# DISTRIBUTION AND ORIGIN OF BEACHROCK CEMENTS, DISCOVERY BAY (Jamaica)

# REPARTITION ET ORIGINE DES GRES DE PLAGE, DISCOVERY BAY (Jamaïque)

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**ABSTRACT**

Extensive but locally discontinuous Holocene beachrock crops out within the intertidal of Northern Jamaica. A systematic beachrock coring and interstitial water sampling program was conducted 0.5 km west of the Discovery Bay Marine Lab. The unit ranges up to 44 cm in thickness and consists of fine to medium calcarenites of sorted Goniolithon, Halimeda, and coral fragments. The allochems are lithified by at least five distinctive cements: micritic envelopes of high Mg calcite, equant to bladed high Mg calcite, micritic high Mg calcite, pelletoidal high Mg calcite, and equant to fibrous aragonite. The cements vary laterally and vertically contributing to a variety of petrographic fabrics typically indicative of other carbonate environments. Cement mineralogies approach chemical equilibrium with the pore waters and can be directly related to the dissolved $CO_2$ activity. Whole rock $^{14}C$ dates suggest accumulation-cementation rates of 1.4 mm $yr^{-1}$ below a rock depth of 14 cm and almost instantaneously above 14 cm.

**RESUME**

De nombreux affleurements de grès de plage, localement discontinus, sont visibles dans la zone intertidale du littoral Nord de la Jamaique. Un programme de carottage des grès de plage et de prélèvement d'eau interstitielle a été mené de façon systématique dans un secteur situé à 0,5 km à l'Ouest du laboratoire marin de Discovery Bay. L'affleurement a une épaisseur de plus de 44 cm et comprend des calcarenites fines à moyennes formées par des débris isométriques de Goniolithon, Halimeda et de coraux. Les allochemes sont cimentés par au moins 5 types de ciments : enveloppes micritiques de calcite magnésienne, calcite magnésienne en cristaux équigranulaires à aciculaires. Les ciments varient latéralemnt et verticalement, constituant un ensemble de faciès pétrographiques typiques d'autres environnements carbonatés. Minéralogiquement, ces ciments sont pratiquement en équilibre chimique avec les eaux interstitielles et sont fonction de l'activité du $CO_2$ dissous. Les datations $^{14}C$ de la roche totale indiquent que les vitesses de sédimentation - cimentation sont de 14 mm par an à la profondeur de 14 cm et presque instantanés au-dessus de 14 cm.

## INTRODUCTION: POSING THE PROBLEM

As both lithified reef and intertidal calcarenites can be indistinguishable in allochem composition and cement mineralogy, potential problems of discrimination of these facies in the ancient can result. This paper will examine a Holocene beachrock occurrence with the purpose of attempting not only to link process-result, but also to describe the systematic heterogeneity of cement morphology, chemistry, and geometry diagnostic of beachrock.

By definition, beachrock refers to any beach deposit lithified syn-depositionally or soon thereafter, consequently it may consist of quartz sand grains, coconuts, bottles, anything found on a beach. Most commonly, beachrock allochems are composed of calcareous skeletal material. Nelson (1840) first described beachrock in Bermuda (although the actual occurrence studied was not beachrock, but a meteoric calcite-cemented Pleistocene eolianite). Since then beachrock has been reported from many parts of the world, predominantly in the tropics and subtropics: e.g. Brazil (Branner, 1904), south Florida (Ginsberg, 1953), southern coast of Spain (Alexandersson ,1969), Quatar (Taylor and Illing, 1969),and Grand Cayman (Moore, 1971). Hypotheses proposed for its formation range from evaporation of seawater at low tide (Dana, 1851), degassing of $CO_2$ (Branner 1904; Hanor, 1978), meteoric-marine water-mixing (Schmalz, 1971), organic activities (Moore, 1973), to no single unique origin (Moore, 1977). Beachrock cements are characteristically heterogeneous in distribution and mineralogy (Ginsburg, 1953; Moore, 1973).

## PHYSICAL SETTING

Beachrock is extensive but locally discontinuous in outcrop on the northern coast of Jamaica and until now has received little study. The beachrock locality investigated in this paper occurs approximately 0.5 km west of the Discovery Bay Marine Lab (Fig. 1). The size of the lithified allochems depends upon the energy of the local beach environment. For example, the beachrock in the study area, a protected pocket beach, consists of sand size particles, while cobble-size fragments of coral can be observed in a cemented berm along a higher energy section a few hundred meters east of the study area. The beachrock unit is laterally and vertically discontinuous with unconsolidated beach sands surrounding it. The unit crops out in the intertidal and dips seaward at an angle of 10°, comparable to the dips of lithified beach sands found at many other localities around the world, e.g. Grand Cayman (Moore, 1973) and south Florida (Ginsburg, 1953). The unit contains megascopic (scale of meters) open orthogonal fractures which are oriented parallel and normal to the shore line. The unlithified sediment cover in the intertidal to supratidal part of the study area averages only a few centimeters in thickness. The sediment is underlain and flanked laterally by the Middle Pleistocene Falmouth Formation (named by Hill, 1899), a sparry calcite/ dolomite cemented limestone containing a typical suite of rock types belonging to a fringing reef setting (Land and Epstein, 1970). In the subtidal, the lithified sands grade into unlithified coralline-calcareous algal meadows. The average surf on this beach is relatively mild. The breaking waves have an amplitude of six to ten cm at high tide, and at low tide the waves are so small that they merely lap up onto the beach. Northern Jamaica experiences a maximum tidal range of 1.5 m with a mean annual rainfall at nearby Falmouth of 102 ± 25 cm (Vickers, 1979). During the time of study (July-August 1982), this region was experiencing a drought.

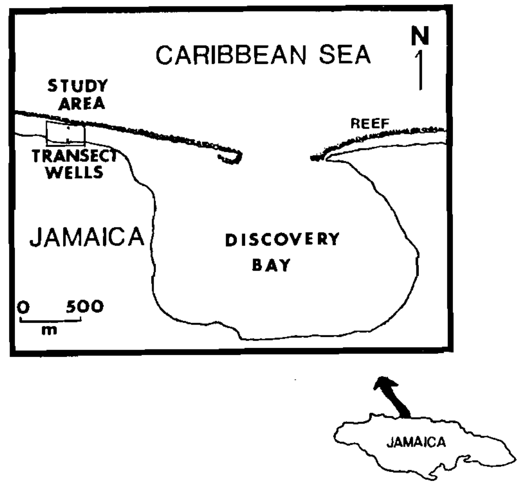


Figure 1: Location Map of Discovery Bay, Jamaica, and the study area. Map drawn from air photograph.

## METHODS OF DATA ACQUISITION

A Hydradrill® was used to drill the transect from the intertidal to just behind the reef crest (Fig. 2). For offshore drilling, two 1.5 m high platforms were built to subaerially support the rig and water pump in the backreef. Borehole cave-ins prevented the drilling of wells on the supratidal beach. One meter tungsten carbide core barrel bits were used to gather cores thoughout the drilling process; recovery averagaed about 80 per cent. Drilling rates averaged 30 cm per hour, and in all, five wells were completed in 20 days. The recovered cores were washed immediately with fresh water to prevent salts from precipitating in the pores. Cores taken from the transect wells were slabbed and thin-sectioned. Rocks were named according to both Folk (1962) and Dunham (1962) and cements classified according to Folk (1965). To reinforce the petrographic observations, small chips from the cores were analyzed on an ETEC Scanning Electron Microscope (SEM). To help delineate cement mineralogies, e.g. aragonite or Mg-calcite, qualitative energy dispersive spectrographic readings were taken. Back scattering imagery and more quantitative analyses for CaO, MgO, SrO, and FeO, which will be reported in greater detail elsewhere, were conducted on six selected specimens courtesy of Phillips Petroleum Research and Development's Jeol microprobe.

The petrographic characteristics of the beachrock vary considerably both vertically and laterally. For that reason we shall systematically describe each well from the surface downward beginning at the upper intertidal and moving oceanward (Fig. 2).

## PETROGRAPHIC OBSERVATIONS

### Upper Middle Intertidal Zone: Well H-2

From zero to thirteen cm deep: In thin section this rock is a fine calcarenite: sorted biosparite, fossiliferous grainstone. The allochems are (in order of decreasing predominance) Goniolithon sp., coral chips, Halimeda sp., and intraclasts. The intraclasts are probably fossils that have been micritized. Sorting is good, and all allochems are subrounded. Well H-2 has the least amount of cementation of any of the beachrock wells. The cement is equant or slightly bladed microspar, isopachous and occasionally meniscus. The steeply inclined, pointed bladed crystals are indicative of a

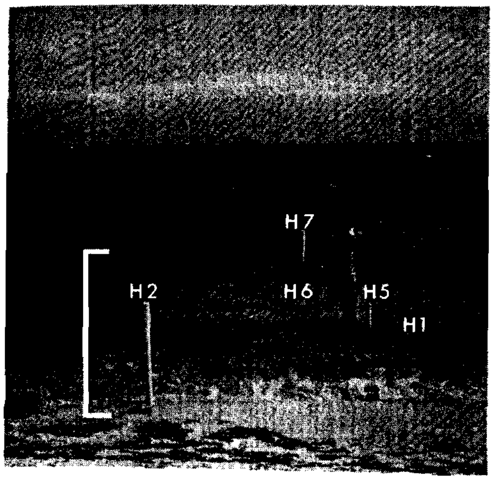


Figure 2: Mean tide view of cased transect wells from the beachrock to just behind the reef flat. The bracket indicates the location of the beachrock.

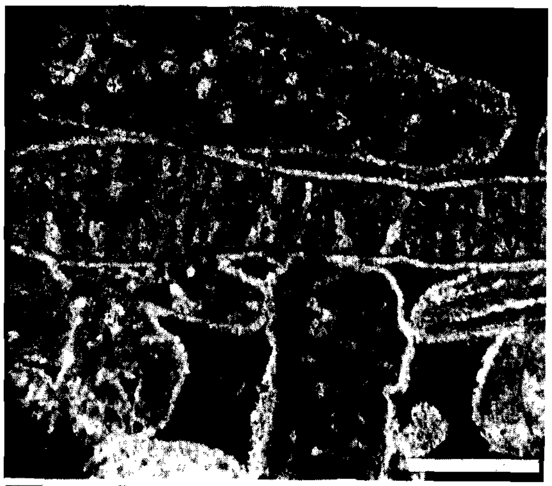

Figure 3: Cross polarized photomicrograph of beachrock from well H-2. Although appearing only slightly cemented, SEM analysis reveals these allochems to be well covered with a high Mg-calcite cement. Bar is 0.2 mm.

Figure 4: Cross polarized photomicrograph of beachrock at 22 cm in H-1. Two generations of high Mg-calcite cements (HMC) and one generation of aragonite cement (A) are present. Bar is 0.2 mm.

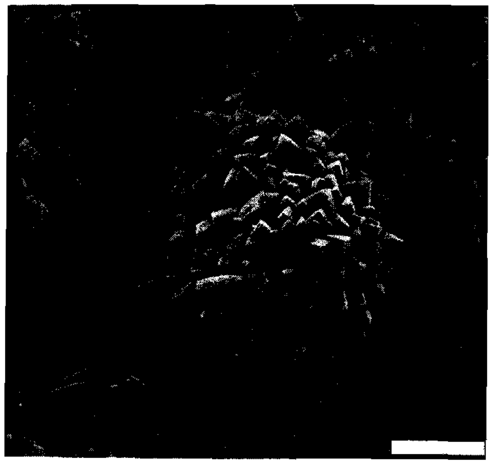

Figure 5: Scanning Electron Microscope photograph of beachrock cement from 22 cm in H-1 *showing* the radial growth of the Mg-calcite cement in spectacular clusters of rosettes. Bar is 10 micrometers.

Figure 6: Scanning Electron Microscope photo of beachrock from H-5. Note the two generations of cements: 1) *aragonite* needles and 2) equant high Mg-calcite crystals. Bar is 10 micrometers.

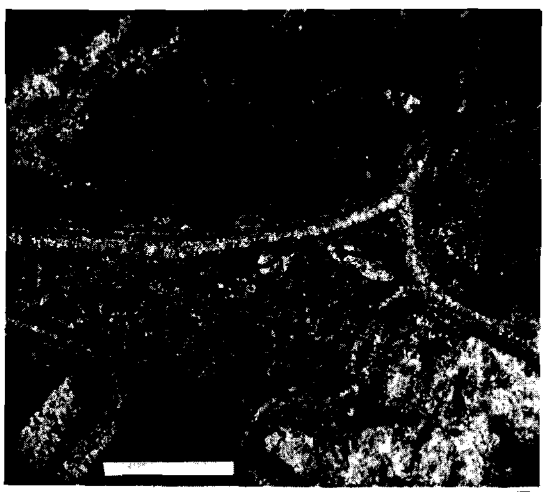

Figure 7: Cross polarized light photomicrograph from 22-26 cm in H-7. Up to seven generations of micritic and bladed *high magnesian* calcite cements form these unusual pisoliths. Bar is 0.2 mm.

high magnesian calcite cement. The cement code according to Folk (1965) is P.$E_1$-P.$B_2$C. Supportingly, microprobe analysis confirms the cement to be a 16.86 ± 0.3 mol % Mg-calcite.

From seventeen to 25 centimeters deep: The grain size is slightly coarser, making this section of the core a medium calcarenite: sorted biosparite, fossiliferous grainstone (Fig. 3). The allochems in decreasing predominance are Goniolithon sp., Halimeda sp., coral fragments, molluscs, foraminifera, echinoid fragments, and intraclasts. The cement is an initial isopachous crust, P.$B_2$C. The cementation is better developed than cements up section, but the cement is still a high Mg-calcite. The SEM photo of the cement shows ubiquitous and well formed rhombohedral crystals of high Mg-calcite.

From 30 to 36 cm deep: Within this interval, the rock is a fine calcarenite: sorted biosparite, fossiliferous packstone, texturally classified as a packstone owing to the presence of micrite as an interparticle cement. The rock is grain supported and the cement type is similar to the cements higher in the well. Allochems consist of Goniolithon sp., coral fragments, echinoid plates, bryozoa, foraminifera, and intra- clasts. Allochems are entirely coated by isopachous high Mg-calcite, P.$B_2$C.

## Middle Intertidal Zone: Wells H-1 and H-5

Petrographically, the cores from the lower intertidal wells H-1, H-5, and H-6 are more complex than well H-2. A greater variety of cement types and amounts of cementation exists even within one thin section.

The beachrock unit in H-1 is 33 cm thick and directly overlies the Falmouth Formation. A medium calcarenite: sorted Goniolithon sp., Halimeda sp. biosparite, fossiliferous grainstone is found two cm deep in H-1. Bivalve fragments, foram- inifera, echinoid plates, and intraclasts are also present. The first cement, at two cm, is an isopachous micrite P.$E_1$ followed either by aragonite fibers P.$F_3$C (Fig. 4) or by a microspar with a crystal morphology of a high Mg-calcite.

At four cm deep: The rock is a fine calcarenite, with three distinct cements: two layers of micrite cement inside an aragonite isopachous rim. The first micrite layer is a micritic envelope, approximately 20 micrometers thick. The high angle crystal terminations on the second cement P.$E_2$, a boarderline microspar, are indicative of high Mg-calcite. The allochems are micritized so heavily at four centimeters that it is difficult to identify them.

At 22 cm: The Mg-calcite crystals form spectacular rosettes (Fig. 5), P.$E_2$C. These crystal faces are curved, in contrast to the other Mg-calcite cements. Similarly, Marshall and Davies (1981) have identified curved high Mg-calcite crystals in submarine cemented rocks on the Great Barrier Reef. Ginsberg, et al (1971) also noted curved high Mg-calcite crystal faces in Bermuda submarine cements, postulating that these curvatures were caused by the inclusion of $Mg^{2+}$ ions in the calcite lattice. However, as not all high Mg calcite crystals are curved, the reason for this curvature is still quite problematical.

A microprobe transect from the surface of well H-1 downwards delineates two distinct cement generations: aragonite and a high Mg-calcite cement which spatially varies in magnesium from 12.6 ± 0.2 to 29.37 ± 0.30 mol %, with a mean value of 17.78 ± 7.79 mol %.

Well H-5 is also in the lower intertidal zone and lies approximately one meter west of H-1. The beachrock is at least 30 cm thick, unfortunately its total thickness is unknown because the core barrel bent and forced abandonment before completion in the underlying Falmouth Formation.

From zero to five cm deep: The surface of the beachrock is covered with living vermitids and green algae. The rock is a medium calcarenite: sorted Halimeda sp., Goniolithon sp. biosparite; fossiliferous grainstone. Other allochems are gastropods, foraminifera, coral fragments, and echinoid plates. Aragonite is a predominant cement, appearing as isopachous rims P.$F_3$C and as a pore filling cement P.$E_1$. Microprobe analysis of this rock confirms aragonite micrite as an initial cement and aragonite needles as a subsequent cement. The Halimeda sp. flakes are heavily micritized, and there is noticeable dissolution of some Goniolithon sp. Aragonite is filling in the pores. SEM analysis indicates that equant to fibrous high Mg-calcite cement is common, P.$E_1$-P.$F_3$C, a morphology and mineralogy previously described by Ginsberg et al.(1971) for Bermudan submarine cements. This cement type also occurs in H-1. In some areas the Mg-calcite equant cement directly overlies the aragonite needle cement, while in other areas, the aragonite needles protrude through the equant cement. Such cement sequences may either indicate simultaneous to alternating growth of these cement types or the growth of high Mg-calcite around previous aragonite precipitates.

From seven to eleven cm deep: The rock is a fine to medium calcarenite: sorted biosparite, fossiliferous grainstone. Allochems increase from fine to medium grain size with depth. Those at seven to nine cm are subrounded to subangular coral fragments, Halimeda sp., and Goniolithon sp. From ten to eleven cm the allochems are rounder and much larger (a medium calcarenite). Here, Halimeda sp., Goniolithon sp., bivalve fragments, coral fragments, and gastropod shells are the major allochems present. The cements vary in type and amount in this thin section also. From seven to eight cm deep, the rock is heavily cemented with three distinct cement generations: 1) a micritic high Mg-calcite envelope surrounding the allochems, 2) isopachous aragonite needles P.$F_3$C, and 3)isopachous high Mg-calcite equant microspar P.$E_3$.

From 24 to 27 cm deep: The beachrock is a medium calcarenite: sorted biosparite; fossiliferous grainstone. The allochems consist of coral fragments, Halimeda sp., Goniolithon sp., bivalves, and echinoid plates. The same three cement types that were seen at seven to eleven cm in this well are seen at 24 to 27 cm. The micritic envelope is best developed at 24 cm and is followed by aragonite needle cement, P.$E_3$C. The cementation is less at 25 cm, the micritic envelopes become fewer, and the aragonite needles disappear, leaving only a micritic and equant microspar high Mg-calcite cement. At 27 cm, the micritic envelope disappears entirely.

## Lower Intertidal Zone: Well H-6

The lower intertidal beachrock is characterized by an extensive cover of vermitid tubes and green calcaerous algae. Well H-6 is located in the lower intertidal and is approximately 50 cm seaward from H-5. At this location, the beachrock is the thickest, 44 cm, and directly overlies the Falmouth.

From zero to four cm deep: The rock is a medium calcarenite: packed biomicrite, fossiliferous packstone. The allochems are similar to the other cores, and include fragments of Halimeda sp., coral, Goniolithon sp., echinoid plates and foraminifera. In contrast to the other wells, the cement consists of high Mg-calcite micrite which is pelletoidal with local areas of high Mg-calcite isopachous bladed cement P.$B_2$C. Furthermore, aragonite is noticeably absent. Micirite is not restricted to envelopes but becomes pervasive to the allochems. The aragonitic Halimeda sp.

and high Mg-calcitic Goniolithon sp. are particularly susceptible to micritization. Another diagenetic peculiarity is the incipient replacement of some forams by phosphate.

From 41 to 44 cm deep: The rock is a fine calcarenite: packed biomicrite, poorly washed microsparite, fossiliferous packstone. The allochems are intraclasts (which may be unidentifiable micritized biogenic allochems), coral, Halimeda sp., Goniolithon sp., and mollusc fragments. The cement is predominantly pelletoidal micrite, isopachous micrite, and bladed microspar. All cements are of high Mg-calcite mineralogy. Pelletoids, fifteen micrometers in size, as well as allochems are being cemented by the isopachous high Mg-calcite cement P.B3C indicating that the microspar is younger or at least as old as the pelletoids. Pelletoids have been found in submarine cemented rock by Land and Moore (1980) and Marshall and Davies (1981). Moore (1973) suggested pelletoids to be "fine clastic material trapped by intergranular algae or fungal filaments". However in these thin sections no algal or filamental structures are observed. Alternatively, Chafetz and Folk (1984) has suggested that bacterial colonies form some pelletoids in carbonate rocks. Supportingly, bacterial cocci and bacilli are petrographically observable and abundant in both these beachrock pelletoids and micritic cements.

**Upper Subtidal Zone: Well H-7**

Well H-7 is located in the upper subtidal zone where beachrock is present and directly overlies the Falmouth. Here the tidal water depth varies from approximately ten to 25 cm with the rock surface never becoming subaerial. The thickness of the unit is 24 cm, thinner than in the intertidal zone. Seaward of H-7 the beachrock abruptly ends. Unlike the lower intertidal sites, no vermitids or green calcareous algae are present. Lithologically, the rock is most similar to the core from H-6 and is described as a medium calcarenite: packed biomicrite/poorly washed microsparite, fossiliferous packstone.

From zero to ten cm deep: The allochems are Halimeda sp., Goniolithon sp., pelletoids, intraclasts, and coral fragments. The cement is isopachous and meniscus high Mg-calcite micrite and microspar P.B13C. The microspar crystals are well formed rhombohedra typical of high Mg-calcites. Pelletoids are abundant between the grains and in intragranular pores.

From 22 to 26 cm: The beachrock cement is extremely extensive and contains multigenerations of isopachous high Mg-calcite micrite and microspar. There are as many as seven layers of radial and concentric pendulous cement around the allochems forming an unusual pisolitic rock (Fig. 7). The pelletoids between the pisoliths are geopetal, cemented with microspar. At 24 cm the beachrock contacts the Falmouth Formation. The contact itself is irregular, obscured by pervasive micrite.

**ACCUMULATION-CEMENTATION RATES FROM CARBON 14 DATING**

Cores from three vertical zones in well H-2 were radiocarbon dated to aid in determining the age of the lithified sediments and rates of sedimentation - lithification of the beachrock. Whole rock radiocarbon dating was necessary, with post-depositional and age-contaminating cementation yielding a maximum age "dilution" of less than 5%.

Four cm from the surface, the whole rock age is 690 + 50 years. The age is 670 + 50 years at a depth of fourteen centimeters. The similarity in ages indicates an almost simultaneous deposition-lithification for these ten centimeters of rock. The age date of the third sample, at a depth of 22 cm, is 1240 + 50 years; in sharp contrast to the shallower section, this date suggests an earlier, slower sedimentation-lithification rate, averaging 0.14 mm $yr^{-1}$.

**WATER CHEMISTRY SYNOPSIS**

Waters withdrawn from the cased beach rock wells and from ambient waters were sampled in the field for pH, $P_{CO2}$, temperature, and later for carbonate alkalinity, activity of $Ca^{2+}$, and activity of $Mg^{2+}$. Saturation states were calculated with respect to aragonite and a variety of Mg-calcites (using the solubility data of Plummer and Mackenzie, 1974). Results are to reported in detail elsewhere, but Table I summarizes the more salient points applicable during mean tide. Briefly, the surf zone demonstrates the lowest dissolved $CO_2$ activity owing to mechanical wave degassing with consequently the highest saturation states. With depth the beach rock waters from the middle intertidal show the lowest saturation states, approaching equilibrium with aragonite (its only cement locality). These lower saturation states are for the most part due to the advection of fresh waters (decreasing the Cl °/oo down to 11.06) with high dissolved $CO_2$. In sharp contrast, both the upper intertidal and upper subtidal environments show insignificant fresh water dilution, low dissolved $CO_2$, and substantially higher saturation states, approaching stoichiometric equilibrium with respect to the more soluble Mg-calicites of high mol% $MgCO_3$.

**SYNTHESIS AND INTERPRETATION**

The beachrock within the study area is located in a protected pocket beach. The bulk age of the beachrock is approximately 670 to 1240+ 50 years; deposition-lithification rates vary episodically from an almost instantaneous few cm $yr^{-1}$ to a minimum sedimentation-lithification rate of 0.014 cm $yr^{-1}$.

We document five distinct beachrock cement types in Jamaica. They are: 1. equant and bladed high Mg-calcite cement; 2. micritic high Mg-calcite cement; 3. pelletoidal high Mg-calcite cement; 4. aragonite equant and needle cement; and 5. micritic aragonite cement. The high Mg-calcite cements contain between 12 and 29 mol % $MgCO_3$. The cements can occur together as intergrowths or as distinct layers. An interpretive beach profile of the distribution and mineralogy of the cements is presented in Figure 8. Interestingly, some pore spaces in the uppermost part of underlying Falmouth (not described here) have similar cements as the beachrock, indicating that the same processes of cementation can occur in any rock situated in the intertidal zone provided that the conditions are right.

The pore water chemistry reflects the equilibrium cementation which is continuing in the Holocene beachrock of Jamaica. High Mg-calcite is the dominant mineral phase, with the exception of the anomalous aragonite cement dominance which occurs in the lowest carbonate saturated waters of wells H-1 and H-5. As noted earlier, the beachrock is fractured orthogonally, not unlike other beachrock occurrences reported by Ginsburg (1953). As these large open fractures enhance rock permeabilities, possibly the low chlorinities in these middle intertidal wells are due to extensive fresh water advection through the proximal fractures.

The more soluble higher Mg-calcite cements (15-29 mol%) are precipitates which thermodynamically are the most favored during an increase in water saturation states, such as when $CO_2$ degasses through agitation of the surf during the higher tides. Conversely, during the low tide, when the surf is next to nonexisitent, the $CO_2$ does not mechanically degas. Further, it is during the low tide that fresh water is more

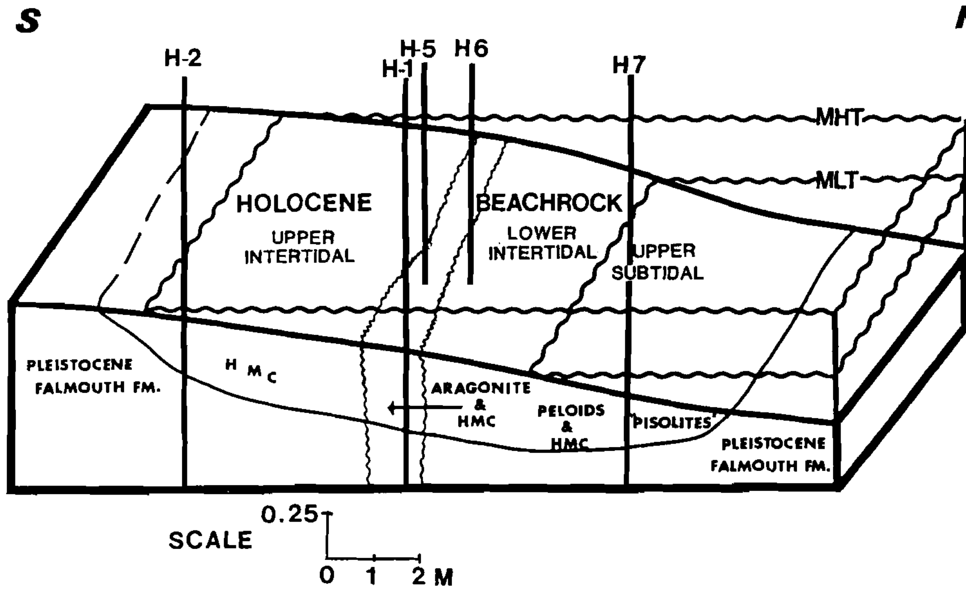


**Figure 8: Diagrammatic 3D cross-section of beachrock cement facies.**

likely to flow seaward in a process known as tidal pumping (Hanor, 1978). The combination of $CO_2$ buildup with tidal pumping of meteoric waters affects greatest the chemistry of the middle intertidal pore waters, e.g. wells H-1 and H-5. During the low tide then, the equilibrium precipitates are the lower soluble aragonite and lower Mg-calcites (12 to 15 mol%). Prolonged time spent under such conditions could ultimately lead to dissolution, micritization, or neomorphic fabrics of more soluble mineral phases.

It is these oscillations in water saturation states, especially that of dissolved $CO_2$, through time and space which have given rise to the observed sequential and lateral variability of cement mineralogies in Jamaican beach rock. Possibly, such oscillations are important in producing the heteorgeneity of cement mineralogy and fabric observed in beachrock environments elsewhere.

## ACKNOWLEDGEMENTS

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TABLE I: MEAN TIDE DATA

| SAMPLE LOCATION | SURF (Ambient) | UPPER INTERTIDAL (H-2) | MIDDLE INTERTIDAL (H-5) | UPPER SUBTIDAL (H-7) |
|---|---|---|---|---|
| T (°C) | 27.1 | 25.7 | 27.8 | 27.1 |
| pH | 8.515 | 8.135 | 8.404 | 8.545 |
| Cl (°/oo) | 21.01 | 22.01 | 11.06 | 20.58 |
| $A_{H_2CO_3*}$ ($\mu$ mol $l^{-1}$) | 6.88 | 9.16 | 12.7 | 12.6 |
| $A_{Ca^{2+}}$ (m mol $l^{-1}$) | 2.32 | 3.32 | 0.54 | 1.83 |
| $A_{Mg^{2+}}$ (m mol $l^{-1}$) | 27.5 | 27.8 | 4.67 | 14.7 |
| $Alk_C$ (meq $l^{-1}$) | 3.05 | 2.38 | 2.50 | 2.49 |
| $\Omega_{ARAGONITE}$ | 4.21 | 2.49 | 0.95 | 2.92 |
| MAX. MOL % $MgCO_3$ IN Mg-CALCITE @ SATURATION | 19 | 16 | 9 | 17 |

*Dissolved $CO_2$

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