Wave-Forced Hydrogeology and Diagenetic Responses in Tague Reef, St. Croix, U.S. Virgin Islands

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INTRODUCTION

As long as geologists have been studying the lithology of reefs, they have realized the importance of wave-forced water flow through the reef framework as an agent in the diagenesis of reef sediments. Previous studies on St. Croix reefs have shown that significant chemical gradients are developed between interstitial water and sea water (Zankl and Multer, 1977) demonstrating the importance of advective processes controlling mass transport of chemical constituents. In order to better understand the relationship between physical processes and diagenetic responses, a study is under way to begin quantifying the effect of wave forcing on pore-water flow rates and paths in a bank-barrier reef (Adey and Burke, 1977) near the West Indies Laboratory. The position of Tague reef (Fig. 1) exposes it to trade wind waves and storm swell from the Atlantic, both attenuated by the bank-interior location of the reef on the island's northeast coast. Tague reef rises from 10-m water depths on the bank to a depth of one meter at the reef crest and drops off to a five-meter deep lagoon behind. The study of the interrelated hydrological, geochemical and petrographic aspects of early marine diagenesis is centered on a cored transect across the reef. The core transect consists of seven sites, each containing up to four, 1 to 5-m deep cored holes. These were completed as piezometers by cementing PVC pipe in place (Fig. 2). Hydrological data and geochemical samples were taken at the open bottom end of the piezometers.

HYDROGEOLOGY

In order to evaluate the the effects of local hydrological conditions on pore-water flow, both surface waves and reef interior responses were monitored. Wave spectra measured on Tague reef show that the most prominent waves include (1) wind waves and swell , with 5 to 15 second periods and heights of 0.25 to over one meter, (2) an approximately 30 minute infragravity wave of several centimeters height and (3) tides with a mixed diurnal pattern and range of a couple tens of centimeters (Roberts *et al.*, 1988, Lugo-Fernandez, in prep).

Darcy's law, $v = -K \, dh/dl$, (where v is the Darcy velocity, K is the hydraulic conductivity and dh/dl is the hydraulic gradient or change in head over a specific distance) is used to evaluate wave driven flow inside the reef. Hydraulic conductivity was measured by standard bail tests and pumping tests (Cedergren, 1967) where the wells were in shallow enough water to be extended above the water surface in the backreef and reef crest. Typical values for K are on the order of 100 Darcies, a value similar to that of coarse sand. These values were projected into the deeper forereef on the basis of similar lithologies.

The driving force for flow, the hydraulic gradient, was determined by measuring the differences in water pressure within the reef as waves passed over the surface. The data were gathered by electronic pressure transducers placed in the wells and in the water column, sampling at one second intervals over twenty-minute time series. The recorded pressures were then transformed to hydraulic head values relative to a mean sea level. Instantaneous hydraulic-head differences were obtained by subtracting simultaneous measurements of head taken at different levels within the reef at the same site. Typical values were from one to ten centimeters of head difference over vertical differences of about one meter. An important consideration is the pattern of flow over the time interval of one wave period. Numerical modeling indicates that the oscillating nature of wave-pressure variations exerts a strong effect on pore-water flow. Each oscillation produces a pattern of pore-water particle motion of vertically oriented ellipses a few centimeters in diameter or less, and decreasing exponentially in size with depth.

Flux of water across the reef surface was estimated from the theory of Riedl *et al.,* (1972) using local hydrological and wave data. The maximum gross flux of water across the sediment-water interface (both up and down) was estimated to be about 0.5 cubic meters per meter squared per day. The net flux is some fraction of
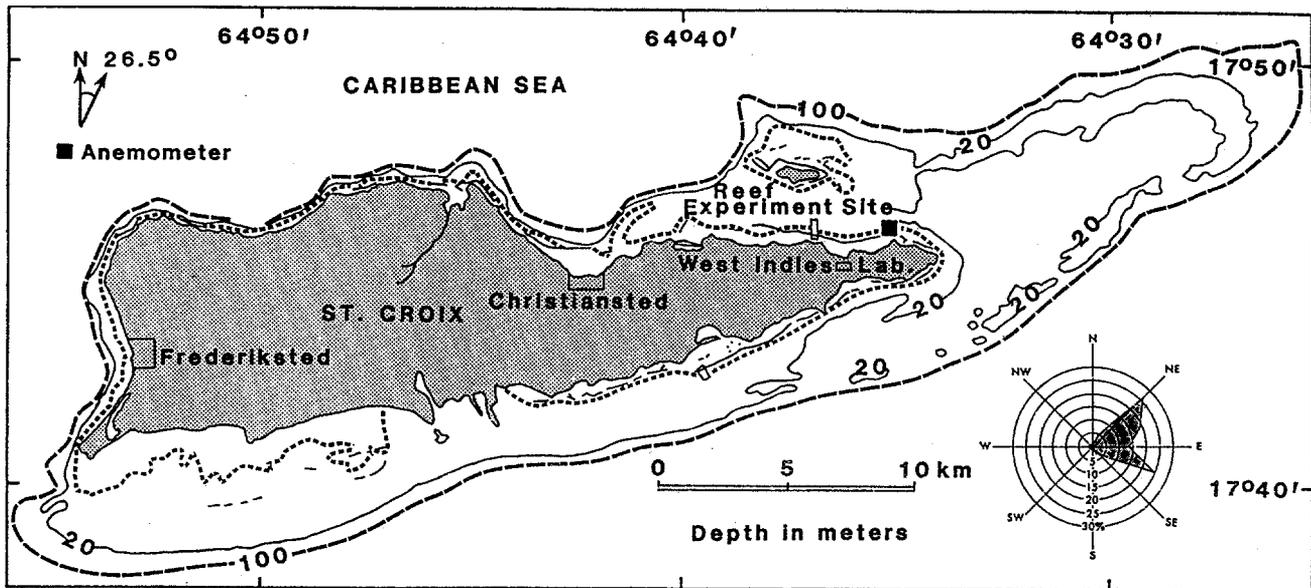
Figure 1. Study area on the island of St. Croix, U.S. Virgin Islands with a wind rose diagram.

this figure that is mixed downward into the reef by mechanical dispersion. This flux is strongly affected by reef zonation (Fig. 3) with the maximum at the reef crest and shallow forereef, and considerable attenuation in the backreef.

As a result of these particle flow patterns and the magnitude of the mass flux, net water transport into the reef is limited to essentially vertically oriented exchange. The effective depth of reasonably frequent mixing (days) is limited to a range between a few tens of centimeters and approximately a meter down into the reef. Lateral transport is limited by wave particle motion and by the low tide range. Thus, the exchange between the water column and reef pore water appears much more limited than might be initially presumed, and is also strongly controlled by reef zonation.

GEOCHEMISTRY

Gradients in pore-water composition and diagenetic environments are governed by the combination of pore-water flow and geochemical transport and reactions. Pore-water samples were taken from the well by devices that isolated the screened portion of the well, ensuring that uncontaminated pore water was acquired.

The most important modification of pore-water chemistry was hypothesized to be related to organic respiration by microbial communities (Pigott and Land, 1986, Sansone et al., 1988). Net aerobic respiration in the reef interior consumes dissolved oxygen and produces carbon dioxide that lowers the pore-water pH. As respiration continues, anaerobic conditions develop, first reducing iron and manganese, then sulfate (Coleman, 1985). Sulfate reduction in turn produces hydrogen sulfide and bicarbonate, increasing pore-water alkalinity. Our

sampling indicates that within one meter of the reef surface, the pore water in the backreef is anoxic, but that the forereef and reef crest are suboxic (Fig. 4). Values for pH show a decline from around 8.1 for sea water to below 7.6 in the pore water, also within one meter of the reef surface (Fig. 5). There were no significant diurnal fluctuations of pH in the well samples. Hydrogen sulfide was measurable in the backreef and crest, and was noticed in the shallow forereef by its odor during pumping experiments.

Saturation states for carbonate minerals were calculated based on the carbonate ion concentration which
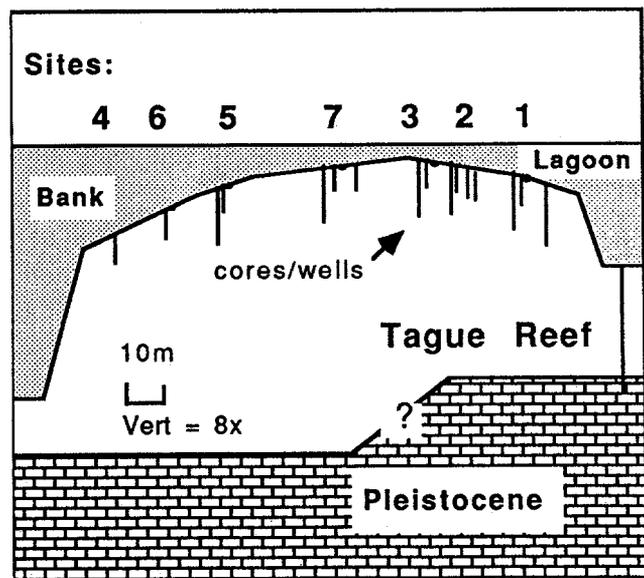
Figure 2. Cross-section of Tague reef showing the location and depth of cored holes with installed piezometers.
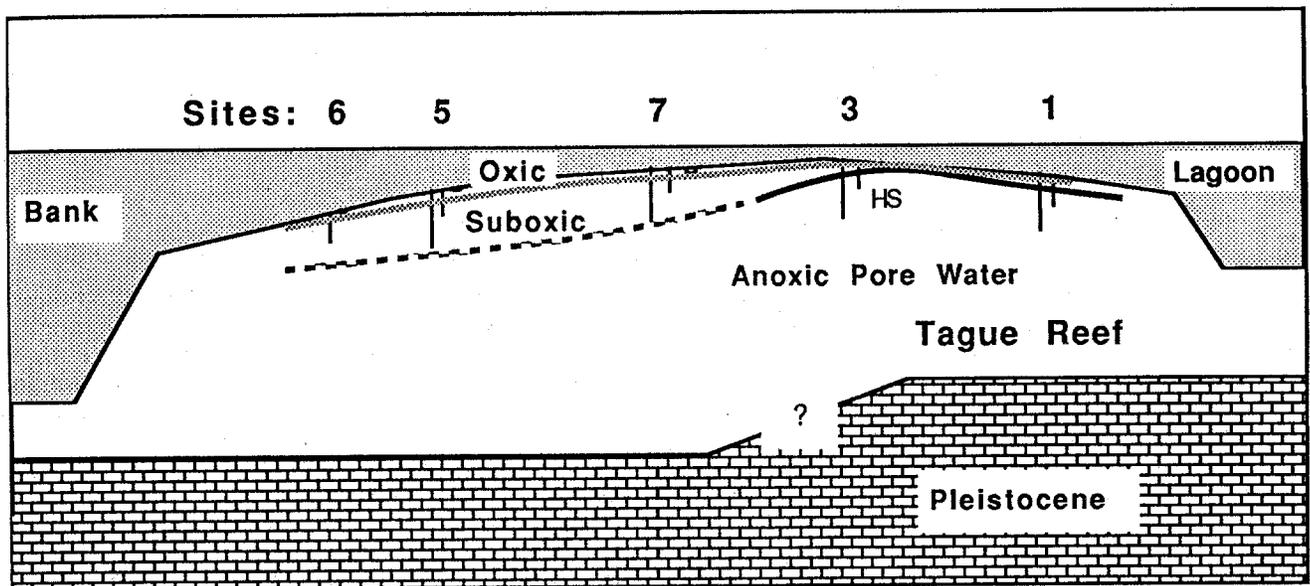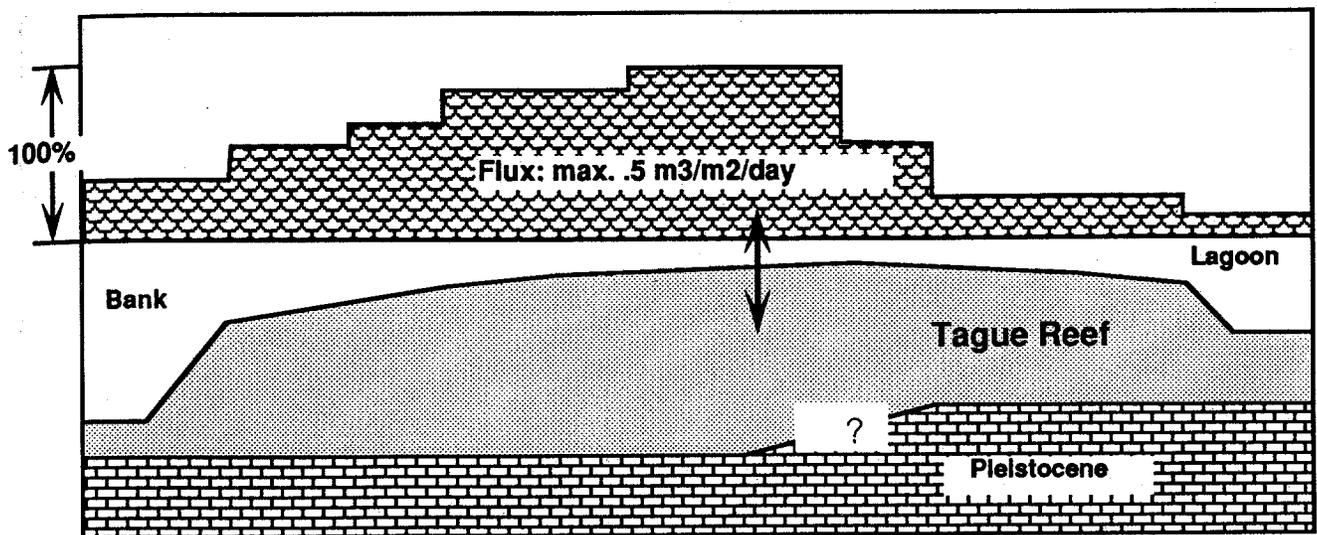
Figure 3. *(above) Cross-section of reef showing relative flux of water forced across the reef sediment-water interface as controlled by water depth and wave height with a constant hydraulic conductivity of 100 darcies.*

Figure 4. *(below) Cross-section of reef displaying contours of oxygen concentration levels within the reef where anoxia occurs very shallow in the backreef and suboxic to very near anoxic levels in the forereef.*

is an exponential function of pH and a linear function of alkalinity. Thus, although sulfate reduction increased alkalinities in some pore waters by about 50%, the decrease in pH measured throughout the reef caused a decline in saturation states to near saturation "or undersaturation with respect to aragonite. These values are consistent with studies in reef-related sediments in Jamaica (Pigott and Land, 1986) and in the Pacific (Buddemeier and Oberdorfer 1986; Sansone *et al.,* 1988). Thermodynamic and kinetic considerations should likely limit the possibilities for significant cementation to the shallowest portions of the reef, although unique micropore

environments may exist that significantly alter geochemical conditions (Sansone *et* al., 1988).

PETROGRAPHY

The diagenetic response to the hydrological and geochemical conditions summarized above was determined from cores taken from the same sampling locations and can be divided into carbonate mineral responses and the presence of oxide and sulfide phases sensitive to the pore-water oxidation state. Carbonate cementation is dominantly found in the forereef and reef crest.
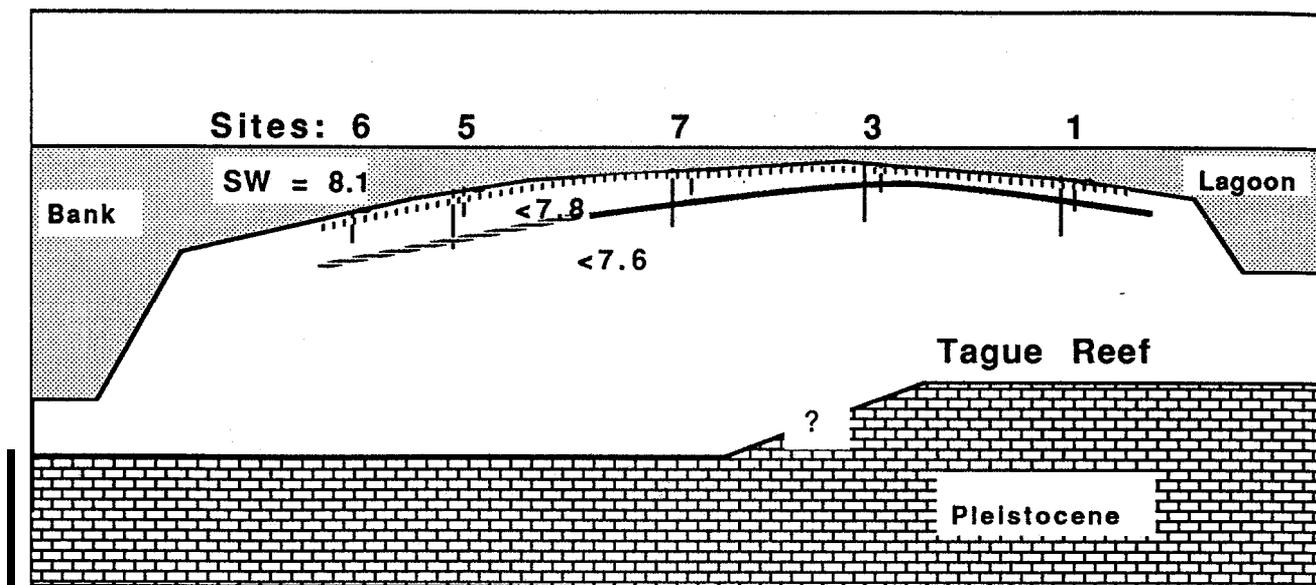
Figure 5 *Cross-section of the reef contoured to show changes in pH from around 8.1 in sea water to 7.6 or less within the first meter of depth into the reef.*

Intergranular cementation found near the present reef surface occurs exclusively at the crest and shallow forereef. It binds poorly sorted sand to gravel-size reef rubble with a very thin circumgranular crust or with more abundant, fine-grained, peloidal pore-filling cement (Fig. 6). Void-filling cements and sediments are common in the forereef and crest and are mostly fine-grained peloidal cements and detrital silt, although occasional coarse-crystalline bladed cements also occur. A thin, irregularly cemented horizon, about one meter deep in the backreef, associated with fragments of the common reef-crest hydrozoan *Millepora,* may indicate the presence of reef-crest cementation at a former reef surface.

Iron and manganese oxide and sulfide coatings are common in the reef indicating the presence of different oxidation states of the pore water. Dark-grey iron sulfides are commonly disseminated in sediments and cements in the backreef and rarely in the deepest sampled reef crest and fore-reef. Iron-oxide coatings appear stratigraphically **above the sulfides, in the shallow backreef and** intermediate reef crest and forereef. Manganese-oxide coatings occur rarely in the very shallowest backreef and are abundant in the upper reef crest and forereef. The distribution of these phases (Fig. 7) seems to represent a time-averaged diagenetic response to the position of oxic and anoxic pore waters within the reef. This implies that iron and manganese reduced in the anoxic zone are transported into the oxic zone to be re-precipitated as oxides. These observations appear to confirm that the reef interior is largely anoxic within one meter of the surface in the backreef, and below about two meters in the reef crest and forereef. The correlation between saturation states and oxidation-state zonation may allow us to infer the regions for likely cementation on the basis of the

distribution of oxide and sulfide coatings, by constraining cementation to the upper oxic zone.

CONCLUSIONS

We offer the following tentative conclusions on the interrelationships of hydrology and geochemical/petrologic responses of the Tague Reef system. Pore water circulation appears to be dominantly a vertically-oriented mixing process due to forcing by the oscillatory motion of wind waves and swell. The relatively moderate wave state develops only a shallow depth of mixing that is strongly controlled by reef zonation.

The effect of this on pore-water chemistry is to render the reef interior anoxic with low pH's due to continued microbial respiration within the reef. These conditions depress carbonate saturation states so that cement precipitation would be expected only in the very upper reef zone, even where sulfate reduction increases alkalinity within the reef.

Carbonate cements are commonly observed in reef sediments, dominantly as pore-filling, fine-grained peloidal cements, but also as thin circumgranular crusts and as coarse crystalline, void-filling cements. Cements are largely restricted to the reef crest and shallow forereef, where exchange with open sea water is maximal. The distribution of iron and manganese oxides and sulfides correlates with the time-averaged extent of oxic and anoxic pore water zones.

ACKNOWLEDGEMENTS
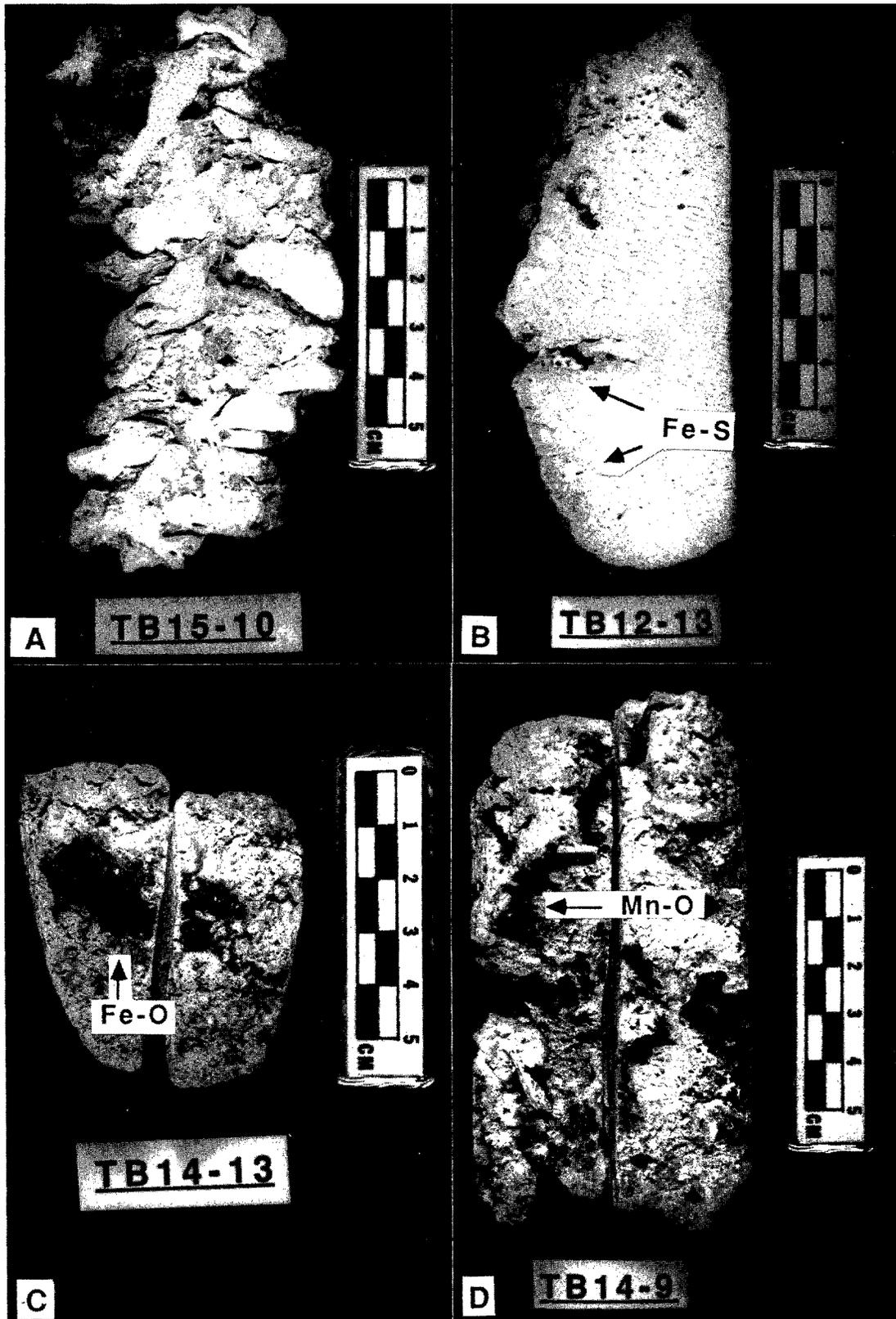
Figure 6. *Diagenetic phases within the reef. A. Cemented, very poorly-sorted reef sediments from the reef crest, B. Iron sulfides (Fe-S) disseminated in a coral fragment from the forereef, C. Iron oxides (Fe-O) coating the bottom of a coral fragment from the reef crest. D. Manganese oxides coating a conduit through a coral fragment from the reef crest, slightly shallower than (C).*
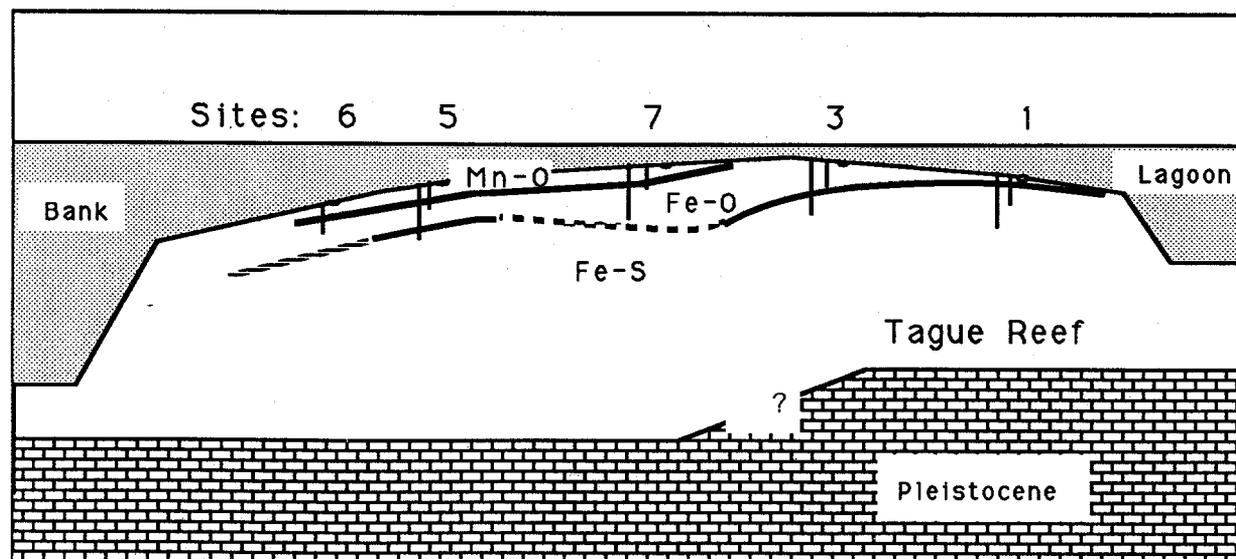
Figure 7. *Distribution of sulfide and oxide coatings on reef sediments*.

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