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Exceptional Preservation of Corals and Molluscs by Iron Oxide Replacement in Holocene Beach Rock, Pulau Sibu, Johore, Peninsula Malaysia

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Abstract: Large tracts of coral that have been preserved by pseudomorphic replacement with goethite were found on beaches around Pulau Sibu, an island consisting of calc-alkaline tuffs off the coast of Johore in Peninsula Malaysia. The iron is brought to the sites of replacement by joints and fractures in the volcanics, and whether replacement takes place at a given locality may be controlled by the local flow regime of percolating groundwater through the pile of chemically unstable tuff. The actual replacement may be related to an increase in iron activity due to surface evaporation, since the layers of replaced coral resemble hard iron oxide crusts found in soils..

INTRODUCTION

This discovery of exceptionally well preserved "fossil" corals and mollusks that have been replaced by iron oxide was made while conducting a University of Malaya student sedimentology field trip to Pulau Sibu in September 2005. The island is accessible by ferry from Tanjong Leman that can be reached by road from Mersing via Jemaluang (Figure 1).

GEOLOGICAL SETTING

Pulau Sibu is one of a chain of small islands, formed by Late Triassic to Early Jurassic calc-alkaline volcanism, located off the coast of Johore, Peninsular Malaysia. While the nearby Pulau Tinggi (9km to the northeast) hosts lava flows (dacitic to rhyolitic), Pulau Sibu, being further away from the eruption center, consists only of fine to medium grained ash-fall and lapilli tuffs containing varying amounts of quartz, feldspar and mica phenocrysts in a devitrified glass matrix, and 5-10 % opaque minerals. Silica contents are high (62-68%), while Na2O ranges between 18-20%, CaO is about 6% and FeO between 1.5 to 2.8% (Mohd Azman Sulaiman, 1989)

LOCALITIES OF REPLACED FOSSILS

There are two easily accessible coastal localities where such iron oxide replaced beach rock with fossils is found. The first (Locality 1, Figure 2) is located at Tanjung Buah Keras located 0.7 km km north of the jetty at Kg. Duku. The second locality (Locality 2, Figure 2) is about 0.25 km north of Tanjong Keramat in the southeastern part of the island.

FIELD OCCURRENCES

Locality 1 Tanjung Buah Keras (N 020° 12.713', E104° 04.457'): This is the bigger and more prominent of the two localities where the iron oxide replacement had been observed. It is located south of the Twin Beach Resort Jetty and occurs amidst mangrove patches that extend outwards from the beach line. The patch of iron-oxide beach rock covers an area of about 30 m^2 and is split in the middle by an ephemeral stream (Figure 3). The iron oxide replaced hardgrounds are of varying thicknesses. Those parts near the beach are flat and tabular and generally thickens and become more irregular with numerous pits and cavities when traced seawards ending rather abruptly with a steep edge that drops about 0.5 m to the muddy floor of the mixed flat (Figure 4). The iron

Figure 1: Map showing the location of Pulau Sibu, off the coast of Johore.

Figure 2: Map of Pulau Sibu, showing the sampling locations

oxide replacement has not only affected the dead corals (Figure 5) and molluscs (Figure 6) embedded in the beach rock but also replaced some of the roots of the mangroves (Figure 7) that had been growing there before the iron pan development. This is an indication of how recent the iron oxide replacement must have occurred as the mangroves are still growing right next to the iron pan and indeed within cavities in it. Other interesting observations were a flat piece of unreplaced coral (Figure 8) sitting in a cavity in the iron pan beach rock. Why was it not replaced? Could it be that it was not part of the original beach rock that was replaced but a later, post-iron pan deposit? This is a good indicator that connection with the underlying porous sediment was essential to the replacement to take place and it was stopped once permeability was cut off. The fact that the piece of coral lies in a depression may also indicate that a reversal of reactions might have occurred selectively dissolving the iron pan adjacent to the coral.

The stream that cuts through the middle of the patch of replaced beach rock has a sandy floor. The intermittent flushing by the moving waters of the stream probably inhibited the precipitation of iron oxide to form iron pan.

The resistant iron oxide duricrust enveloping the replaced beach rock is uneven in thickness and can be quite thin in places. The most spectacular iron oxide replacement was for the compound coral with long cylindrical coralites belonging to the genus *Oulastrea* (Figure 9) that appears not to have been transported over a great distance due to its massive size and fragile irregular form. While trying to excavate an iron oxide replaced *Fungia*, it was discovered that soft orangey red soil followed by leached white weathered rock material lies just below the less than 5 cm thick duricrust (Figure 10). Polychaete worms were dwelling in the soil horizon below the surface. This could be an indication that mobilized iron in solution has been drawn from the weathering rock at the base upwards to progressively concentrate near the surface that was exposed to the air and on drying forms the duricrust iron pan. This upward movement of iron rich solutions could have been facilitated by repeated wetting and drying of the porous beach rock deposited above the weathering volcanics when the tides changed daily or perhaps on a longer seasonal cycle with repeated drying during the dry season. Laterite and bauxite deposits have been developed over similar volcanics in southeastern Johore where the bauxite has been sufficiently abundant to be mined in the past. This bauxite deposit has been attributed to have been formed under a periodically wet and dry climatic regime over a stable area with low rates of denundation during the Neogene. (Stauffer,1973). He mentions that such favorable conditions suitable for bauxite formation serve to reemphasize that the southern tip of the peninsula has remained near sea level for a long time, whereas areas to the north have suffered uplift and erosion.

Locality 2 Coastal outcrop 0.25 km north of Tanjong Keramat in the southeastern part of Pulau Sibu (N 02° 11.961', E 104° 05.202'): This is a smaller locality but an important one because it clearly shows the preferential selective replacement of the corals and other debris is related to joints in the rock. The outcrop (Figure 11) consists of a joint-filled patch of brownish iron oxide that has replaced some corals (Figure 12) within it. The primary big joint that cuts across the bedding is oriented 0101/75 E and tapers from a narrow crack near its base to more than 20 cm at the opening. Iron oxide has also formed along the bedding plane joints that are oriented in a curved open plunging anticline that has limbs oriented 083/40S and 300/88N. The corals replaced here belong to the *Favia* genus.

PRESERVATION

The original aragonite of the corals have been pseudomorphically replaced by goethite (FeO(OH), confirmed through X-Ray Diffraction) with the fine structures in the coral skeletons (Figures 13) and mollusk shells preserved. As can be seen in the electron microprobe element maps (Figure 14), the aragonite has been replaced by goethite, while the internal, empty spaces have been filled with a as-yet unidentified material containing Ca, Al (not shown) and Si. No clay peaks were

Figure 3 (below): Stream bisecting patch of iron oxide replaced beach rock at Locality 1.

Figure 4 (above): Steep edge of iron oxide cemented beach rock at locality 1.

Figure 5 (below): Well preserved iron oxide replaced *Fungia* corals at locality 1.

Figure 6 (above): Large iron oxide replaced bivalve shell from locality 1.

Figure 7 (below): Iron oxide replaced roots of mangrove beneath coral in irregular iron oxide beach rock at locality 1.

Figure 8 (above): Flat piece of recent coral in depression in iron oxide beach rock at locality 1.

Figure 9 (left): Iron-oxide replaced cylindrical corallites in *Oulastrea* coral at locality 1.

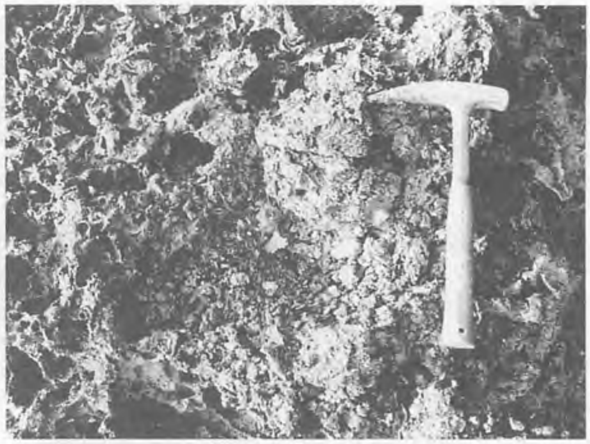

Figure 10: (right) Leached soil horizon beneath iron oxide replaced Fungia coral at locality 1.

Figure 11 (left): Joint and bedding planes partially filled with iron oxide at locality 2.

Figure 12 (right) Iron oxide replaced *Favia* coral in joint at locality 2.

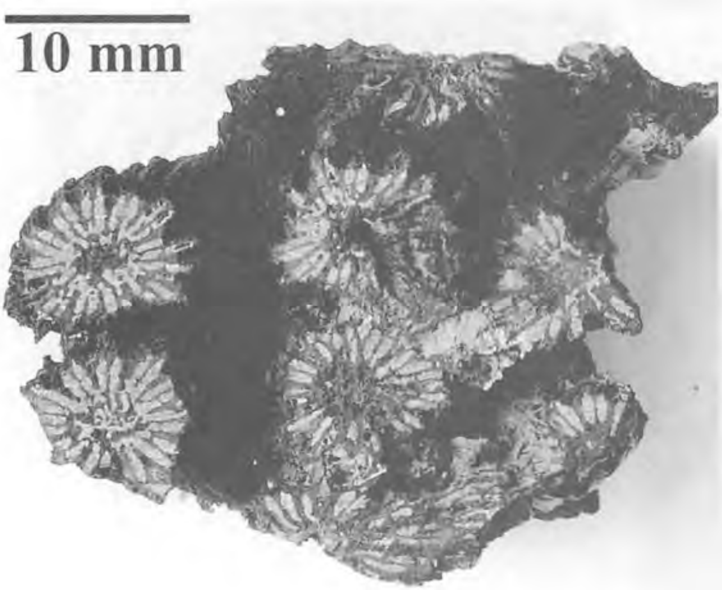

Figure 13: Close up of *Oulastrea* coral showing replacement of delicate septa by iron oxide.

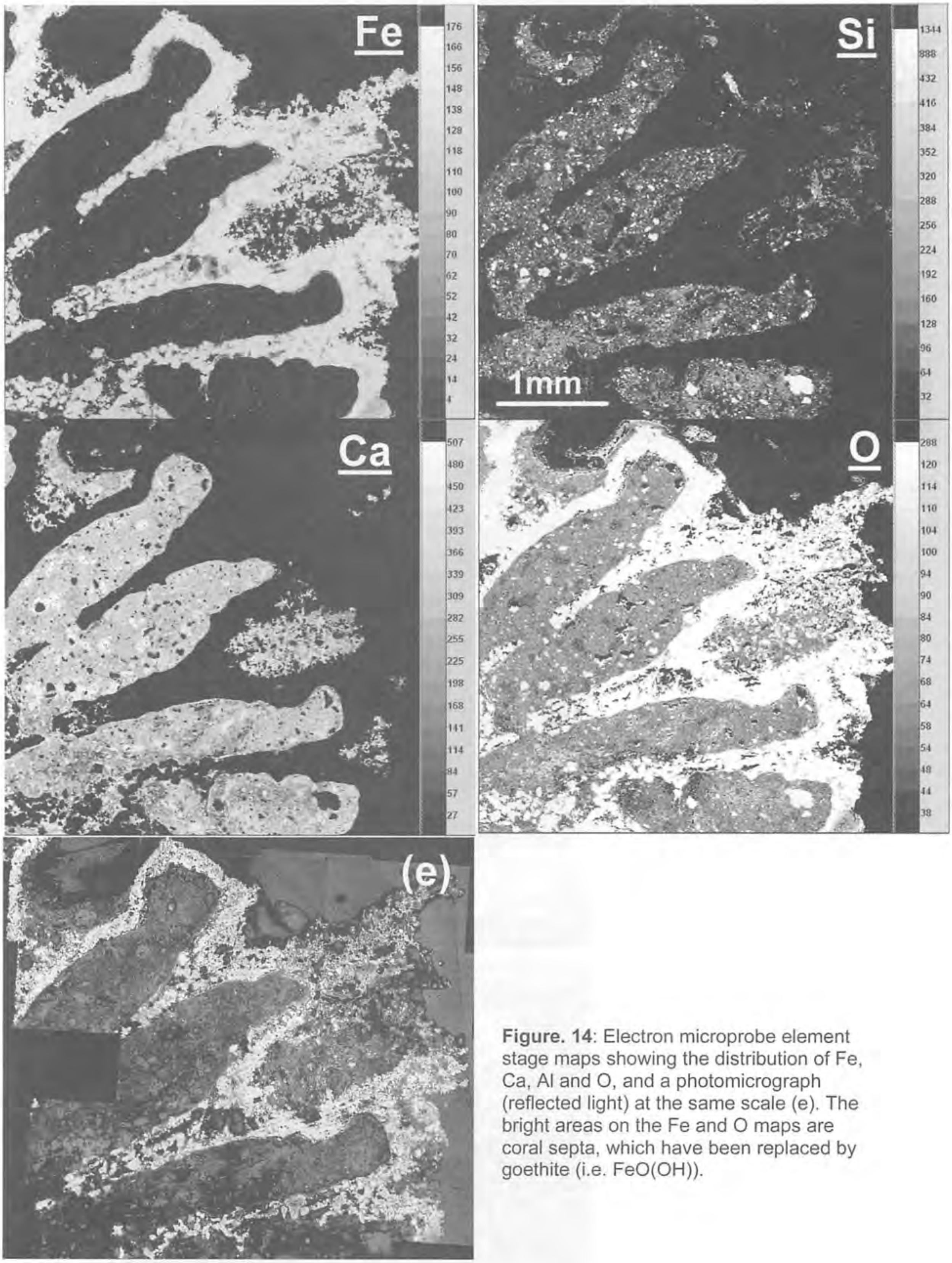

Figure. 14: Electron microprobe element stage maps showing the distribution of Fe, Ca, Al and O, and a photomicrograph (reflected light) at the same scale (e). The bright areas on the Fe and O maps are coral septa, which have been replaced by goethite (i.e. FeO(OH)).

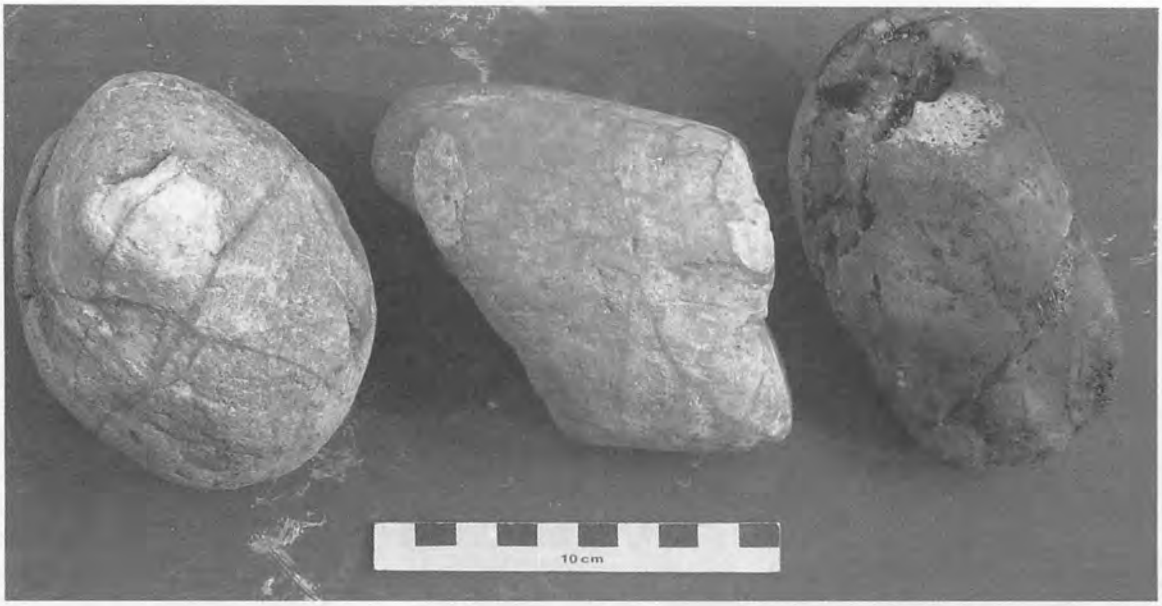

Figure 15 (above): Volcanic pebbles from Pulau Lima showing progressive weathering and outward growth of iron oxide from joints into fresh rock.

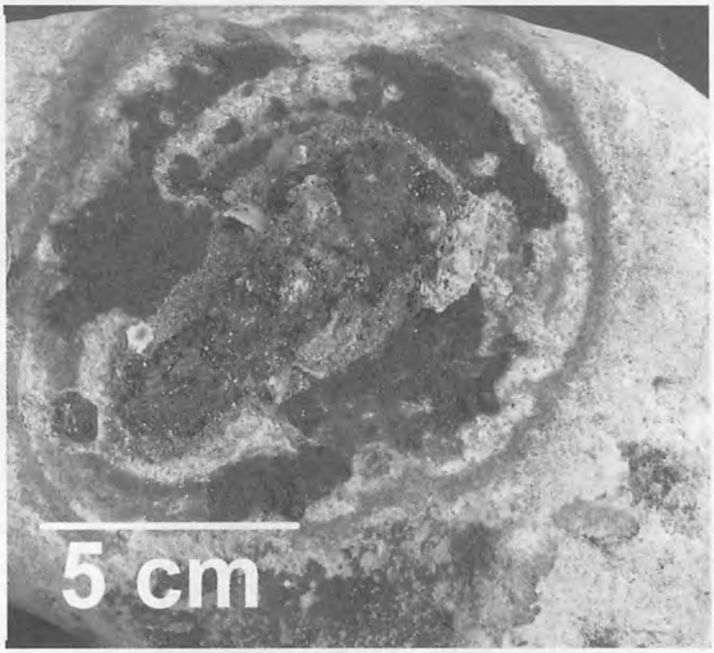

Figure 16: Rusted iron artifact strongly cemented to a volcanic cobble from a beach on Pulau Nanga Kechil (2.5 km south of Pulau Tinggi).

Figure 16: recent coral block from beach at Teluk Tagal, south Pulau Sibu.

observed on the XRD chart, so this material is probably not a clay. Some aragonite remains, as slow effervescence is observed when dilute acid is applied.

DISCUSSION

Replacement reactions require oversaturation of the mineral being deposited. In this case, the necessarily high activity of iron in the percolating groundwater is easy to explain. Volcanic tuffs contain a large quantity of glass, which contain iron, and is very unstable, leading to rapid alteration and dissolution. The devitrification process releases iron, as would the weathering of magnetite and iron-bearing micas in the rock. Thus, one would expect high iron (and silica) activities in groundwater to be high in volcanic terranes.

Evidence that groundwater percolating through the volcanic pile brings the iron for replacement reactions can readily be found. Large bands of iron replacement can be seen, centered around cracks and joints, in the volcanic rocks at sea level, particularly on wave-cut platforms on headlands on the east side of the island (e.g. Tanjung Pasir Belakang). The replacement in these cracks is gradational - there is a progression from unreplaced volcanic rock, to partially replaced material with slight iron staining, to complete replacement, as seen in pebbles (Figures 15) collected from the beach at the northern part of Pulau Lima, a small island of similar volcanics located about 8 km east of Pulau Sibu.

The chemistry of pseudomorphic replacement has been described in Merino and Dewers (1998), and in Fletcher and Merino (2001). Preservation of textures can only take place if the growing material precipitates immediately upon the dissolution of the material being replaced. The growing material exerts pressure on the material being replaced, otherwise there would be no room to grow. This stress induces the dissolution of the replaced material. The amount of stress self-adjusts so that the rates of growth and dissolution become equal. The reaction must, of course, be driven forward by the chemical affinity for the growth of the replacement material being greater than that for the growth of the material being replaced. Reactions must be written based on the preservation of volumes, and therefore balanced according to molar volumes.

The process can be very rapid, as seen in Figure 16. Here, a piece of iron is embedded by cementation into a volcanic cobble. This must have happened in a matter of days to weeks or months, rather than years. The process must be quick in the case of corals exposed to wave action, if *in-situ* preservation is to take place. Otherwise, the corals would be destroyed by wave erosion. In fact, not all corals exposed on the beach on Pulau Sibu have been altered and preserved – large fragments of unreplaced heads of coral were observed at Teluk Tagal on the southern part of Pulau Sibu (Figure 17). The preservation of corals, or the lack thereof, may be related to the local groundwater flow regime, which might be influenced by nearby topography, or by the porosity and permeability of nearby volcanics. That the replacement (of both coral and volcanic rock) takes place mainly at sea level might indicate that the groundwater bearing iron exits the rock there, since this represents the hydrologic base level. The resemblance of the replacement to iron crusts found in soils suggests that evaporation may play a role in further increasing saturation.

Given that coral on volcanic islands with a tropical/equatorial climate is not uncommon; such iron replacement of corals should be widespread. It would be very surprising indeed if the iron replacement seen in Pulau Sibu corals turned out to be a rare phenomenon. Yet, a search of the literature bears no results.

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