰. These values suggest that the δ value of the carbon in all three carbonates is determined by the same reservoir and that little carbon has been derived from the soil zone.

The δO^{18} values of the calcites show a considerable variation with values ranging from -5.5‰ for the limestone to -2.8‰ for the gray calcite veins. These variations in the δ values for the oxygen can be explained by variations in the O^{18} content of the water from which the calcites precipitated or exchanged or by variations in the temperature at which the calcites formed if they formed from water with the same δO^{18} value. Since it can be shown that the limestone contains fragments of marine organisms, its δO^{18} value indicates that it has undergone diagenetic isotopic exchange during diagenesis.

Differentiation of diagenetic environments using O^{18}/O^{16} and C^{13}/C^{12} ratios.

The δO^{18} and δC^{13} values of the core samples from Bikini and Eniwetok Atolls show the same type of relationships that were found in the Recent sediments and Pleistocene limestones of Bermuda. The agreement of the results from these studies lends support to the hypothesis that fresh water diagenetic effects in limestones can be distinguished where the geological relationships are simple. In islands such as Bermuda and the Pacific atolls, the diagenesis must take place in either a fresh or marine environment. It has been shown that the isotopic composition of carbonates is controlled by the δO^{18} and temperature of the water from which they are deposited and by the δC^{13} value of the bicarbonate in the water. In the fresh water diagenetic environment, the δC^{13} value of the bicarbonate appears to be controlled by the CO_2 produced by biological processes in the soil. Data are not available to show that similar δC^{13} values of the bicarbonate could not be produced by some combination of factors in a marine environment.

The McLish limestone is an example of a type of diagenetic alteration which appears to be quite common in limestones. In this type of diagenetic alteration the original δC^{13} values are little changed by diagenetic alteration but the δO^{18} values become more negative than the original δ values of the carbonate sediment. This type of alteration was found in analyses of marine limestones by Baertschi (1957), and Clayton and Degens (1959). Clayton and Degens interpreted this alteration as an isotopic exchange between the carbonate and the interstitial fluids. They thought that the negative δO^{18} values indicated exchange with fresh water (i.e., negative δO^{18} values) at relatively low temperatures or exchange with sea water ($\delta O^{18} = 0$) at more elevated temperatures.

Additional work is required on marine limestones which can be shown to have remained submerged in sea water since their deposition to determine if the group of intermediate δ values (δO^{18} = -1 to -7 ‰, δC^{13} = 0 to -3 ‰) represent the effects of mixtures of skeletal fragments or if some type of diagenetic alteration or isotopic exchange with sea water has occurred in these sediments.

With the data presently available, it appears that the O^{18}/O^{16} and C^{13}/C^{12} ratios are the most useful in detecting Pleistocene fresh water diagenetic alteration of carbonate sediments in geologically simple situations such as Bermuda or the Pacific atolls.

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APPENDICES

APPENDIX I

DETERMINATION OF O^{18}/O^{16} AND C^{13}/C^{12} RATIOS

Sample preparation and analysis

Water samples were prepared for analysis using the techniques described by Epstein and Mayada (1953). Carbon dioxide was extracted from the carbonate samples using the techniques developed by McCrea (1950) and Urey et al. (1951). The analyses were made on a mass spectrometer of the type described by Nier (1947) with modifications by McKinney et al. (1950).

Definition of terms

The isotopic analyses of the samples are reported as deviations in the isotopic ratios from the isotopic ratio of a standard gas. The standard gas is CO_2 extracted from a Cretaceous belemnite from the Pee Dee formation. (McKinney et al., 1950; Urey et al., 1951). These results are reported in terms of the quantity δ which is defined as

$$\delta = \left(\frac{R_{\text{sample}} - R_{\text{standard}}}{R_{\text{standard}}}\right) \quad 10^3$$

where R is the ratio of the abundance of the ions as recorded by the mass spectrometer. In the analysis of the oxygen isotopes, R is the ratio of ions with mass 46 ($C^{12}O^{18}O^{16}$) and mass 44 ($C^{12}O^{16}O^{16}$). In the analysis of the carbon isotopes, R is the ratio of the abundance of ions of mass 45 ($C^{13}O^{16}O^{16}$) and mass 44 ($C^{12}O^{16}O^{16}$). These ratios are approximately the ratios of O^{18}/O^{16} and C^{13}/C^{12} respectively. All the δ values determined by the mass spectrometer were corrected for mixing in the valve system (Craig, 1957).

Analytical technique

The carbonate and water samples were analyzed in groups of 8 to 10 samples. The data for each group of analyses were corrected relative to the substandard prepared from the Belmont limestone,Stoke's Point, Bermuda, so the analyses are internally consistent to ± 0.2‰.

APPENDIX 2

X-RAY DIFFRACTION TECHNIQUES

Sample preparation

The samples were crushed in a steel mortar to a grain size of less than 0.5 mm and then ground in an agate mortar until all the sample passed through a 100 mesh silk screen. The powder was then mixed and stored in glass vials prior to analysis.

Equipment

A North American Phillips Company X-ray diffraction unit fitted with a goniometer spectrometer and Geiger counter was employed for all the analyses in this study. A Brown chart recorder was used to record the results. In some instances a Berkeley timer and automatic printer were used to record and print the time required to accumulate a pre-set number of pulses in the Geiger tube.

Sample mounting techniques

A flat, aluminum, rotating sample holder was used for the analyses. The holder was covered with a thin coating of Vaseline and approximately 2 mg of sample was brushed through a silk screen onto the greased surface. The excess sample on the holder was removed by gentle tapping of the inverted holder. A small amount of fluorite

(CaF_2) was added to the sample to serve as an internal standard. This technique is similar to that used by Chave (1954a) and Harker and Tuttle (1955). Using this technique and a rotating holder, the effects of preferred orientation were minimized. Although the average sample was approximately 2 mg, reproducible results were obtained from samples as small as 0.25 mg.

Mg determinations by X-ray diffraction analysis of calcite

Chave (1952) showed that there is a relation between the amount of $MgCO_3$ in solid solution in calcite and changes in the 3.04A peak of calcite. His curve was based on a series of organic calcites analyzed by wet chemical and spectrochemical techniques (Chave, 1954a). The analytical error in the analyses is not given. Chave's data, which were reported in weight percent $MgCO_3$, were recalculated to mol percent $MgCO_3$ and the portion of his curve below approximately 20 mol percent $MgCO_3$ is plotted in Figure A-1.

Goldsmith et al. (1955a) analyzed 34 organic Mg-calcites by spectrochemical methods and determined the changes in their interplanar spacings by X-ray diffraction. The resulting curve is also plotted in Figure A-1.

Goldsmith and Graf (1958) synthesized a series of Mg-calcites at high temperatures. From these inorganic Mg-calcites and "Specpure" calcite they determined a slightly different relationship between

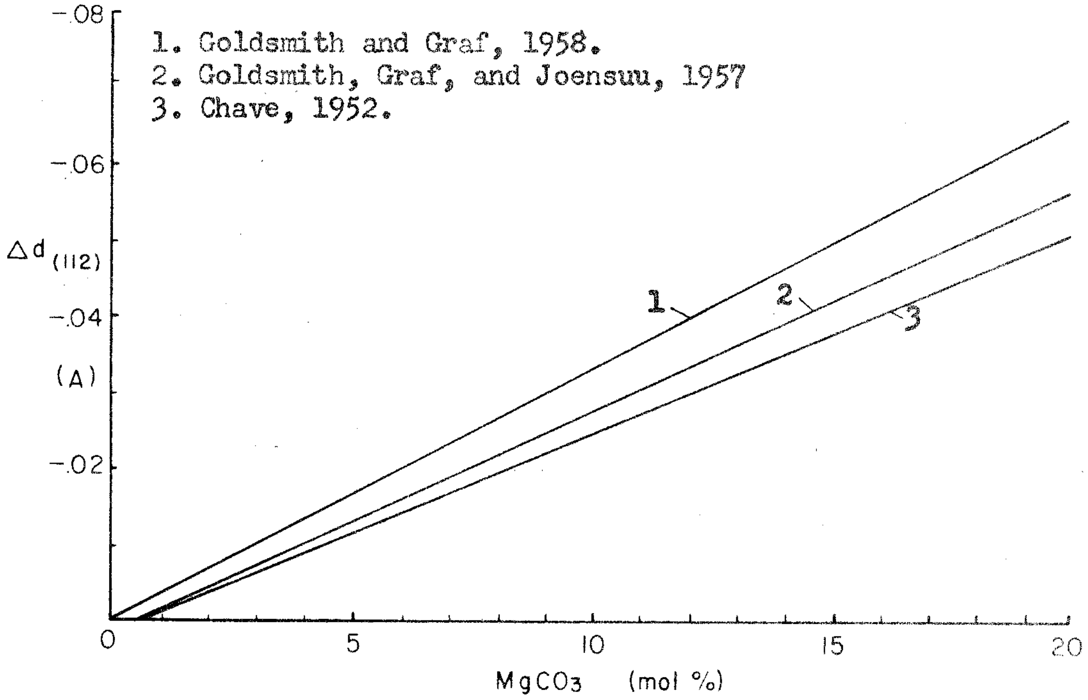


Figure A-1. Variation of $d_{(112)}$ spacing of Mg-calcites with increasing substitution of Mg.

the amount of $MgCO_3$ present and the interplanar spacings than was found in the organic calcites. This curve is also plotted in Figure A-1.

Figure A-1 indicates that the apparent $MgCO_3$ content of a calcite depends on the curve used for the analysis. For this study, the curve obtained by Goldsmith et al. (1955a) was used, because their study was based on organic Mg-calcites similar to those in the Bermuda sediments.

Resolution and accuracy of the determination of $MgCO_3$ content in calcites

From the analysis of prepared mixtures of Mg-calcites it has been determined that the instrumental conditions described are capable of resolving the 3.04 Å peaks of calcites containing different amounts of $MgCO_3$ if the peaks are separated by more than 0.20° (equivalent to approximately 7 mol percent $MgCO_3$) and if the two calcites are present in roughly equal amounts. Where the instrument is not capable of resolving the individual peaks, the resulting composite peak location is that for the average of the compositions of the two calcites.

The standard deviation of 0.01° 2θ is equivalent to an uncertainty of approximately 0.3 mol percent $MgCO_3$. Using the internal standard technique for the analysis, the results obtained are reproducible to within ± 0.5 mol% $MgCO_3$.

Variations in intensity of the diffraction pattern of Mg-calcites

The analysis of prepared mixtures of Mg-calcites from echinoid spines and tests, which contain different amounts of $MgCO_3$, indicated a decrease in the intensity of the diffraction pattern of calcite with increasing amounts of $MgCO_3$ in solid solution. In addition to the echinoid materials, Mg-calcites from lithothamnoid algae, Goniolithon, and Homotrema rubrum were carefully weighed and mixed with fluorite (7 parts calcite, 1 part fluorite).

Each of these mixtures was analyzed and the ratio of the intensity of the calcite peak to the fluorite peak (I_c/I_f) was determined. The results shown in Figure A-2 indicate a definite decrease in the relative intensity with increase in the $MgCO_3$ content. No effect of crystal size on this trend is apparent, as the same results were obtained from mixtures of calcites from echinoids (large single crystals) and from algae and foraminifera (small crystals).

The ratio of the areas under the calcite and fluorite peaks was determined in three cases to see if the reduction in intensity was simply caused by a broadening of the peak. These area ratios (Fig. A-2) show the same trend that was found for the intensity ratios. Therefore no advantage is obtained from the use of the areas of the peaks.

To compensate for the reduction in intensity shown in Figure A-2, correction factors were determined (Fig. A-3). The low-Mg

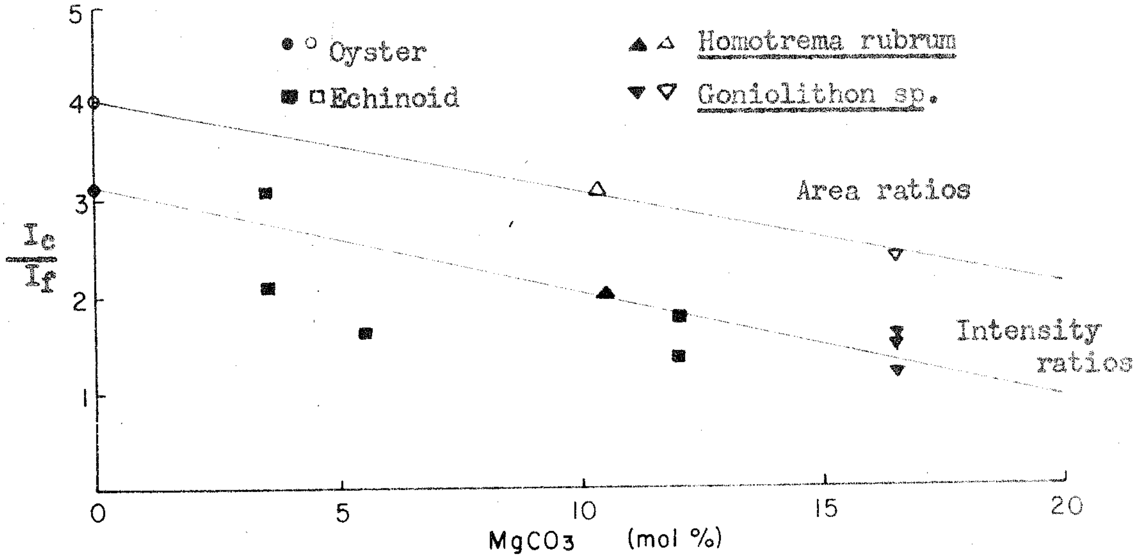


Figure A-2. Reduction of intensity of (112) reflection of Mg-calcites with increasing $MgCO_3$ content.

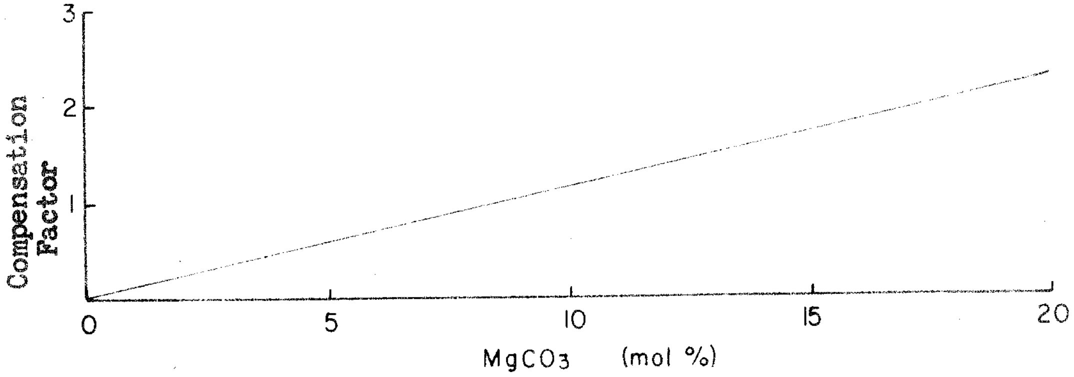


Figure A-3. Compensation factors for Mg-calcites.

calcite from an oyster (Woods Hole, Mass.) was used as the standard because the calcite-aragonite technique for determining the amount of aragonite in a calcite-aragonite mixture was based on a low-Mg calcite. These compensation factors were used in all cases where it was necessary to determine the intensity of a calcite peak.

Analysis of Mg-calcite mixtures

X-ray analysis of the Mg-calcites in the sediments shows a multiple peak, made up of overlapping but distinctly different peaks. The multiple peaks indicate the presence of calcites, containing different amounts of $MgCO_3$ in solid solution. The number and location of these multiple peaks is limited by the ability of the instrument to resolve the separate reflections.

From such multiple peaks the relative amount of each type of calcite can be calculated by graphically determining the intensity of the component peak. Correction for the mutual interference of the peaks is made by assuming that each peak is symmetrical, and by graphically determining the apparent intensity of each peak. The error introduced by the peak asymmetry, resulting from the time constant in the circuit, is reduced by scanning the peak in both directions; i. e., through increasing values of 2θ and decreasing values of 2θ. Averaging the results obtained in each scan tends to cancel the errors. The apparent intensity is corrected by the appropriate compensation factors (Fig. A-3). The location of each component peak is determined graphically and its apparent position is corrected for any displacement of the fluorite peak.

Mixtures of calcites from sediment contributors with different $MgCO_3$ contents were prepared and analyzed to determine the accuracy of the method. Table A-1 shows the resulting apparent and corrected data. Using the technique and compensation factors discussed above, results were found to be within 10 percent of the true values..

Procedure for aragonite determinations

The portion of the diffraction pattern containing the 3.40 peak of aragonite was scanned to determine the presence of aragonite. If aragonite was found, the goniometer was set at the point of maximum intensity and the chart recorder was used to record the intensity of the peak. The background intensity was determined in a similar manner. The same results were obtained using the rate meter circuit with a Berkeley timer and automatic printer to determine the time required to accumulate a pre-set number of pulses.

The calcite intensity was determined by graphically determining the intensity of the calcite peaks. The average intensity was corrected by the appropriate compensation factor, as discussed in the preceding sections.

Determination of the amount of aragonite in the sediments

To calculate the amount of aragonite in the sediments, the

TABLE A-1. X-ray diffraction analyses of prepared mixtures of Mg-calcites.

Source of Calcite	$MgCO_3$ Content (mol %)	True Composition	Apparent Composition	
			Intensity Uncompensated	Intensity Compensated
Iceland Spar xl	0	50%	60%	52%
Echinoid	11.5	50%	40%	48%
Echinoid	6.7	50%	54%	49%
"	12.0	50%	46%	51%
Echinoid	4.4	50%	56%	49%
"	11.5	50%	44%	51%
Echinoid	12.0	50%	45%	53%
"	4.5	50%	55%	47%
Echinoid	6.7	50%	26%	44%
Iceland Spar xl	0	50%	74%	56%

assumption is made that the intensity of the diffraction peaks of calcite (after compensation) and aragonite varies linearly with different amounts of the minerals present. It was also assumed that the sample mounting techniques, discussed earlier, minimized or eliminated preferred orientation in the sample and that the sample was ground finely enough to eliminate self-absorption of X-rays.

The intensity ratios of the calcite and aragonite peaks were converted to the weight percentage of aragonite by the following equation:

$$\frac{kA}{kA + C} = \text{weight percent aragonite}$$

where A is the intensity of the 3.40 A peak of aragonite and C is the compensated intensity of the 3.04 A peak of calcite. The normalizing factor k corrects for the difference in apparent intensity observed from equal amounts of calcite and aragonite. For mixtures of low-Mg organic calcites and aragonite, the value of k = 3.76 has been determined (A. A. Chodas, personal communication).

The importance of using the compensation factor to correct for the decrease in the calcite diffraction intensity can be seen in Figure A-4. Figure A-4a shows the results obtained from prepared mixtures of Mg-calcites and aragonite without the use of the compensation factors. The same data are shown in Figure 36b after the calcite intensities have been compensated. These mixtures were made from the materials listed in Table A-2.

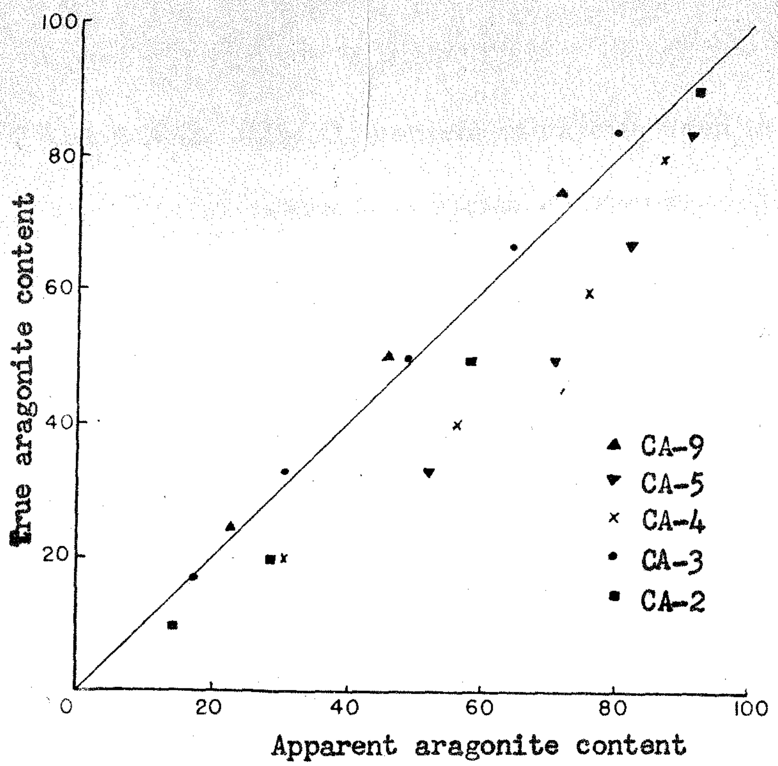


Figure A-4a. Apparent aragonite content of prepared mixtures of calcite and aragonite (calcite peak intensity uncompensated).

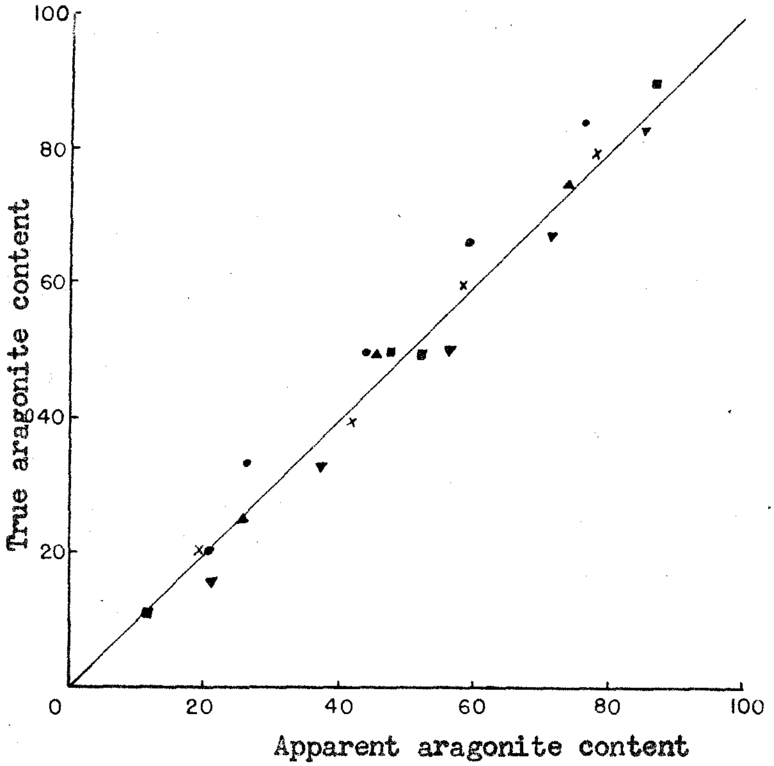


Figure A-4b. Apparent aragonite content of prepared mixtures of calcite and aragonite (calcite peak intensity compensated).

TABLE A-2. $MgCO_3$ content of calcite used in prepared aragonite-calcite mixtures.

	Aragonite	Calcite	$MgCO_3$ in the calcite(mol%)
CA-1	*Strombus gigas*	Echinoid	12.0
			6.7
CA-2	"	"	4.5
			6.7
CA-3	"	"	4.5
			12.0
CA-4	*Halimeda sp.*	*Homotrema rubrum*	11.3
CA-5	"	"	
	Strombus gigas	*Goniolithin sp.*	16.6
CA-9	*Halimeda sp.*	*Homotrema rubrum*	11.3
	Strombus gigas	*Amphistegina lessonii*	2.5

The results obtained for the mixtures, as shown in Figure A-4, still exhibit systematic differences from the true values. However, the use of the appropriate compensation factor greatly reduces the error so that the results when corrected are within 5% of the true value.

An additional check on the accuracy of the method is available. From the results of the petrographic analyses, the percentage of aragonite in the sediment can be calculated from the known mineralogy of each sediment with an estimated accuracy of 10%. For these calculations it was assumed that the unknown grains had the composition of the average beach sediment in Bermuda, approximately 50% aragonite. The results are shown in Table A-3. The data obtained from these two techniques agree within 2%.

TABLE A-3. Aragonite content of Recent sediments as determined by X-ray diffraction and petrographic techniques.

	X-ray diffraction	Petrographic analysis
Shelly Bay beach sand	70%	71%
Mangrove Bay beach sand	48%	47%
Tucker's Town dune sand	48%	48%
Elbow Bay dune sand	47%	49%
Warwick Long Bay beach sand	35%	36%
Devonshire Bay beach sand	44%	43%
John Smith's Bay beach sand	36%	35%

APPENDIX 3

EMISSION SPECTROGRAPHIC ANALYSES FOR $MgCO_3$ AND $SrCO_3$ CONTENTS OF CARBONATES AND WATER SAMPLES

Limestone-DC Arc Method

Certain of the impure limestones were analyzed by an optical emission, DC arc, spectrographic method developed by A. A. Chodas and E. Godijn to determine the concentration of Sr and Mg. One part of the limestone sample was mixed with 24 parts of a 1:5 mixture of CuO and graphite to control the burning characteristics. The samples were placed in an electrode and arced to completion in a Jarrell-Ash Varisource spectrograph. The spectrum was recorded on III-0 plates. The Cu in the matrix served as the internal standard for these analyses. Standards were made from National Bureau of Standards limestone (No 1a) diluted with "Spec-pure" calcium carbonate.

The transmission of various spectral lines was determined on a Jarrell-Ash microphotometer. Lines whose transmission was less than 5% or greater than 95% were rejected. The transmission of each line was converted to intensity and the ratio of the intensity of each line to the intensity of the Cu 3073.8 Å line was calculated. Working curves relating the intensity of the standards to the known composition were drawn for each plate. From these working curves, the composition of each sample was determined, using the lines as shown in Table A-4. At least two analyses were made of each sample and the results appear to be reproducible to within ± 10% of the amount of the element present.

Limestones - Cu spark methods

For limestones in which only the variation in the Sr and Mg content was desired, the Cu spark method developed by A. A. Chodas (Goldsmith and Graf, 1958a) was used. The line intensities were determined in the same manner as for the DC arc method. For Mg, the line pair Mg 2802.7Å/Mo 2848.2Å was used for the analyses with the concentration limits as shown in Table 29. Similarly, for Sr the line pair Sr 4077.7Å/Mo 3903.0Å was used. The standards were made from "Spec-pure" Sr and Mg carbonates diluted with calcium carbonate.

The results of this method appear to be more accurate than the DC arc method. The results are considered to be accurate to within ± 5 to 10%.

Waters - Cu spark method

The above method for limestones was slightly modified by E. Godijn to determine the variation in the Sr and Mg content of the ground waters. A 3 ml sample of filtered water was mixed with 5 ml of the Mo internal standard solution and the volume adjusted to 10 ml by adding 1% HCl solution. The remainder of the procedure is identical to that described above. The sensitivity of the method is shown in Table 29.

Analysts

The analyses made by E. Godijn are identified by EG and those made by the writer are identified by MGG.

TABLE A-4. Concentration limits of emission spectrographic analyses.

Limestones - DC Arc Method (Internal standard Cu 3073.8A)

Element	Line (Å)	Concentration limits (wt. percent)
Sr	4607.3 Å	0.01 - 0.05
Mg	2779.8 Å	0.1 - 3.0

Limestones - Cu Spark Method

Element	Line (Å)	Concentration limits (wt. percent)	Internal Standard
Sr	4078.0 Å	0.04 - 5.0	Mo 3903.0 Å
Mg	2802.7 Å	0.01 - 5.0	Mo 2848.2 Å

Ground Waters - Cu Spark Method

Element	Line (Å)	Concentration limits (ppm)	Internal Standard
Sr	4078.0 Å	1 - 200	Mo 3903.0 Å
Mg	2802.7 Å	1 - 150	Mo 2848.2 Å

APPENDIX 4

PETROGRAPHIC TECHNIQUES

Sample Preparation

Unconsolidated samples were split with a Jones microsplitter until an appropriate volume of sample was obtained. This volume of sample was impregnated with plastic so that the sample could be sawed and thin sections made in the normal manner (Ginsburg, 1956). Most of the consolidated rocks were also impregnated with plastic to facilitate the handling and to prevent excessive plucking during the making of the thin sections (R. von Huene, personal communication).

Thin Section Analysis

The method of volume estimation for thin sections described by Chayes (1949) was used to determine the relative proportion of each constituent in the samples. This method employs a mechanical stage which moves the thin section in small increments along uniformly spaced traverses. At each step, the type of grain immediately beneath the cross hair is recorded on a counter. At the end of a predetermined number of traverses, the relative proportion of each constituent can be calculated.

The greatest potential source of error is the possibility of misidentification of the constituent grains. This is most serious where the grains have been altered. The questionable grains were included among the unknowns or marked as questionable determinations in the cases where there were obscure indications of the grain's origin. A discussion of the criteria employed for each type of sediment contributing organism is given below.

All grain sizes are present in the samples of Recent sediments which are analyzed. As the individual grains become smaller it becomes increasingly difficult to distinguish the origin of a specific grain. Grains smaller than approximately 30 microns cannot be distinguished. When a particular grain could not be distinguished it was included among the unknown grains.

The Pleistocene limestones and most of the Recent sediments are well sorted and made up primarily of sand sized material (2 mm - 0.062 mm). Grain size analyses of the Recent sediments indicated that only the very poorly sorted sediments from the vicinity of North Rock contained as much as 20% silt sized grains. Thus, the difficulty in distinguishing silt sized grains does not limit the accuracy or significance of the analyses of Recent sediments except in the very poorly sorted sediments.

Four thin sections were analyzed to determine the amount of statistical fluctuation which might arise from counting only a small

TABLE A-5. Comparison of modal analyses calculated from different number of points.

	Shelly Bay-beach sand			Warwick Long Bay-beach sand			Walsingham - Govt. Quarry			Belmont limestone, Grape Bay			
Calcareous algae													
Halimeda													
Preserved	16.0%	15.5%	17.2%	5.1%	5.1%	5.8%	0%	0.2%	0.3%	2.6%	2.5%	2.3%	2.3%
Mold	0	0	0	0	0	0	0	0	0.3	0	0	0	0
Cast	0	0	0	0	0	0	0	0	0	0	0	0	0
Lithothamnoid algae	2.0	1.6	1.8	11.9	13.2	11.5	11.1	9.9	9.0	8.0	9.8	9.5	8.7
Amphiroa	0.3	0.8	0.9	3.7	3.3	2.9	0.2	0.1	0.2	3.0	2.1	1.8	1.6
Foraminifera													
High Mg	5.7	4.2	3.5	17.2	15.6	18.6	11.2	10.7	12.3	35.7	34.4	35.4	37.0
Low Mg	0	0	0	0	0	0	19.0	17.6	16.5	0	0	0	0
Molluscs													
Preserved	18.7	20.75	22.2	13.8	13.5	13.2	2.9	2.8	2.3	11.6	12.9	12.3	11.1
Mold	0	0	0	0	0	0	0	0	0	0	0	0	0
Cast	0.3	0.4	0.2	0	0	0	9.2	8.6	8.4	0	0	0	0
Coral													
Preserved	0	0.5	0.3	3.1	4.1	3.5	0.4	0.6	0.5	0.2	0.1	0.1	0.4
Mold	0	0	0	0	0	0	0	0	0	0	0	0	0
Cast	0	0	0	0	0	0	0	0	0	0	0	0	0
Echinoids													
Test) Spines)	0.65	0.3	0.2	0.8	0.7	0.7	0	0	0	0.2	0.6	0.6	0.6
Miscellaneous	2.3	1.7	1.1	32.8	34.4	36.8	0	0	1.0	0.2	0.1	0.3	0.3
Unknown	13.0	11.6	9.4	11.6	10.3	9.1	3.1	2.5	2.3	8.2	7.3	7.8	7.3
Cement	0	0	0	0	0	0	31.0	32.7	33.4	22.9	22.9	23.2	24.0
Pores	40.0	42.9	41.3				6.3	7.3	6.1	7.0	6.2	6.4	6.4
Total points counted	299	607	956	354	667	1066	478	853	1313	498	920	1070	1293

number of grains. The results shown in Table A-5 indicate that reasonable accuracy is obtained for the major sedimentary contributors from analyses where as few as 200 points were counted.

Calcite and Aragonite Determinations in Thin Sections

Feigl's solution (Feigl, 1937), which is a specific stain for aragonite, was used on thin sections and polished sections for aragonite determinations. Thin sections may be stained with the solution before the cover glass is emplaced if the cutting oil is completely removed. This is easily done with CCl_4 which must then be completely washed off. The stain does not work well with very fine grained materials or with carbonates containing large amounts of organic material.

The mineralogy of the carbonate cement was determined in the thin sections by comparison of the indices of the minerals with the index of the mounting medium. Calcite and aragonite have the following indices: (Winchell and Winchell, 1951, p. 107, 117).

Aragonite $N_x = 1.530$
$N_y = 1.681$
$N_z = 1.685$

Calcite $N_o = 1.658$
$N_e = 1.485$

The index of Canada balsam is $N = 1.5417$ (von Huene, 1949). Therefore, the lowest index of aragonite is essentially the same or slightly lower than that of Canada balsam, while the lowest index of calcite is considerably lower than that of Canada balsam. This method requires that the grain be located adjacent to the cementing agent at some point, and that the margins of the grain be clean and sharp for accurate determinations.

PETROGRAPHIC CHARACTERISTICS OF THE SEDIMENT CONTRIBUTORS

The characteristics of carbonate secreting organisms as seen in thin section have been described by Cayeux (1916), Hatch, Rastall and Black (1938) and Johnson (1951). Detailed descriptions of calcareous algae are available (Johnson, 1954) and there is a detailed discussion of the mollusca by Bøggild (1930).

The following section is intended to present the criteria used to differentiate the various sediment contributing organisms and to indicate the reliability of the data. The contributing organisms are grouped in the general order of their abundance in the Recent sediments as: major contributors (contributing more than 10% of the sediments); minor contributors (contributing between 2 and 10%); and accessory contributors (contributing less than 2%). The reliability of the data is summarized in Table A-6.

MAJOR SEDIMENT CONTRIBUTORS:

Lithothamnoid algae

The lithothamnoid algae are recognized by fine, rectangular

TABLE A-6. Reliability of identification of constituent grains.

	Recent sediments		Slightly altered limestone		Highly altered limestone	
	Coarse	Fine	Coarse	Fine	Coarse	Fine
ALGAE						
Halimeda -						
Preserved	G	G-F	G	F	F	P
Molds & casts			G	F-P	F	P
Lithothamnoid	G	F	F	P	F-P	P
Amphiroa	VG	G	VG	G	G	F-G
FORAMINIFERA						
Homotremidae	G	G	G-F	F	G-P	F-P
Archaias	G	G	G-F	F-P	F-P	F-P
Miliolidae	G	G-F	F	F-P	P	P
Amphisteginidae	G	G	G	G	G	G
Gypsina	G	G	G-F	G-F	G-F	G-F
COELENTERATA						
Madreporarian coral						
Preserved	VG	G-F	F-P	P	?	?
Mold			P	VP	P	VP
Alcyonarian spicules	G	G	?	?	?	?
ECHINODERMATA						
Echinoidea-Spines	VG	G	G	G	G	G-F
Test fragments	VG	G	G	G	G	G-F
MOLLUSCA						
Preserved	G	G-F	G-F	F	G	G-F
Mold			G-F	F-P	G-P	F-P
Casts			G-F	F-P	G-P	F-P
CRUSTACEA (Decapods)	G	F-P	F	F-P	F	P

Symbols:

VG - very good
G - good
P - poor

P - poor
VP - very poor
(?) - fragments have not been identified

cells arranged in rows. In thin sections of Recent sediments the fragments are normally dark yellowish brown and the cell structure is easily seen. A few of the fragments contain the spore cases or conceptacles on which the generic classification is based (Johnson, 1954). When altered, the fragments become darker colored and the cell structure becomes obscured. Viewing the altered fragments under crossed nicols often helps to distinguish the remnants of the original cell structure. The fragments containing conceptacles are recognizable because the cavities become filled with secondary calcite which preserves their characteristic shape.

Halimeda

The internal tube structure of the calcified segments of the plants and their surface texture are the most valuable characteristics in the recognition of *Halimeda*. In a given fragment, the tubes are more or less the same size and where the surface of the fragment is cut by a thin section, the tube openings all tend to be the same size. This aids in distinguishing altered *Halimeda* segments from altered *Homotrema* fragments. In the Pleistocene limestones, the *Halimeda* segments are often represented by casts. These are recognizable because the tubes in the segments become filled by secondary calcite or detrital material which remains intact when the aragonite of the *Halimeda* segment is dissolved. Thus, the internal structure and some of the surface features tend to be preserved in the casts. In some of the highly altered rocks, Halimeda fragments are identifiable only under crossed nicols where the remnants of the original tube structure can be distinguished.

Foraminifera

In the thin section analyses, Homotrema rubrum, Amphistegina, Gypsina, and Archaias are recorded separately, as they are abundant and easily distinguished. The several genera of the Miliolidae are grouped together since they are not abundant in the sediments. In the text foraminifera are grouped into low-Mg foraminifera which includes only Amphistegina, and the high-Mg foraminifera which includes all other foraminifera. The reason for this distinction is discussed in the section on the chemistry of the sediment contributors. The criteria for recognition of each of the genera or families is discussed below.

Homotrema

Homotrema is easily recognized in the Recent sediments by its red color, rounded chambers and thick, laminated walls. In the altered Pleistocene limestones the color is faded or absent, and the skeletal material may be altered until only the more massive portions of the cell structure and the outer walls are recognizable. The remainder of the test appears to be filled with cryptocrystalline calcite and the thinner chamber walls are altered to cryptocrystalline, almost isotropic calcite.

In some of the altered limestones it is easy to confuse Halimeda with poorly preserved fragments of the outer wall of Homotrema. They may be differentiated using the size and distribution of the pores. In Homotrema the large irregularly shaped pores on the outer surface are all the same size, but widely spaced. Halimeda has smaller, more closely spaced holes on the surface. Where the thin section cuts into the interior of a Halimeda segment, the tubes can be seen to curve sharply near the surface. Also the edges of Halimeda fragments are usually serrated. Homotrema fragments, on the other hand, usually have smooth margins.

Archaias

The genus is easily recognized by a regular, concentric arrangement of the rectangular chamberlets. The light yellowish brown calcite walls are essentially cryptocrystalline and do not extinguish under crossed nicols. In the Pleistocene limestones the chamberlets normally are filled with secondary calcite, but the diagnostic structure can be recognized.

Miliolidae

Foraminifera of this family are easily recognized in the Recent sediments by the external shape and the arrangement of the chambers.

The walls are formed of yellowish brown, cryptocrystalline calcite; the walls of the agglutinating forms contain detrital carbonate fragments. These foraminifera are difficult to recognize in the Pleistocene limestones unless the external shape is preserved. Small fragments of these foraminifera probably could not be recognized.

Amphistegina

Amphistegina are recognized by their lenticular-shaped tests and the thick outer walls made of calcite crystals oriented perpendicular to the cell wall. Under crossed nicols, parts of the cell walls extinguish as a unit and the whole test has a radial extinction. Cementation and diagenetic alteration tend to accentuate the radial extinction so that species of this genus are easily recognized in the Pleistocene limestones.

Gypsina

The external walls have a distinctive polygonal pattern of slightly raised ridges of calcite. The depressed areas between these ridges are perforated by coarse pores. This genus appears to be rather resistant to diagenetic alteration, and the fragments are easily recognized in the sediments and limestones in all stages of diagenetic alteration.

Mollusca

Fragments of mollusc shells in the Recent sediments show the characteristic layered structures (Bøggild, 1930). The outer layer in most fragments examined consists of prisms oriented roughly perpendicular to the outer shell margin. The inner layer of the shell commonly consists of thin layers, usually of aragonite, which are parallel to the inner margin of the shell. These features were used to distinguish mollusc fragments in the Recent sediments and well preserved fragments in the altered Pleistocene limestones.

From the study of Recent beach and shallow water deposits it was found that, with few exceptions, the tubular, slightly curved grains were mollusc fragments. This use of the grain shape is extremely valuable in altered limestones where the mollusc fragments are preserved as casts or molds.

MINOR SEDIMENT CONTRIBUTORS:

Amphiroa

Amphiroa fragments are elongate, and in thin section the rods show a central structure of alternating transverse rows of long and short rectangular cells. Several rows of small cells occur along the margins. These characteristic features are well preserved in the Pleistocene limestones so that *Amphiroa* is easily recognized.

Echinoids

Echinoid spine fragments are distinguished by their unit extinction under crossed nicols and the reticulate or radial pattern of the porous calcite which makes up the spine. The test fragments also display unit extinction under crossed nicols but lack the distinctive structure of the spines.

No effort was made to record the spine and test fragments separately where the total amount of echinoid fragments was small. However where the echinoids were significant contributors, they were differentiated.

Scleractinian Coral

The most distinctive feature of skeletal fragments of corals is the radiating, feather-like structure which the septae display under crossed nicols. This structure can usually be recognized in coral fragments in the Recent sediments. Porites has an anastamosing pore structure which is easily recognized and was differentiated in some of the analyses of Recent sediments.

The coral fragments tend to be more equant than the mollusc fragments in the Recent sediments. This feature was used in the altered Pleistocene limestones where the more equant molds and casts were classified as possibly the remains of coral fragments.

ACCESSORY SEDIMENT CONTRIBUTORS:

Crustacea (Decapods)

Decapod fragments have a distinctive grayish brown color in thin sections. The thinly laminated structure is penetrated by irregularly spaced canals, roughly perpendicular to the surface.

Bryozoa

Bryozoa are distinguished by the tabular or sack-like shape of the chambers. In individual colonies the chambers may be arranged in a radial or fan-like pattern depending on the orientation of the fragment in the thin section.

Bryozoa may be confused with the foraminifera *Gypsina*. *Gypsina* has thicker walls and the outer surface is perforated by a series of regularly spaced coarse pores which are absent in Bryozoa.

APPENDIX 5

FRESH WATER IN BERMUDA

Ghyben-Herzberg Principle

Because of the density contrast between fresh and sea water, the fresh water floats on top of the sea water. Assuming hydrostatic equilibrium between the fluids of different density, the Ghyben-Herzberg relationship can be derived (Todd, 1959, p. 278-296).

$$h_s = \frac{\rho_f}{\rho_s - \rho_f} \quad h_f$$

where ρ_f is the fresh water density, ρ_s the salt water density and g is the acceleration of gravity. Figure A-5 shows the significance of h_s and h_f. Taking representative values for $\rho_s = 1.025$ g/cm^3 and $p_f = 1.000$ g/cm^3, the above equation reduces to:

$$h_s = 40 \ h_f \ .$$

The equation is valid for static equilibrium and requires that the top of the fresh water surface lie above sea level and slope downward to sea level at the edge of the island mass. The maximum thickness of the fresh water lens occurs in the center of the island and decreases toward the coast.

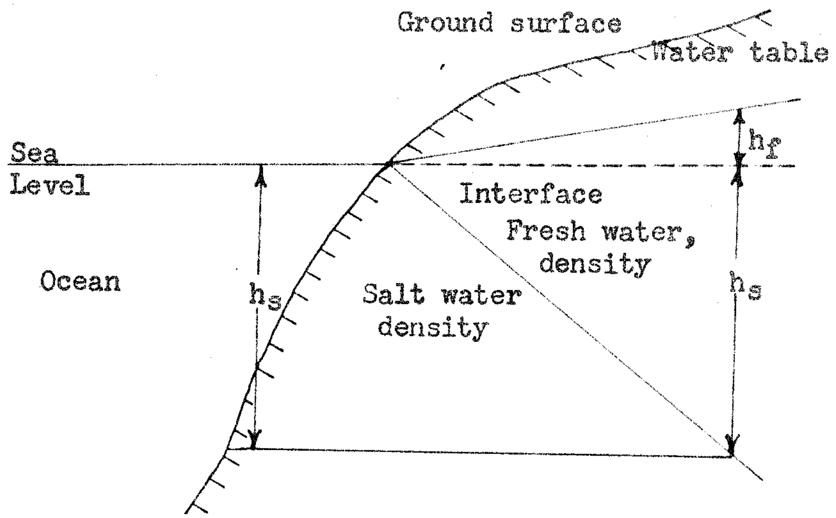


Figure A-5. Schematic representation of the fresh- and salt-water distribution in an unconfined coastal aquifer, illustrating the Ghyben-Herzberg principle (after Todd, 1959, p. 279)

Several conditions must occur for a fresh water lens to develop (Wentworth, 1951). These essential conditions are 1) suitable permeability of the aquifer; 2) adequate infiltration or recharge to the ground water layer; 3) limited tidal range; and 4) essentially uniform permeability of the aquifer. If the first two conditions are not satisfied, the amount of fresh water is not sufficient to form and maintain a fresh water lens. The last two conditions are necessary to prevent mixing of the fresh water with the salt water.

Ground water distribution in Bermuda

Numerous references to the occurrence of fresh water wells along the coasts may be found in the early publications on Bermuda geology (Nelson, 1840; Verrill, 1905). The Naval Wells on the North Shore produced large quantities of water for shipping and were used into the last century. Wells at Cooper's Island and at Spittal Pond were used for watering cattle within the memory of living residents. No references are found to indicate the early existence of fresh water wells in the interior of the islands, although fresh water wells have been developed in similar geological settings in the Bahamas (Riddle, 1933). The Watlington Water Works, completed in 1932, now produces approximately 80,000,000 gallons per year of slightly brackish water from a series of infiltration galleries located on the north side of Devonshire Marsh.

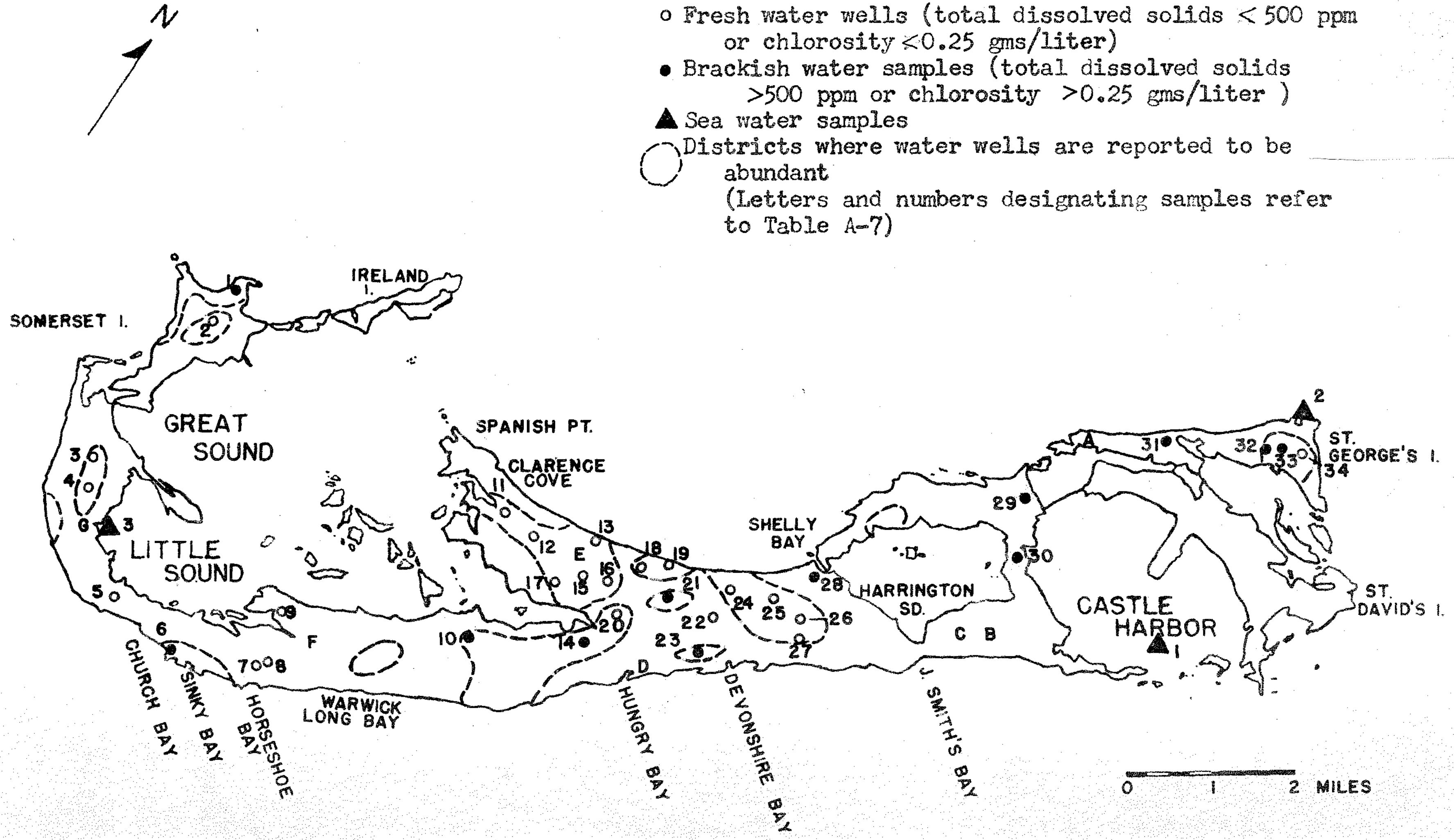
Water samples were collected during the field seasons of 1959 and 1960 to determine the size and composition of the Ghyben-Herzberg lens under Bermuda. Figure A-6 shows the location of the samples and districts where water wells are reported to be abundant (Mr. G. Kendall, Inspector Health Department, personal communication). Mr. F. W. Dascombe of the Bermuda Health Department estimates that between 500 and 1000 wells are currently in use. Those wells do not necessarily produce fresh water, as colonial law prohibits the drinking of water from household wells.

Figure A-6 shows that wells occur over much of the colony, especially in the central and western portions. The islands adjacent to Castle Harbor are the only areas in which there are no wells. Much of this area appears to be underlain by cavernous Walsingham limestones which may not have the proper permeability to prevent mixing with the sea water.

The data suggest that drinkable fresh water appears to occur under approximately 2/3 of the island. The distribution and density of the wells is largely controlled by the depth of the water table and the local history of ground water development. Most of the wells used for household purposes produce only limited quantities of water.

Theoretically the boundary between the fresh and salt water is a streamline, i.e., a line with no flow across it. Observations in many

Figure A-6. Distribution of water samples.



○ Fresh water wells (total dissolved solids < 500 ppm or chlorosity ≤0.25 gms/liter)

● Brackish water samples (total dissolved solids >500 ppm or chlorosity >0.25 gms/liter)

▲ Sea water samples

◯ Districts where water wells are reported to be abundant

(Letters and numbers designating samples refer to Table A-7)

TABLE A-7

Chemistry of the Fresh and Marine Water in the Bermuda Islands.

Wells	Total dissolved solids (ppm)*	Chlorosity grams/liter	δO^{18} (0/00)	pH
1. Cambridge Beaches				
July 1960		0.4_4	-3.7_6	7.7
2. Sandy's Grammer School	300			
3. Tercera's Dairy		0.2_1	-3.3_1	7.7
July 1960				
4. Glebe School	50			
5. Princess Hotel boring - dry hole				
6. The Reefs - July 1960		2.6_4	-3.2_2	7.9
7. James Field Quarry		0.0_5		8.1
July 1960				
8. Butterfield Quarry				
1 Sept. 1959		0.0_6	-3.6_9	
July 1960			-3.2_7	
9. Riddle's Bay	36			
10. Warwick Academy	103,500			
11. St. John's Road				
July 1960		0.0_6		8.2
12. Motyer - July 1960		0.3_9	-3.3_5	
13. Photo shop - July '60		0.0_4	-3.4_0	
Nov '56	170			
May '57	160			
Sept '58	130			
14. Conley		3.1_9	-3.0_2	
15. Dellwood School	250			
16. Central School	200			
17. Samaritan's Hall, Court St.	250			

Table A-7 (continued)

Wells	Total dissolved solids (ppm)*	Chlorosity grams/liter	δO^{18} (0/00)	pH
18. Clayhouse Well				
March 1950	125			7.3
May 1951	170			
Dec 1953	150			
June 1954	130			
19. Clayhouse Inn-July 1960		0.3_7	-3.5_6	8.4
20. Dickinson - April 1960			-3.6_0	
May 1960		0.2_0		7.4
July 1960		0.2	-3.7_4	
Dec 1960		0.2	-3.4_3	
21. Watlington Water Works (see chemical analyses)				
July 1960		1.8	-3.0_2	
22. Mental Hospital	200			
23. Brighton Hill Nursery July 1960		0.6_1	-3.4_5	8.2
24. Devon Creamery Well				
Sept 1958	135			
March 1960	120			
July 1960		0.1_6	-3.3_3	7.9
25. Kugima - May 1958	200			
March 1960	53			
26. Vesey - May 1958	140			
May 1959	135			
April 1960	135			
July 1960		0.1_5	-3.0_8	
27. Penniston - July 1960	120			
28. Jennings - 10 March 1950	2750			
24 March 1950	5800			
31. Mullet Bay Road Dec. 1960		13.2_4	-0.4_2	

Table A-7 (continued)

Wells	Total dissolved solids (ppm)*	Chlorosity grams/liter	δO^{18} (0/00)	pH
32. St. George's Hotel #1 July 1960		0.4_6	-3.3_5	7.8
33. St. George's Hotel #2 July 1960		0.2_8		8.2
34. Barracks Hill				
11 Feb 1950	175			
3 March 1950	125			
Caves				
29. Wilkinson Quarry July 1960		13.1_0	$+0.7_0$	7.6
30. Crystal Cave 1953 (?)		19.7	$+1.0_4$	
Ponds and Lakes				
A. Lover's Lake July 1960		19.2	$+1.4_0$	7.5
B. Trott's Pond				
Aug 1959		15.8	$+1.6_8$	
5 July 1960		15.9	$+1.9_8$	7.6
25 July 1960		16.0	$+1.9_3$	7.4
C. Mangrove Lake - Aug 1959		16.5	$+2.0_1$	
5 July 1960		16.8	$+2.0_8$	
25 July 1960		17.2	$+2.4_6$	
D. Hungry Bay Marsh - Aug 1959		1.4	-2.5_5	
July 1960		2.2		

*Data from the files of the Bermuda Health Dept. and the Royal Gazette, Hamilton, analyses made by Dr. Shaw.

Table A-7(continued)

Ponds and Lakes		Chlorosity grams/liter	δO^{18} (0/00)	pH
E. Pembroke Marsh, East-July 1960		0.2_1	$+0.0_5$	
F. Seymour's Pond		7.4_7	$+4.7_9$	
G. Evan's Pond		19.3	$+1.2_5$	
Rains				
1960				
6 April			-3.4_3	
4 May			-0.9_9	
6 June		0.0_2	-5.5_9	
17 July	Local squall		$+0.2_5$	
22 July	Local squall	0.0_2	-0.2_3	
25 July	Frontal storm (?) beginning	0.0_2	-2.9_5	
6 Sept			-7.7_0	
20 Sept			-4.7_1	
28 Oct		0.0_3	-2.6_4	
1 Nov	Local squall		-2.1_8	
1 Dec	Frontal storm beginning	0.0_2	-1.7_4	
2 Dec	" " middle		-2.5_3	
3 Dec	" " end		-5.4_2	
Drip Waters				
St. David's Cave				
5 July 1960		0.1_3	-3.2_4	
18 July 1960			-1.7_9	
26 July 1960		0.2_3	-2.9_5	
Crystal Cave 1953			-3.2_4	

Table 38 (continued)

Tap Waters (from rainwater reservoirs)		Chlorosity grams/liter	δO^{18} (0/00)
Biological Station			
Aug 1959		0.0_6	-3.9
July 1960			-3.8
Work Shop Tank Dec 1960			-3.5_6
Naval Station			-3.8_3
Marine Waters	Salinity		
M-1 Castle Harbor July 1960 pH 8.3	36.3_5	20.6_0	$+1.0_1$
M-2 Coot's Pond Aug 1959	36.5	20.7_0	$+0.8_4$
M-3 Evan's Bay Aug 1959	34.1_5	19.1_0	$+0.9_3$

areas show, however, that there is a zone of mixing which separates the fresh and salt water. Todd (1959, p. 282) indicates that this zone arises from 1) the dispersion of flow in porous media, 2) movements of the interface caused by tidal movements, and 3) molecular diffusion.

The distribution of brackish water wells shown in Figure A-6 suggests that a relatively wide zone of mixing occurs in Bermuda. With the exception of the Warwick Academy, the Conley well and the Watlington Water Works, all the brackish water wells occur near the coast. The fresh water wells occur along the North Shore and in the interior of the island.

Many of the brackish water wells along the coast produce large quantities of water for use in the hotels. Some of these wells may originally have been fresh and later been intruded by sea water as a result of heavy pumping. This is known to have occurred in the case of the Clayhouse well, near the North Shore (Health Dept. files). This well, drilled during the drought of 1949-1950, produced over 1 million gallons of fresh water (containing approximately 100 ppm total dissolved solids) before the total dissolved solids rose to more than 500 ppm, due to intrusion of sea water. The commercial water wells in the interior of the island have reported no difficulty with intrusion of sea water, although thousands of gallons per day are pumped during the summer season.

Where the interdune depressions intersect the water table, marshes or ponds occur. Devonshire and Pembroke Marshes are examples of this, as well as the smaller marshy areas along the South Shore Road. Some of these depressions contain permanent ponds, such as Warwick Pond and Spittal Pond. The water in these ponds is slightly brackish (see analyses in Table A-7).

Mangrove Lake and Trott's Pond, the largest lakes on the island, are brackish and may have some connection with the sea.

Recharge of the ground water lens

Determination of the proportion of the rainfall which is available to recharge the fresh water lens must take into account the amount of moisture lost by evaporation from the soil or used by the plants. This loss is termed evapotranspiration (Thorthwaite, 1948) or consumptive-use (Blaney and Criddle, 1950) and represents the transport of water back into the atmosphere from the soil. Several methods (Thornthwaite, 1948; Blaney and Criddle, 1950; Penman, 1948) are used to compute the potential evapotranspiration, or the amount of water lost to the atmosphere under ideal conditions. The basis for these methods is the fact that evaporation and plant activity are ultimately controlled by the amount of incoming solar energy. In the calculations of both Thornthwaite and Blaney, the mean monthly air temperature is used as an index of the amount of solar energy. These methods have been criticized for the crudeness of their basic assumptions (Tanner and Pelton, 1960). These methods, however, have the advantage of requiring relatively simple computations, and they require only meteorological data which are readily available.

Thornthwaite's method provides results which he found to be of the right order of magnitude to account for runoff over the whole of the United States. Blaney and Criddle's method has been used extensively for computing water requirements for irrigation and has been found to be approximately correct. Thus, the use of these approximate methods seems justified for the problem at hand.

Both methods were used to compute the evapotranspiration for Bermuda using the average figures for the period 1891-1947 and for the period 1951-1953.

	1891-1947	1951-1953
Average total rainfall	58.1 inches	54.2 inches
Potential evapotranspiration	41.3 "	41.9 "
Amount of recharge	16.8 " (29% of rainfall)	12.3 " (21% of rainfall)
Consumptive use	47.7 "	48.2 "
Amount of recharge	10.4 " (18% of rainfall)	6.0 " (10% of rainfall)

These computations indicate that between 10 and 30 percent of the total rainfall is available for recharge to the fresh water lens each year. Plotting the monthly evapotranspiration against the mean monthly rainfalls (Figs. A-7, 8) shows that most of the recharge of the ground water

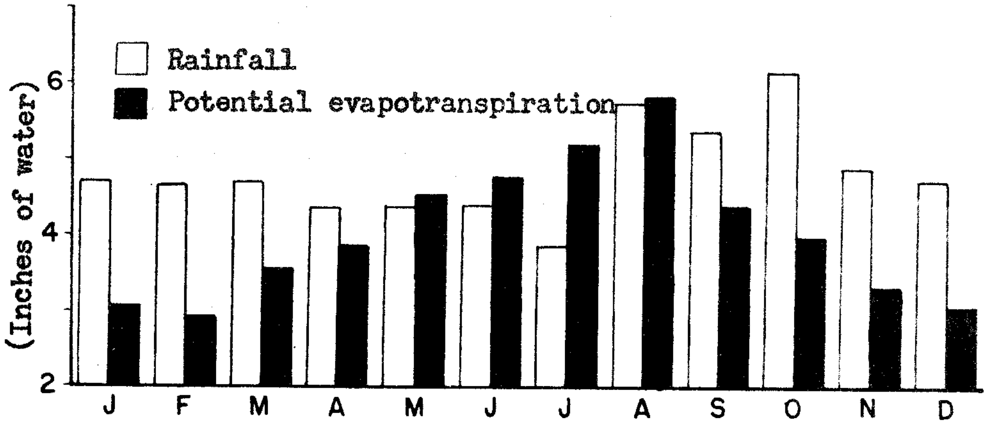


Figure A-7. Mean monthly rainfall and potential evapotranspiration losses, 1891-1947.

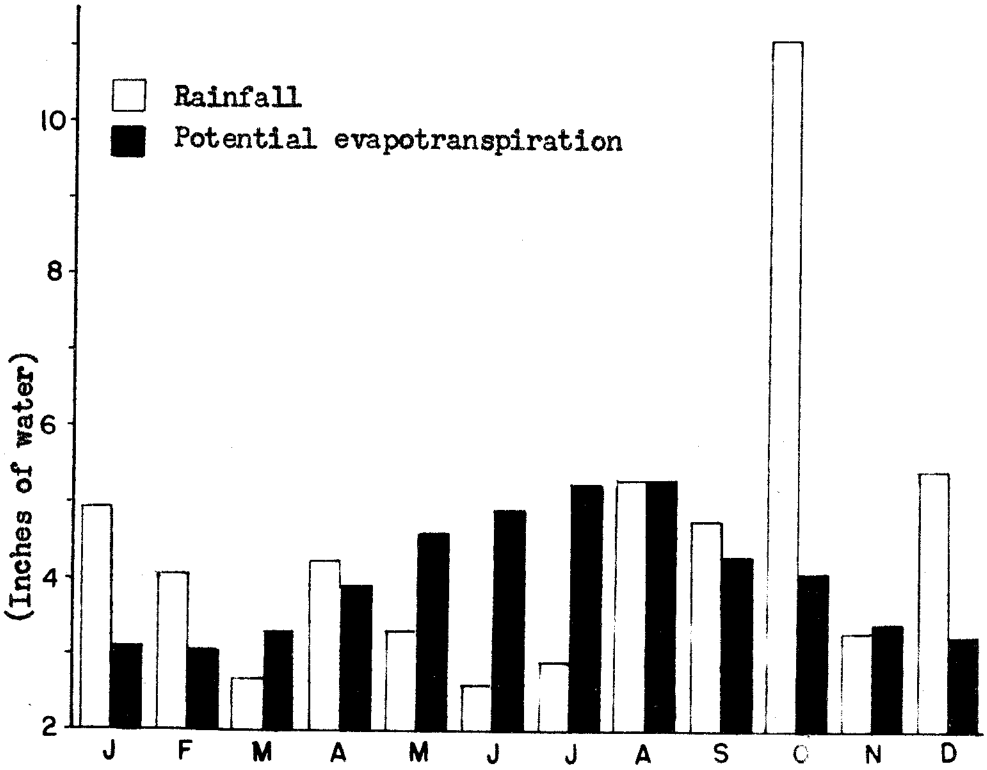


Figure A-8. Mean monthly rainfall and potential evapotranspiration losses, 1951-1953.

lens occurs during the fall and winter season. The spring and summer are times of little or no recharge of ground water.

O^{18}/O^{16} ratios of the ground water, rainwater and sea water in Bermuda.

Ground water samples from all parts of the islands were analyzed for their O^{18}/O^{16} ratios. Despite the fact that the samples were taken during two different field seasons, the O^{18}/O^{16} ratios of the samples are all very close. The samples have δO^{18} values of -3.0 to -3.7‰ (see Fig. A-9 and Table A-7).

In contrast to the small variations in the δO^{18} value of the ground waters, the rain samples showed wide variations in their δO^{18} values (Table A-7, Fig. A-9). The most positive δO^{18} values for rain waters were found in samples collected during the summer. The δO^{18} values for samples of fall and winter rains are, on the average, much more negative.

The wide range in the O^{18} content can be explained in terms of the fractional distillation mechanism proposed by Epstein and Mayada (1953). The first condensate from a vapor mass will be essentially in equilibrium with the vapor mass. Thus it will have an isotopic composition close that that of the water body from which it was evaporated. These early condensates deplete the remaining vapor in H_2O^{18} so that succeeding condensates from the vapor mass have a lighter isotopic composition, i.e., they have a more negative δO^{18}. In the liquid-

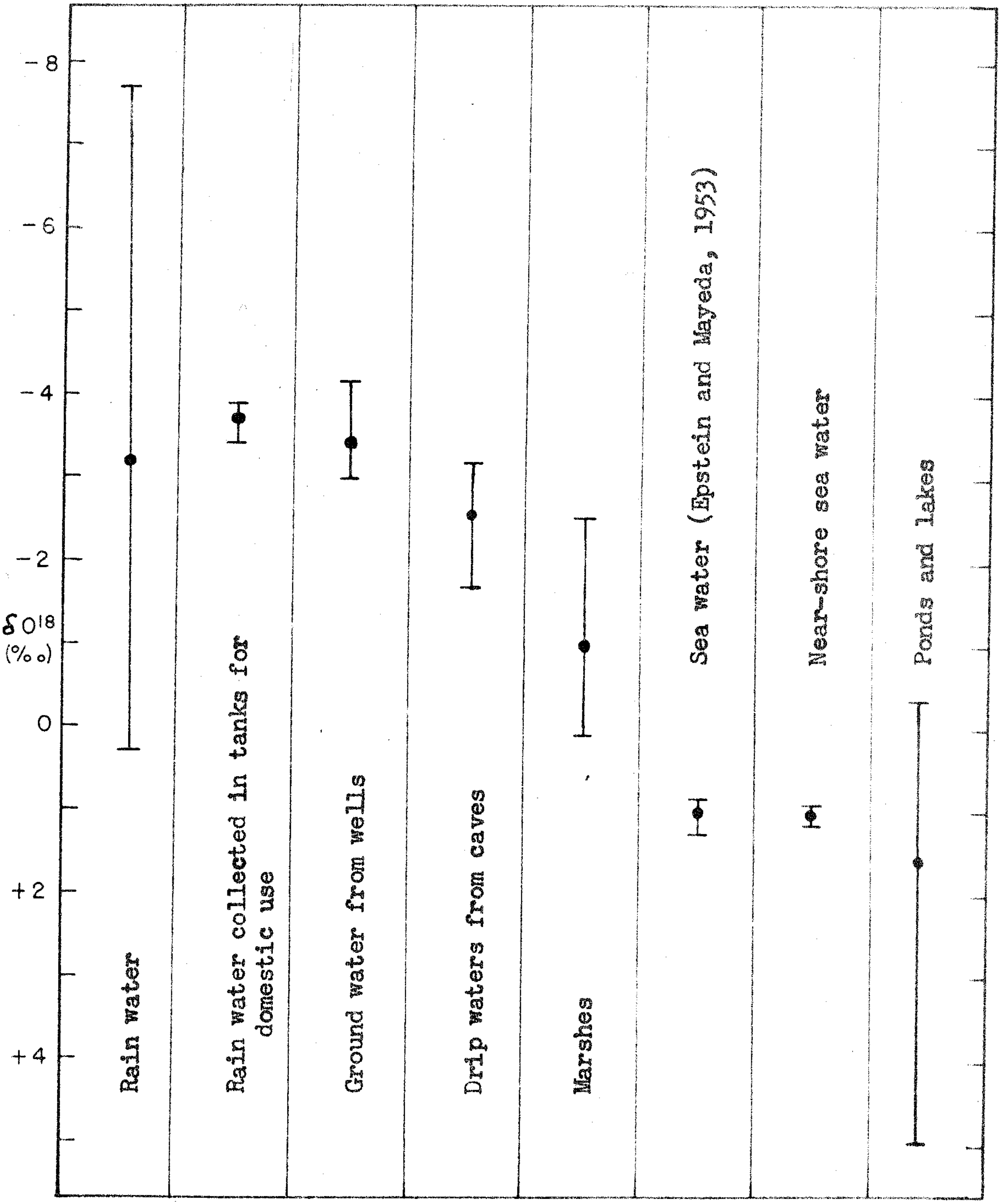


Figure A-9. O^{18}/O^{16} ratios of waters from the Bermuda Islands.

vapor system at 29°C the liquid is 7‰ richer in O^{18} than the vapor phase (Epstein and Mayada, 1953). Thus, in the Bermuda area where the ocean surface waters have a δO^{18} value of around + 1‰, the water vapor in equilibrium with it would be approximately δO^{18} of -6‰. Thus, the summer rains whose δO^{18} values are close to 0‰ appear to represent the first condensates from vapor masses locally derived as squalls or tropical disturbances.

During the summers of 1959 and 1960, samples were taken of the rain water collected and stored for drinking by the local population. The rain water is usually collected by a gutter system and stored in large, semi-closed tanks under the houses. Water collected and stored in this manner appears to undergo little evaporation. The δO^{18} values of the four samples analyzed fall between -3.0 and -3.6‰. These values are close to those determined for ground water (Fig. A-9).

Three analyses were made of the marine waters surrounding Bermuda. These δO^{18} values range from +1.0 to +0.84‰. This is similar to the values reported by Epstein and Mayada (1953) and Epstein and Lowenstam (1954).

Water samples from Mangrove Lake and Trott's Pond (Table A-7) show δO^{18} values which are approximately 1‰ higher than those obtained from the open marine waters. This suggests that any circulation with the adjacent ocean water is rather restricted. Increased communication with the adjacent sea water would result in higher chlorine contents and lower δO^{18} values. The similarity in the composition of the water of these two lakes suggests that there may be some communication between them.

Water samples from the ponds and marshy areas in the interdune depressions show the greatest variability. Lover's Lake and Evan's Pond are similar in chlorosity and in isotopic composition to the adjacent marine waters. This suggests relatively free communication in these two cases. Seymour's Pond on the western end of the island is rather unique, having a chlorosity of 7.47 gms/liter and $\delta O^{18} = +3.9‰$. The other swamps and marshy areas exhibit chlorosities varying from the essentially fresh water in Pembroke Marsh to chlorosities of 2.2 gms/liter in the swampy area north of McGall's Bay on the South Shore. The marshy areas and ponds which contain brackish water are located near the South Shore. It is thought that the chlorine contents are due to accumulations of salt from sea spray blown inland during the winter storms which often come from the south. The salt is then washed down in the rains and accumulates in the undrained lowlying areas.

Implications of the oxygen isotopic composition for the ground water circulation.

Comparison of the δO^{18} values for the ground water samples, rain water and the water collected for domestic use (Fig. A-9) shows no significant differences.

This suggests that the water, which eventually reaches the ground water lens, quickly passes through the portion of the soil where it may be subjected to processes resulting in a loss of H_2O^{16}. From these data it appears that the water in the Ghyben-Herzberg lens under an oceanic island such as Bermuda has essentially the same isotopic composition as the rainfall on the island.

On the other hand, the drip waters collected from caves on the island have somewhat more negative δO^{18} values (approximately 0.5‰) than the ground waters or rain waters. These few data suggest that drip water may undergo some evaporation.

Chemical composition

Chemical analyses are given in Table A-8 for four ground water samples from Bermuda. The three analyses of water from the Watlington Water Works show a change in the chemistry of the water caused by intrusion of sea water. As the sea water intrusion increased, the water changed from a chloride-bicarbonate water to a chloride water in the classification of Clarke (1924) and Chebotarev (1955).

Spectrochemical analyses of selected water samples were made to see if major variations in the Sr and Mg content could be found. As can be seen from the data (Table A-9), the most significant variation is caused by the intrusion of sea water. In the uncontaminated ground waters the Sr and Mg contents do not show any significant variations.

The high Mg content found in water from the Butterfield Quarry well was not found in water from the nearby Field Quarry well.

TABLE A-8. Chemical analyses, Bermuda ground water.

	1	2	3	4
Ca	113(ppm)	151(ppm)	96(ppm)	175(ppm)
Mg	20	87	77	58
Na	-	-	849	324
HCO_3	-	-	46	226
CO_3	-	-	0	0
Cl	272	1195	1545	301
SO_4	26	151	182	31
SO_2	14	20	3.0	7
pH	7.0	7.2	6.6	7.5
TDS	803	2810	2820	557
Total Hardness	363	725		

1. Watlington Water Works, raw water 25 May 1934 (Mitchell, 1948)
2. " " " " " 29 June 1944 "
3. " " " " " 24 Feb 1960
(analysis by Ionics, Inc., Cambridge, Mass.)
4. Devon Creamery Well, March 1960
(analysis by Pur-Water Export Co., Basking Ridge, New Jersey)

TABLE A-9. Sr and Mg contents of rain and ground water samples.

Rain water	Mg ppm	Sr ppm	Chlorosity (gms/liter)
6 June 1960	<0.3	<0.1	0.02
22 July 1960	2	<0.1	0.02
Ground water			
Dickinson well	13	3	0.20
Terceria well	18	3	0.21
Vesey well	9	1	0.15
Butterfield quarry	35	1	0.06
J. Field quarry	10	<0.1	0.05
Ground water contaminated by sea water intrusion			
Brighton Hill Nursery	28	1.0	0.61
Watlington Water Wks.	70	2	1.8

APPENDIX 6

FIGURES

Figure 9. Prismatic calcite cement (Walsingham formation, Government Quarry, Plane polarized light).

Figure 10. Calcite overgrowth on echinoid spine (Walsingham formation, Government Quarry).
(a) Plane polarized light
(b) Crossed nicols

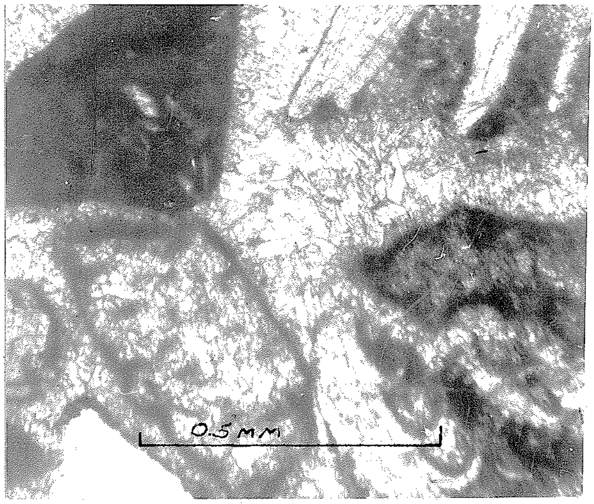


Figure 9.

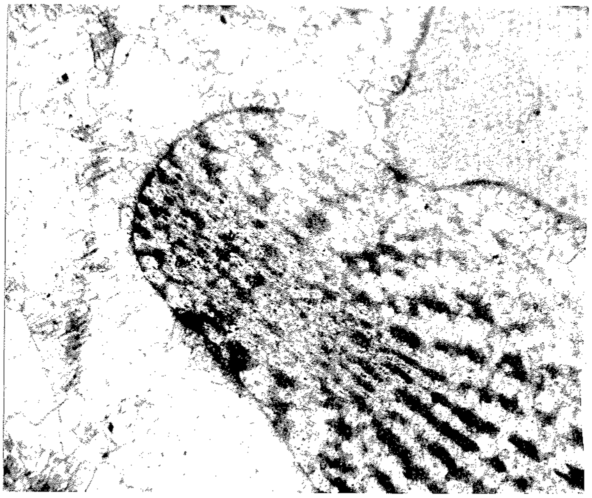


Figure 10a.

Figure 10b.

Figure 11. Typical drusy mosaic (Belmont formation, Esso Tank Farm, Ferry Reach Road, St. George's Island, Plane polarized light).

Note the increase in crystal size away from the dark line which separates the fragment from the surrounding calcite cement. Granular cement is well developed in this specimen.

Figure 12. Typical drusy mosaic. (Belmont formation, Whalebone Bay, St. George's Island, Crossed nicols).

Note the uniformly thick rims of prismatic calcite cement in the upper right hand portion of the figure.

Figure 13. Replacement mosaic in a pelecypod shell fragment. (Belmont formation, Esso Tank Farm, Ferry Reach Road, St. George's Island, Crossed nicols).

Note the large crystals and the relatively straight boundaries between the crystals. Locally the mosaic preserves the gross features of the original layered structure of the shell. The lower right hand portion of the fragment has a drusy mosaic developed.

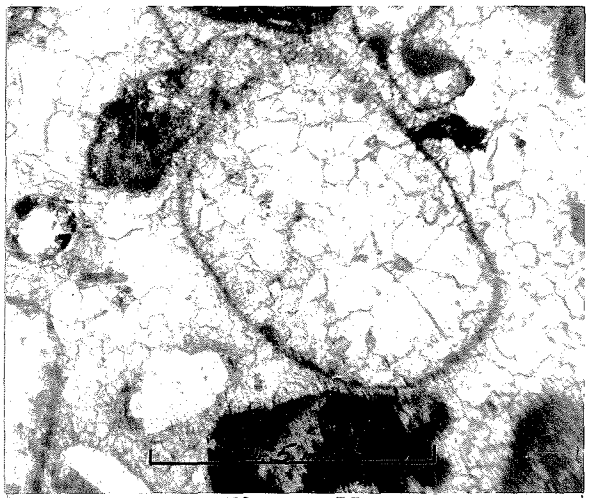


Figure 11.

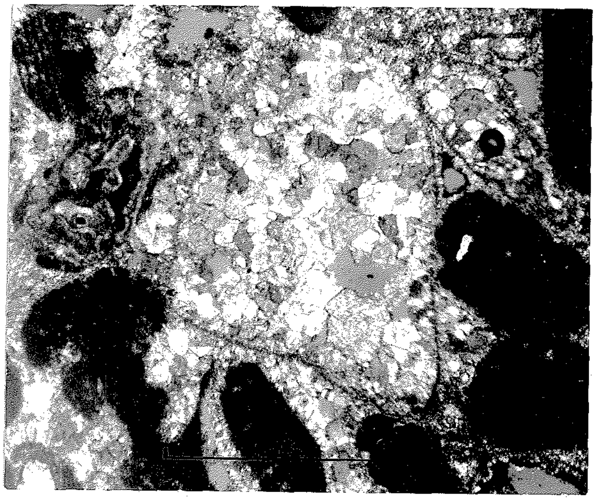


Figure 12.

Figure 13.

Figure 14. Development of a replacement mosaic in a pelecypod fragment. (Marine limestone dredged from Town Cut Channel, St. George's Harbor)

(a) Plane polarized light
(b) Crossed nicols

Not the irregular margin of the replaced mosaic shell structure. Also note that the prismatic calcite cement is confined to the area near the point of grain contact.

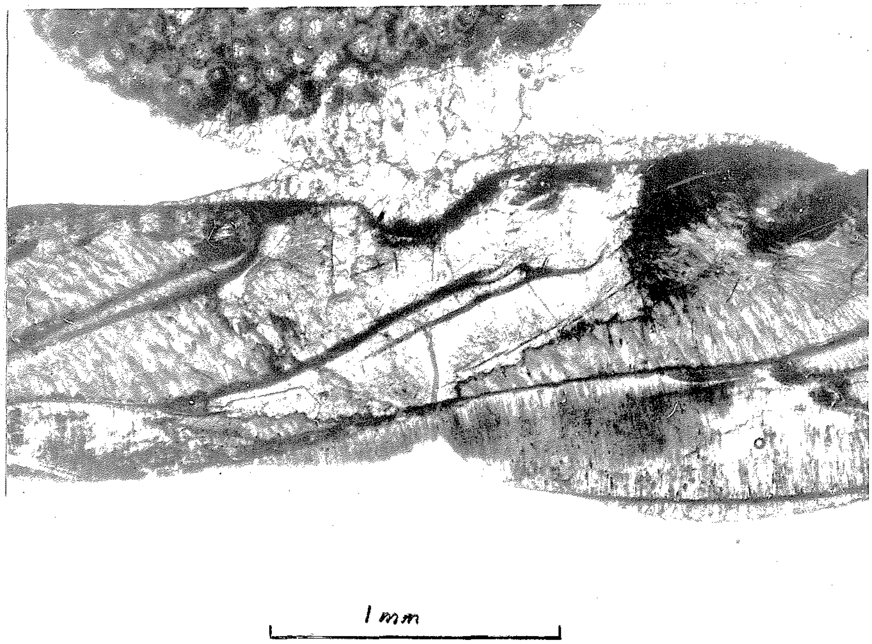


Figure 14a.

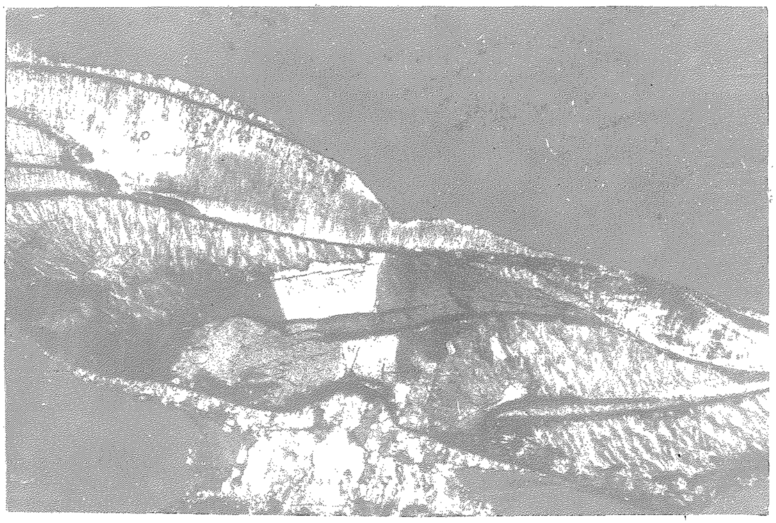


Figure 14b.