DYNAMIC CIRCULATION OF INTERSTITIAL SEAWATER IN A JAMAICAN FRINGING REEF

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ABSTRACT: Twelve 7.62 cm diameter cores were taken along three and a half kilometers of coastline in the vicinity of Discovery Bay, Jamaica, to document the distribution of dolomite previously described (Mitchell *et al.*, 1987). Water was observed to flow actively in and out of the open holes, which range in water depths from 6 to 13 meters. Most of the shallowest holes, and the single deepest one, "exhale" slowly and continuously, little affected by the wind-driven surge. Holes at intermediate depths exhibit a net flow of water into the reef, "breathing" asymmetrically with the wind-driven surge. In one case an integrated current velocity of 86 cm sec^{-1} was measured over a five minute interval into a three meter deep open hole. Astronomical tides, local wind-driven surge, and dispersion due to meteoric water discharge are apparently not direct causes of the phenomenon.

Under normal conditions, dynamic interstitial fluid flow can provide the conditions necessary for extensive submarine cementation (and dolomitization?). Under abnormal conditions (natural fractures or man-made holes), extreme current velocities may be capable of causing the kinds of textures observed in Neptunian dikes and sills in ancient reefs.

INTRODUCTION

The fringing reef along the North Jamaican coast was devastated by hurricane Allen in August 1980 (Woodley *et al.*, 1981). Hurricanes had not affected this area for many years, and consequently a lush reef had become established. Owing largely to the enthusiasm of T. F. Goreau, reefs in this area had become among the best described in the world. The damage inflicted by hurricane Allen demonstrated unequivocally (and painfully to investigators who were conducting long-term studies!) the uniformitarianistic nature of catastrophies. At least one positive result of the hurricane was the removal of most of the unconsolidated sediment, and much living coral, from water depths shallower than about 10 meters. An extensive "hardground" was thus exposed which had previously been described as the "barren zone" by Goreau (1959), but the continuous nature of which had not been recognized.

U/Th age determination on an unaltered sample of *Acropora palmata* from hole "F" (Fig. 1) yielded an age of 147 ± 11 ka, and proves the biolithites beneath the hardground to be Pleistocene in age. As a result of hurricane Allen's "clean-up" and the new age determination, a cross-section of this area can now be constructed (Fig. 2) which differs from that presented previously (Land, 1974, his Fig. 4). Very little Holocene accretion has taken place in water depths less than 10 meters. Infrequent hurricane activity, coupled with extensive bioerosion (Mitchell, 1988), is obviously of paramount importance in controlling shallow water reef morphology and the make-up of shallow reef communities, a fact not recognized in pre-1980 studies.

In the summer of 1987 eleven cores were taken along three and a half km of coastline (samples E through 0, Fig. 1), under the assumption that a Holocene hardground was being sampled. At that time we observed the active flow of water in and out of the 7.62 cm diameter holes (discovered when a rubber stopper, intended to plug one of the open holes, was forcibly sucked from the senior author's hand). Returning in the summer of 1988, wiser as to age of the hardground, and better prepared to study the submarine hydrodynamics, we emplaced two additional holes and deepened several others.

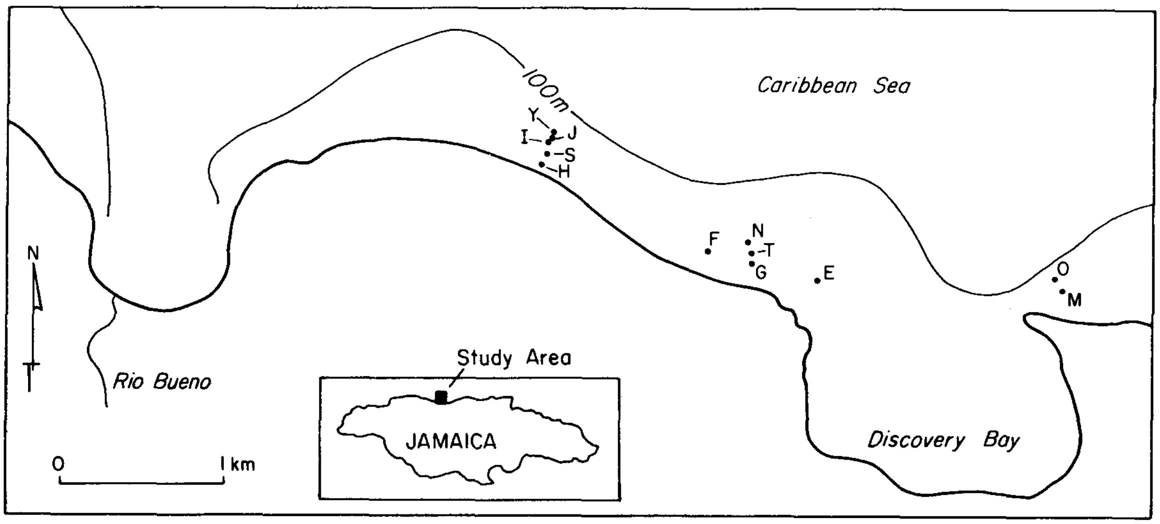

Figure 1.-- Location map of drill holes along the North Jamaican coast in the vicinity of Discovery Bay. The shallowest holes are in water approximately 6 m deep, and the deepest (Y) in 13 m.

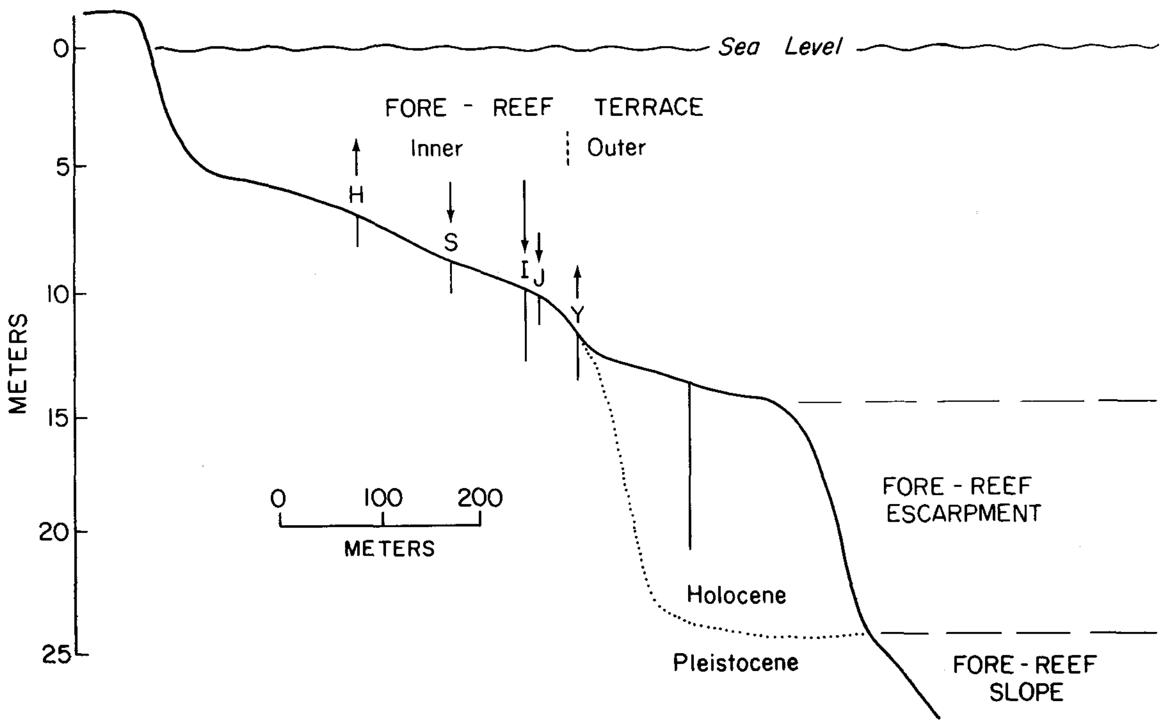

Figure 2.-- Cross section through the north Jamaican fringing reef through drill holes H and Y (see Figure 1 for location) showing the observed water movement in and out of the open holes. Length of arrows depicts relative flow velocities. Considerably less Holocene reef accretion exists than was proposed by Land (1974, his Figure 4). Based on a hole drilled 7 meters into the reef at a water depth of 16 m, seaward of hole E, (Mitchell, 1988, his Appendix III), the thickness of Holocene reef in the vicinity of the fore reef escarpment is similar to that previously proposed, but is very much less on the inner part of the fore-reef terrace. The buried Pleistocene terrace at approximately -25 m is easily reconciled with a similar, but barren, feature exposed at Negril (Hendry, 1982).

BIOLITHITE PETROLOGY AND GEOCHEMISTRY

The recovered biolithites are much more lithified than onshore subareal exposures of the 125,000 year-old (Moore and Somayajula, 1974) Falmouth Formation. Increased lithification is due not only to a longer duration of marine exposure, but to the higher energy offshore facies which have now been cored. Most recovered biolithites exhibit very large, open cavities and megascopic fibrous cements (Fig. 3). Petrographic examination in thin section and by scanning electron imaging confirms extensive marine cementation (Land and Goreau, 1970), and the presence of dolomite in all cores.

Calcite is rare, but thick cements lining cavities in several samples have been identified by both X-ray diffraction and electron microprobe analyses. No evidence of wholesale meteoric diagenesis has been found based on extensive oxygen isotopic analyses of pelloidal micrite. However, dissolution is evident in many samples, and "whisker crystals" (Wright, 1986) are present in a few, possibly due to meteoric processes resulting from the long exposure during glacial sea level lowering. More detailed description of these rocks will be forthcoming (Lund, in preparation; McCullough, in preparation), including age determinations on the dolomite itself. For the present, we merely wish to document that extensive marine cementation has occurred, necessitating extensive fluid flow due to the relatively insoluble nature of the aragonite and Mg-calcite cements.

Nine whole-rock ^{14}C ages have been obtained, ranging in age from 11,750 to 29,100 years B. P. ($\delta^{14}C$ from -768 to -973 o/oo). Based on the known Pleistocene (stage 5) age of the host rocks, then between 3 and 45% Holocene carbon has been added to the biolithites to account for the observed ^{14}C activity. The active fluid flow we will now describe is clearly sufficient to accomplish such a major change in whole-rock chemistry by cement precipitation following Holocene marine submergence approximately 5000 years ago.

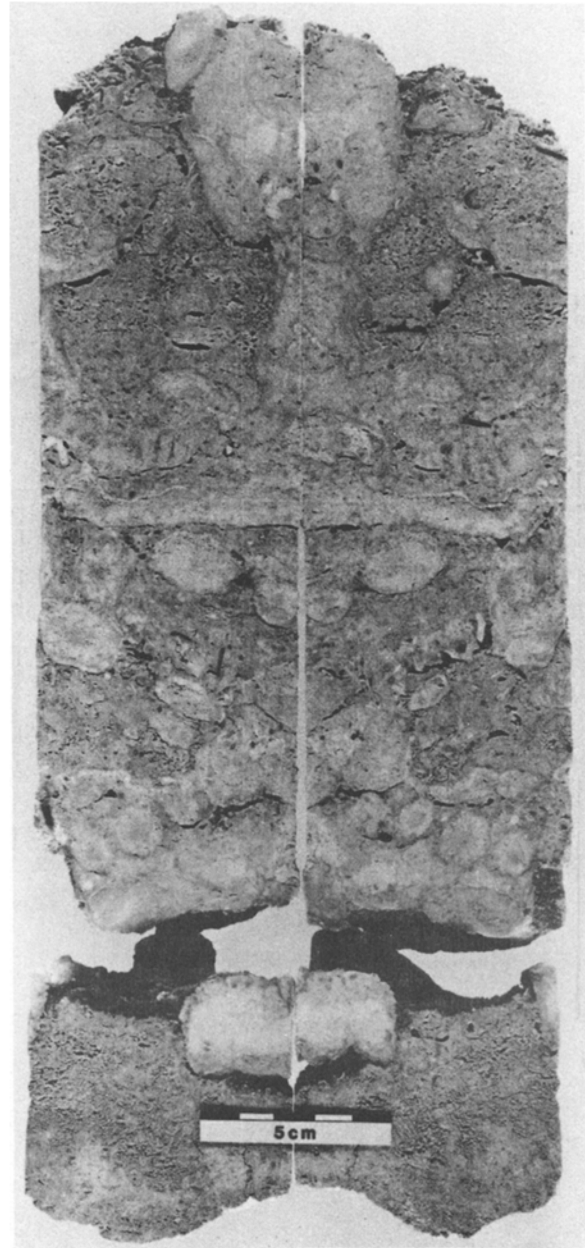

Figure 3.-- Photograph of slabbed biolithite (43 cm below the reef-water interface, hole J) showing large open cavities and megascopic cements.

HYDRODYNAMIC OBSERVATIONS

Active flow of water in and out of the open holes (which were plugged with rubber stoppers between observations) was observed both qualitatively and quantitatively. Qualitative observations were made by holding a bag (Fig. 4) or syringe filled with fluorescein dye over the open hole and noting the movement of water as a function of wave surge and tidal stage.

In the case of holes which exhaled water, samples were taken with a syringe connected to tubing which was inserted through a hole in the rubber stopper capping the well. Alkalinity and

Figure 4.-- Underwater photograph (10 m water depth) showing fluorescein dye being rapidly sucked into open hole I. Subsequent to this photograph, a net water velocity of 86 cm sec^{-1} into the reef was measured using a reversible, mechanical vane-type current meter.

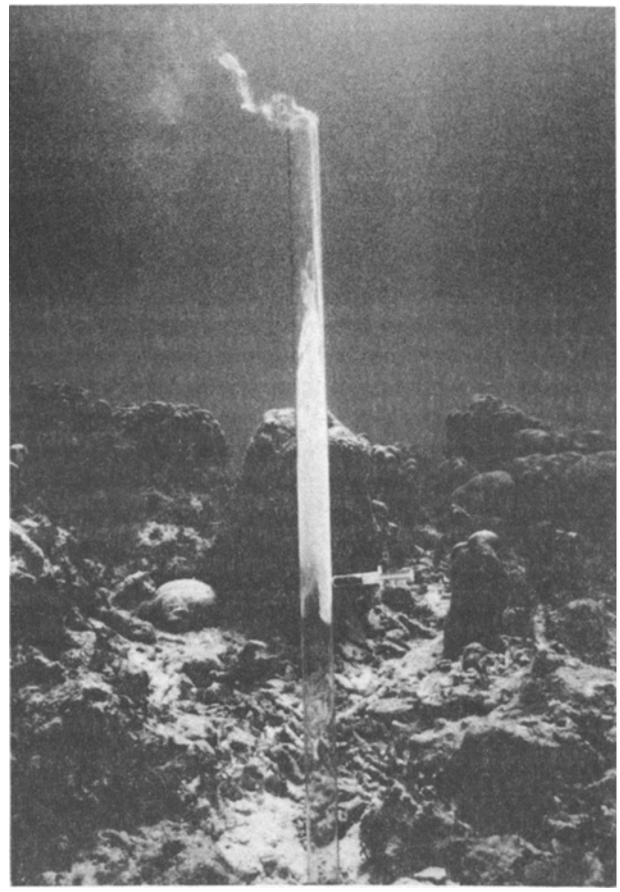

Figure 5.-- Underwater photograph (13 m water depth) showing fluorescein dye exhaling from the seaward-most hole (Y). The syringe containing fluorescein has been inserted in a 25 mm diameter clear plexiglas tube wedged into the open hole. The exhalant velocity was approximately 4 cm sec^{-1}.

chlorinity were determined by appropriate titration immediately upon return to the Discovery Bay Marine Laboratory, and compared to ambient seawater collected immediately above the hole in question. In cases, samples were filtered, acidified, and later analyzed for Ca, Mg, Na, K, and S by ICP-AES. In no case, even the day after 6.2 cm of local rain in December, 1987, in the middle of the "wet" season, did the chemistry of the water exhaling from the shallow wells differ from the chemistry of surface sea water collected immediately above each respective hole by more than 2% of the amount of any component analyzed. On this basis, we rule out dispersive mixing of sea water with a coastal meteoric lens as a cause of the observed water movement.

More quantitative observations of water movement were made during the summer of 1988. For those wells flowing faster than approximately 10 cm sec^{-1}, net velocities were measured using a reversible vane-type current meter equipped with a digital counter which permitted integrated velocities to be obtained. Measurements were typically made over five minute intervals, or else the meter was emplaced near the beginning of a dive and recovered near the end, approximately thirty minutes later. For those wells flowing too slowly to overcome frictional and inertial forces in the mechanical meter, a 25 mm diameter clear plexiglas tube 1 meter long, with a rubber stopper fitted around one end, was placed in the open hole. A syringe filled with fluorescein dye was placed in a small hole drilled through the tube about half-way up (Fig. 5). A "spurt" of fluorescein could then be timed as it exhaled from, or was drawn into, the open hole.

Our observations are summarized in figure 2. In nearly every case the shallow holes (especially G and H, Fig. 1) exhale steadily at velocities of a few cm sec^{-1}. Because shallow water is most susceptible to wave surge, the insensitivity of these wells to the surge is surprising. As stated previously, none of these wells, despite their proximity to the coast line, provided any chemical evidence that meteoric water was involved with the discharge. The single deep hole (Y in Figures 1, 2, and 5) exhibited similar behavior. In contrast, holes at intermediate depths were surge-sensitive (see also Carter *et al.*, 1988), but exhibited a net inflow of water. Net velocities were most often sufficient to be measured with the current meter and ranged from 0.3 to 86 cm sec^{-1}, typically averaging about 50 cm sec^{-1}. In the case of hole I (Figures 1 and 2), net velocities increased as the hole was progressively deepened, and at its final penetration depth of 3 meters the net maximum velocity of 86 cm sec^{-1} into the open hole was observed.

A recording tide gauge was maintained during the period when these observations were being made, and although we could not monitor wells through a full tidal cycle, individual wells appeared to exhibit essentially constant behavior irrespective of tidal stage. Tides along the north coast of Jamaica are mixed semi-diurnal, with a spring tidal range of only 48 cm at Discovery Bay. Although we cannot rule out a tidal component to the flow of water in and out of the open holes (one observation suggests somewhat lower net velocity in hole I at dead low tide), simple changes in the elevation of the sea surface due to the astronomical tides do not correlate with the observed water movement.

The north coast of Jamaica exhibits an orographic island effect during most of the year. During the late afternoon, night, and early morning, winds blow gently seaward (offshore on the North coast) from the relatively cool island. As a result, the coastal sea can be quite calm, or exhibits only a very gentle swell. During daytime heating, air rises over the island, and, augmented by the prevailing onshore trade winds, wind-driven waves typically reach in excess of one meter by early afternoon. Our observations were made under all wave conditions consistent with safety, and the net behavior of all wells was independent of wind-driven wave conditions. Under flat calm conditions, wells at intermediate depths (especially wells S, I, J, N, and T) sucked continuously. Under conditions of strong wind-driven waves, the wells "breathed" with the swell, "inhaling" on the landward surge and the first part of the seaward return, and "exhaling" during the remainder of the seaward surge. Shallow wells (especially H and G) exhaled steadily during calm conditions, but exhaled sporadically, stopping briefly between changes in surge direction, when the surge was strong. Since the net behavior of any single well did not change as a function of wind-driven wave intensity, we conclude that local wind-driven waves are not solely responsible for water movement in and out of the reef. They do act as a modifying force, however.

DISCUSSION

The cause of water flow in and out of the open holes appears to be unrelated to simple changes in sea surface elevation due to the astronomical tides, to local wind-driven wave intensity, or to dispersion due to meteoric water discharge from the coastal aquifer. We conclude that a non-seasonal oceanographic factor, such as convergence or wind "set up" along the coast interacting with the local submarine topography, or conduit flow beneath our observation wells, possibly related to submerged karst features resulting from glacial lowstands, must be responsible.

Although our observations and measurements have not quantified the hydrologic potential, which might be used in conjunction with measured permeabilities of the rocks to calculate natural flow rates, they do demonstrate that considerable hydrologic potential exists. Extensive marine cementation of the biolithites, resulting in the addition of large amounts of Holocene carbon to the Pleistocene rocks, documents the considerable flow which has occurred. We suggest that marine cements may simply be the result of active circulation of large volumes of oversaturated surface sea water through the rocks, which provide abundant surfaces for nucleation, rather than *in situ* chemical or microbial processes which have been previously invoked (e.g. Land and Goreau, 1970; Pigott and Land, 1986).

In addition, our observation of current velocities up to 86 cm sec^{-1} in an open hole may have relevance to the rock record. Many ancient reef systems exhibit vertical and/or horizontal fractures ("Neptunian" dikes and sills) filled with marine cements and internal sediments (e.g. Flugel, 1982; Playford, 1984; Kerans, 1985). In many cases current structures and other observations seem to demand high velocity water flow through open conduits. Large volumes of marine cements filling the fractures document a long duration of presumably lower velocity flow. If earthquakes or compaction of underlying unlithified sediments were to promote natural fracture of the Jamaican hardground, then the kinds of water velocities we have documented could occur naturally. The fact that ancient reef fracture systems are filled with extensive marine cements and with current-deposited sediment, suggests similar extensive, and often violent, flow of water through ancient reef systems.

CONCLUSIONS

1) Water flows actively in and out of open holes in Jamaican fringing reefs, and is not simply related to local astronomical tides, local wind-driven waves, or dispersive mixing with meteoric water.

2) Velocities up to 86 cm sec^{-1} have been observed. Such extreme velocities, and the hydrodynamic potential which must be responsible for them, could emplace thick marine cements and current deposited sediments in natural open fractures.

3) The hydrodynamic potential developed by the yet-unexplained forces can presumably cause considerable fluid flow through the unfractured reef, and could be responsible for the emplacement of considerable volumes of marine cement (and dolomite?). Active fluid flow involving large volumes of oversaturated water may be more important in accounting for marine cements (and dolomite?) than local chemical perturbations.

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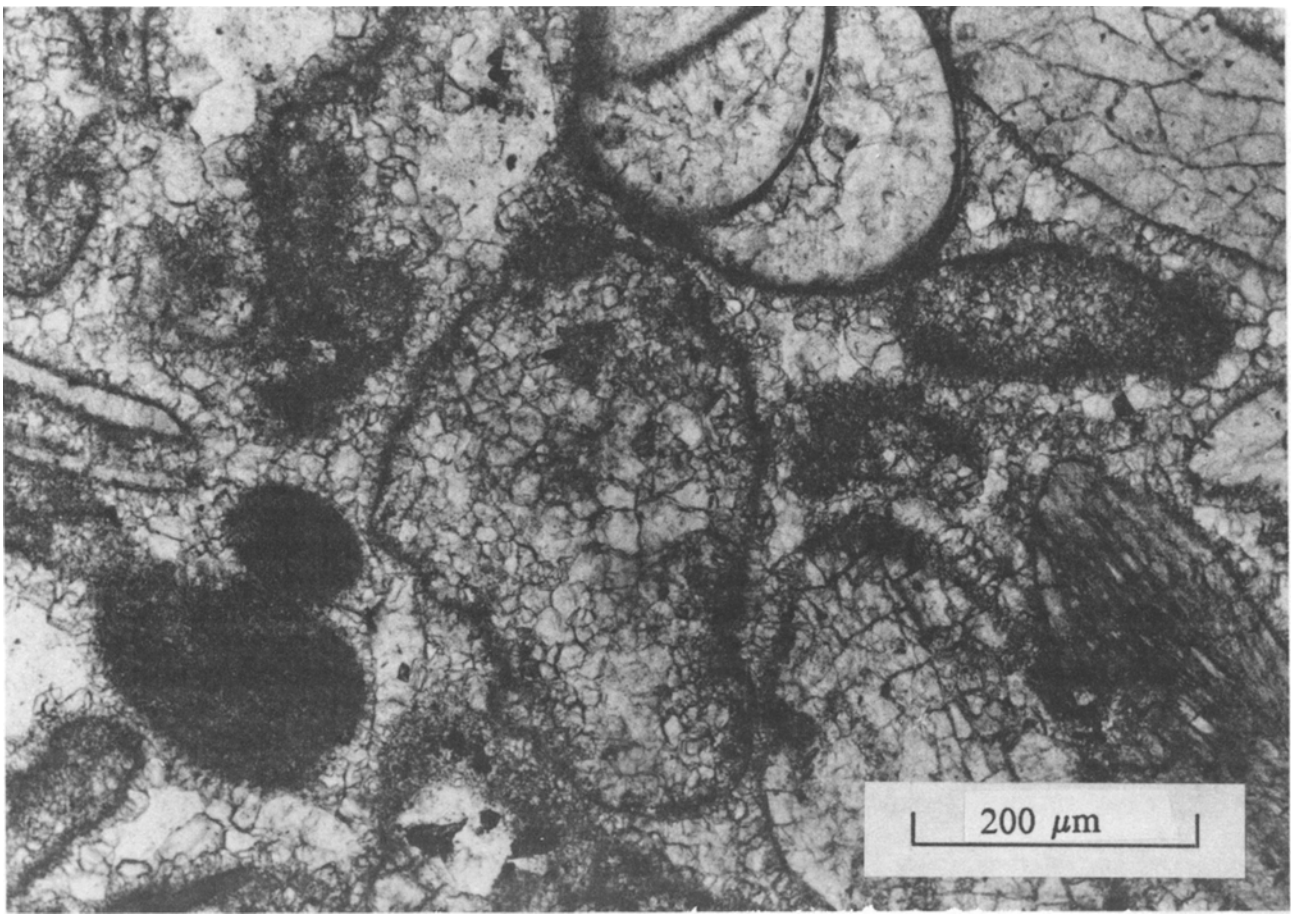

Thin section of Pleistocene carbonate rock, Barranco de los Molinas, west coast of Fuerteventura, Canary Islands, Atlantic Ocean (Gerd Tietz).