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Front Cover: *Porites* colony encrusted by red algae in waters of San Salvador, Bahamas; see paper by Fowler and Griffing., p. 41. Photograph by Pascal Kindler, 2011.

Back Cover:. Dr. Jörn Geister, Naturhistorisches Museum Bern, Keynote Speaker for the 15th Symposium and author of "Keynote Address – Time-Traveling in a Caribbean Coral Reef (San Andres Island, Western Caribbean, Colombia)", this volume , p. vii. Photograph by Joan Mylroie.

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INTERGLACIAL LIMESTONE AND ITS GEOMORPHIC FEATURES ON GUAM: IMPLICATIONS FOR RELATIVE SEA-LEVEL CHANGE AND FLANK-MARGIN CAVE FORMATION

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ABSTRACT

Guam is the southernmost island in the Mariana Archipelago. Northern Guam is almost entirely covered by limestone, with the Plio-Pleistocene Mariana Limestone being the most widespread. The Upper Pleistocene Tarague Limestone deposits found on the northern coast of Guam were studied, where they typically form a terrace up to 20 m in elevation along the coast. Coral reef facies, and to a lesser amount, detrital facies, dominate the outcrops, though pockets of *Halimeda* facies are not uncommon. Petrologic analysis shows that the limestone, particularly the aragonitic fossil biota, has been diagenetically altered in the meteoric realm. Previous researchers have dated 99% aragonitic corals from this unit as ~130 ka (U/Th age), which correlates with the last interglacial period (Marine Isotope Stage 5e). Seaward of the Tarague Limestone terrace, the reefal Merizo Limestone (dated by ^{14}C) formed during the Mid-Holocene highstand (4.75-2.75 ka BP), ~2 m above present sea level, as small patches on the coast all around the island. These have been tectonically uplifted to ~4 m elevation today.

In the study area, the Tarague Limestone contains caves and coastal notches. The caves are dissolutional in origin and exhibit the attributes of flank-margin caves, while the notches appear to be primarily wave-cut and bioeroded. The notches and a single cave in the Tarague Limestone are found ~4 m above present sea level, matching the elevation of the Merizo Limestone surface in this area. Both the single Tarague Limestone cave and the notches are sea-level still-stand indicators, with restricted possible times of origin. They could have formed during the Pacific Mid-Holocene sea-level highstand, and then undergone some subsequent tectonic uplift. Other Tarague Limestone caves, however, show higher elevations at 7 m. A U/Th age of 36 ka for speleothems from one of these 7 m-high caves suggests the caves formed during an earlier and lower sea-level still-stand and were subsequently uplifted to their present elevation. The interstadials MIS 5a (~85 ka) and MIS 5c (~100 ka) are the most likely sea-level events to have formed these caves.

INTRODUCTION

Guam is the southernmost island of the Mariana Archipelago, located at the eastern boundary of the Philippine Sea Plate, under which the Pacific Plate is subducting. Due to its tectonic setting, the island has been uplifting at estimated long-term average rates ranging from 0.1 mm/yr (Randall and Siegrist, 1996) to as high as 1.5

mm/yr (Bureau and Hengesh, 1994). The core of the island is composed of volcanic and volcaniclastic rocks (Tracey et al. 1964). The northern part of the island, separated from the south by a normal fault, is almost entirely capped with limestone (Figure 1). The Miocene-to-Pliocene foraminiferal Barrigada Limestone grades upward and outward into the Pliocene-to-Pleistocene reefal Mariana Limestone, which occupies most of the surface and the coasts (Tracey et al., 1964; Siegrist and Reagan, 2008).

Fossil coral reefs are very good sea-level indicators. Reef flats reflect the lower low-tide level (Dickinson, 2001) while algal ridges can grow up to 1 m above the mean lower low tide, as observed on modern reefs on Guam (Randall and Siegrist, 1996). Between glacial and interglacial stages, sea-level has fluctuated from as much as 120 m below the modern sea level to ~6 m higher (Figure 2). During the last interglacial stage (Marine Isotope Stage 5e, or MIS 5e), between 128 ka to 116 ka before present, sea level in the Pacific was ~6 m higher than the modern one (Muhs, 2002). A remnant of the MIS 5e reef deposited on northern Guam was discovered in the Tarague embayment by Randall and Siegrist (1996), and mapped as the Tarague Limestone by Siegrist and Reagan (2008). The interglacial age of the outcrop was confirmed by U/Th dating of two aragonitic corals that yielded an age of ~130 ka (Randall and Siegrist, 1996).

Subsequent to the MIS 5e interglacial, sea level in the Pacific has risen above the present datum only during the Pacific Mid-Holocene highstand (e.g. Mitrovica and Peltier, 1991; Nunn, 1998; Zong, 2007). In the Mariana Islands, the Mid-Holocene highstand spanned the ~2,500 year interval between 4.75 and 2.25 ka BP, with the peak ~2 m higher than modern sea level (Bell and Siegrist, 1991; Kayanne et al., 1993; Dickinson, 2000). A Holocene coral reef was deposited, and subsequently exposed and eroded as sea level dropped to modern datum. The remnants of this fossil reef, first noted by Tayama (1952), and mapped as the Merizo Limestone by Tracey et al. (1964), is found in small patches all along the perimeter of the island. Its age was confirmed at several locations by ^{14}C dating (Tracey et al.,

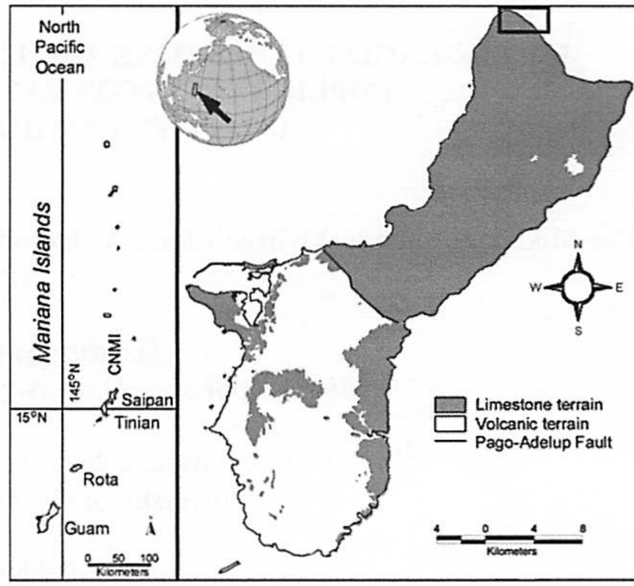

Figure 1. Location of Guam, limestone terrain and the studied area in the black square. Map by Taboroši et al. (2005), with permission.

1964; Easton et al., 1978; Randall and Siegrist, 1996). The current position of the Merizo Limestone at ~4 m elevation reflects ~2 m of tectonic uplift since deposition during the Mid-Holocene. This position yields a mean uplift rate of 1 mm/yr, which falls within the uplift range of 0.1 mm/yr from Randall and Siegrist (1996) and 1.5 mm/yr from Bureau and Hengesh (1994).

The sea-level indicators studied for this project are the coastal notches and flank-margin caves found in the Tarague Limestone. Notches are mainly a consequence of bioerosion (Emery, 1952; Pirazzoli, 1986; Spencer, 1988; Pirazzoli,

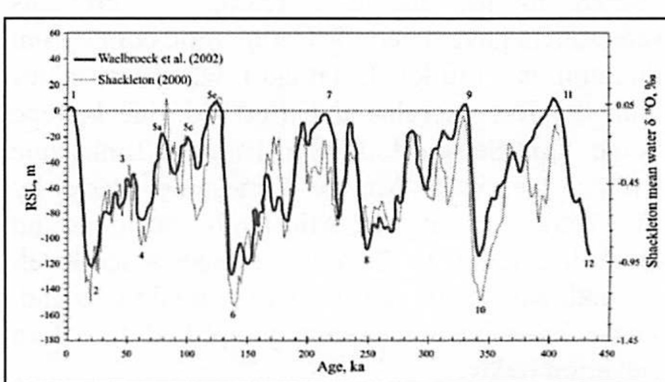

Figure 2. Sea-level curve for the Middle-Late Pleistocene. From Lascu (2005), with permission.

2007). Flank-margin caves, on the other hand, form in the mixing zone between the fresh water from the fresh-water lens and the sea water at the lens margin on the flank of the enclosing landmass (Mylroie and Mylroie, 2007). The vertex of sea-level notches usually reflects mean tide level, though it is argued that it can represent the mean neap tide (Pirazzoli, 2007) or the high-water level, as was also reported for the Guam region (Dickinson, 2000). Similarly, the ceiling of the flank-margin caves reflects the mean high-tide level (Mylroie and Carew, 1990).

Since the MIS 5e highstand, there were many other sea-level stillstands besides the Mid-Holocene highstand, all of which at levels lower than modern sea level (Figure 2), although a Mediterranean example suggests MIS 5a could have reached +1 m (Dorale et al., 2010). They should have all lasted long enough to leave geomorphic signatures (i.e., notches and/or caves, as described above). Subsequent uplift of the island could have been high enough to bring these caves and notches above modern sea level. In this study, we closely examined the Tarague Limestone including the sea-level notches and flank-margin caves within it, and tried to discern their relationships to known sea-level stands. This study provides insights into the rate of formation of flank-margin caves as well as uplift magnitudes and rates in the study area.

METHODS

A field survey was done in the area southeast of Ritidian Point, the northernmost part of the island (Figure 1). In order to discriminate between the different limestone units, thin sections of the bedrock were prepared and studied. The Feigl test (Ayan, 1965) was used to differentiate aragonite from calcite. Sea-level notches and caves in the Tarague Limestone were located and mapped. Notch and cave elevations, as well as the elevation of remnants of the Mid-Holocene reef, were measured by differential leveling. As a reference point, a USGS survey benchmark with mean sea level as a datum was used. Its precision in elevation is ±10 cm. A more general elevation analysis was done by GIS Digital Elevation Model (DEM) analysis (Figure 3); the details of the DEM construction are available in Miklavič (2011). The same method was used to confirm the elevation of the survey points that could be identified on the DEM. Planiform locations of caves and sea-level notches were recorded with a GPS unit. The GPS points were imported to a GIS and overlain onto a LiDAR-derived hillshade of the area (Figure 3). U/Th dating (Edwards et al., 1987) was used to date speleothems by TIMS at the University of Texas-Austin.

RESULTS AND DISCUSSION

Southeast of Ritidian Point, the limestone adjacent to the sea was identified by facies comparison as the Mid-Holocene Merizo Limestone, which forms low terraces locally extending into the sea as headlands between beach deposits. Most of the upper part of the Merizo Limestone is a fossil algal ridge veneering a coral-algal reef. Thin-section analysis, together with Feigl tests, showed that the original aragonitic skeletons in the reef have not undergone significant recrystallization, which is consistent with reports by previous investigators (Tracey et al., 1964; Bell and Siegrist, 1991; Siegrist and Randall, 1992).

Immediately behind the beaches and adjacent Merizo Limestone terraces, which are often covered with storm deposits, one finds a continuous platform of a different limestone unit forming a gently seaward-sloping terrace, which sometimes gradually tapers down to the Merizo Limestone, and sometimes ends abruptly as a 1-to-3 m-high scarp or very steep slope. Coral reef facies predominate, though extensive detrital facies can be found in some places, and pockets of *Halimeda* facies are not uncommon. The lavish diversity of coral communities in this limestone unit, best seen at the seaward edge of the terrace, suggests that it was deposited in shallow water of no more than 20 m depth (Wells, 1967; Cabioch et al., 1999). Macroscopic observations, as well as thin-section analyses, show that this rock is undergoing early meteoric diagenesis, in which the aragonite is inverting to calcite. The mixed mineral composition observed in fossil organisms known to originally have had aragonitic skeletons was confirmed with the Feigl test. Such rock facies are observed upslope in the gently seaward-sloping terrace, which rises to an elevation of ~20 m, as shown on the DEM model (Figure 3). Inland, it ends abruptly in a high cliff or the associated talus of the Mariana Limestone. Given its early diagenetic grade, setting, and visual similarity to the dated deposit in the Tarague embayment, it is therefore reasonable to infer that the entire terrace is part of the same geologic unit, i.e., the MIS 5e Tarague Limestone. Its thickness and the nature of its base have not been examined, but it is assumed that it lies disconformably on the eroded surface of the older Mariana Limestone.

Within this same locale, we observed and mapped several sea-level notches and caves. In particular, sea-level notches are found where the Tarague Limestone terrace ends at a scarp within ~50 m of the shoreline. Three such sites were identified, in which remnant sea-level notches extend laterally from a few meters to up to 25 m. In a few of the scarps, we found no notch. The absence of a notch in these locations is most probably due to removal by subaerial erosion. Also in this area, we found 6 small caves, up to 5 m in diameter. All the caves are dissolutional in origin and exhibit diagnostic attributes of flank-margin caves (Mylroie and Mylroie, 2007): phreatic dissolutional surfaces; low, wide chambers; and a circular to oval plan.

The elevations of the four highest remnants of Merizo Limestone—all algal ridge facies—were measured at ~4 m (Figures 3 and 4). Given that the algal ridge elevation indicates high-water level rather than mean sea level, the Mid-Holocene sea-level would have been somewhat lower than the 4-meter mark. Since the Mid-Holocene sea-level highstand was only ~2 m higher than the present datum, the difference in elevation, somewhat less than 2 m, can thus be attributed to net tectonic uplift since Merizo Limestone deposition. The elevations of the vertexes of the measured notches in the Tarague terrace match the elevation of the tops of the Merizo Limestone remnants, and are similarly uniform in elevation. All are ~4 m above sea level, it is therefore reasonable to infer that the carving of these Tarague Limestone notches was concurrent with the deposition of the Merizo Limestone.

The elevations of the highest parts of the ceilings of the caves, on the other hand, show more variability. One cave has the same elevation as the terrace notches and the Merizo Limestone tops, and could have therefore formed during the Mid-Holocene highstand. The other measured caves, however, have ceilings considerably higher, at the elevation of ~7 m above the modern mean sea level, likely corresponding to an additional cave forming event. Two dated speleothems from one of these higher caves, Tokcha Cave, (Figure 3) yielded ages of ~36 ka (Miklavič, 2011). Given that it contains Pleistocene speleothems, this cave obviously could not have formed during the Mid-Holocene sea-level highstand between 4.75 and 2.25 ka BP. The speleothem ages of 36 ka provide only a minimum age for the cave; there is no reason to assume that the cave was formed just before the

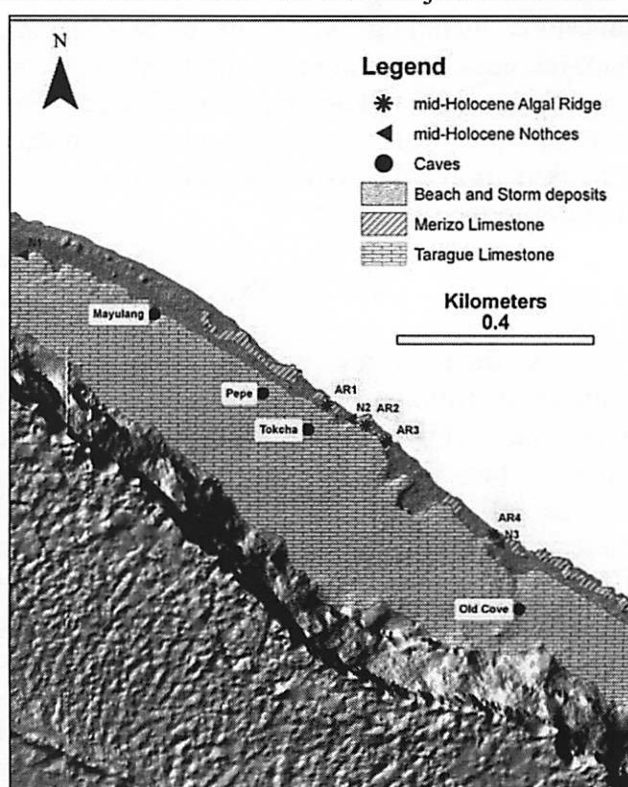

Figure 3. DEM of the research area with locations of the measured notches and caves.

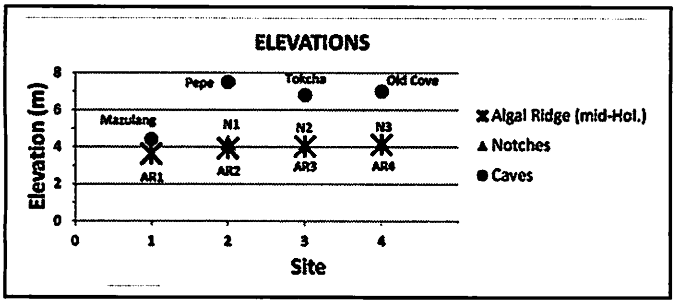

Figure 4. Plotted elevations of the studied caves, sea-level notches and Mid-Holocene algal ridges.

speleothems were deposited.

If we compare these field relationships and ages with the sea-level curves of Waelbroeck et al. (2002) and Shackleton (2000) (Figure 2), the 36 ka age of the speleothems inside the cave indicates that during MIS 3, when sea level was ~50 m below present, the cave was in a vadose setting, which brings up the question of the age of the cave itself. If the cave itself had formed during MIS 3, shortly before the speleothems were deposited, there would have been ~50 to 60 m of uplift in the past 50,000 years to bring the cave to its present elevation of ~7 m. This change seems unlikely, given the known uplift rates. Based on the preceding evidence, we infer that the caves now at +7 m elevation in the MIS 5e Tarague terrace were most likely formed during MIS 5c and/or MIS 5a.

Field observations indicate the Tarague Limestone outcrop spans a variety of elevations, from near modern sea level to elevations of 20 m (Miklavič, 2011). While the upper reaches of the Tarague Limestone could have been deposited near wave base, the entire unit could not have been; deposition was distributed over a submarine relief of at least 20 m. Some uplift of the Tarague reef likely occurred during its deposition, such that higher portions became subaerially exposed while deposition continued in the lower portions during MIS 5e.

The Tarague Limestone has now undergone subaerial denudation for 120 ka, so the original depositional elevation must have been several meters higher, including the portions now at 20 m elevation. Ignoring denudation for the moment, if the very top of the Tarague terrace was deposited at wave base during the MIS 5e highstand of +6 m, there has been a minimum of 14 m of tectonic uplift since MIS 5e, in order to raise the surface to the current elevation of 20 m. Assuming 2 m of denudation in the past 120 ka (Miklavič, 2011), the post-Tarague uplift would have to be 16 m. If denudation was more than 2 m, or if the reef crest was built below wave base, then the uplift would have to exceed 16 m accordingly. Using the inferred 16 m tectonic uplift value (with the implicit assumption of 2 m denudation) as a minimum over the 120 ka since MIS 5e, the mean uplift rate is 0.13 mm/yr, which falls near the low end of the uplift range of 0.1 mm/yr from Randall and Siegrist (1996) and 1.5 mm/yr from Bureau and Hengesh (1994).

The observed cave horizons within the Tarague Limestone are restricted to a narrow band of 4 to 7 m elevation. Mylroie and Mylroie (2007) have demonstrated that during glacioeustatic cycles, highstands and lowstands are the only sea-level positions stable long enough to allow a fresh-water lens to create flank-margin caves. In other words, during the relatively rapid movement of sea level between highstand and lowstand positions, the fresh-water lens (which follows sea-level position) is not at a given position long enough to produce macroscopic dissolutional voids, i.e., caves. Flank-margin caves can form very fast, in just a few thousand years (Mylroie and Mylroie, 2009), but their formation is not instantaneous, so a rapidly moving sea level does not leave a cave record.

The caves seen today at 7 m elevation in the lower portions of the Tarague Limestone would have to have formed during one or more sea-level stillstands *lower than the MIS 5e elevation*, but still high enough to intersect the Tarague Limestone. Moreover, *the caves must have been formed prior to MIS 3*, by which time the 36 ka speleothems were growing in them. Assuming the minimum uplift rate calculated above (0.13 mm/yr), caves formed during MIS 5c, which occurred at ~100 ka (Figure 2), would have formed after only ~2.5 m of post-5e uplift, which by itself would not have taken the base of the Tarague reef above the MIS 5c sea level. MIS 5c sea level stood at about -20 m relative to modern sea level (Figure 2). For sea level to have been at 20 m below modern sea level at 100 ka and produce caves in the Tarague Limestone that are now at 7 m above modern sea level, requires a minimum of 27 m of uplift in 100 ka. These values indicate an uplift rate of 0.27 mm/yr, corresponding to twice the aforementioned minimal value, but still within the range of the Randall and Siegrist (1996) and Bureau and Hengesh (1994) studies.

MIS 5a occurred at ~85 ka (Figure 2). Waaelbrock et al. (2002) place it at about minus 18 m elevation; Shackleton (2000) has it exceeding modern elevation by a few meters. Dorale et al. (2010) provides evidence for a MIS 5a highstand of +1m, but that is for the restricted Mediterranean basin in a tectonically-active setting, and is not directly comparable to the western Pacific. Splitting the difference between the low and high interpretations, for argument's sake, we assume a MIS 5a sea level of -8 m relative to modern sea level. To place the fresh-water lens in the Tarague Limestone such that the caves are at 7 m today requires 15 m of uplift. Taken over 85,000 years, this is an uplift rate of just less than 0.1 mm yr, at the low end of the range between the Randall and Siegrist (1996) and Bureau and Hengesh (1994) estimates.

MIS 3 was an unstable interstadial, with highstand peaks ranging in elevation from -60 to -45 m relative to modern sea level (Figure 2) over the time span from 35 to 55 ka. The highest sea level of this interstadial, at -45 m, occurred ~55 ka. It is difficult to imagine how the Tarague Limestone could have been at such a low elevation (-45 m) at that time (which would have been required in order to put the fresh-water lens in position to form the caves). Given that the Tarague Limestone was deposited in shallow-water conditions during the MIS 5e highstand of +6 m (confirmed by the U/Th dating of Randall and Siegrist, 1996), the island would have had to have *subsided* by 50 m or more between MIS 5e and MIS 3 time in order to bring the 20-m thick Tarague platform down to the MIS 3 sea-level, where the freshwater lens would have been. Moreover, it would have to have subsequently been uplifted by about the same amount to bring the Tarague platform to its current elevation. This scenario would require a radical revision of our current model of Mariana tectonic history; thus MIS 3 can be reasonably excluded as a cave-generating episode for the observed Tarague Limestone caves.

The one Tarague Limestone cave at 4 m could have been formed during the Mid-Holocene sea-level highstand that also formed the notches found at 4 m. The 3-m difference in elevation from the others, however, does not necessarily put it outside of the horizon in which the processes that formed the others might have operated. There are no speleothem data to constrain this 4-m elevation cave, so the question remains open.

The Late Quaternary sea-level curve, coupled with the observations that the Tarague Limestone is a slightly denuded and uplifted shallow-water limestone from MIS 5e, indicate that some post-MIS 5e sea-level highstand generated the flank-margin caves found at 4 to 7 m elevation today. While the 4-m elevation cave could have formed during the Mid-Holocene highstand, the higher caves at 7 m elevation must have formed during other sea-level highstands. MIS 5a (85 ka) and/or MIS 5c (100 ka) are the most reasonable candidates.

CONCLUSIONS

During the last interglacial (MIS 5e) the Tarague Limestone was deposited at an elevation range of potentially +6 to -20 m relative to modern sea level. During the Pacific Mid-Holocene sea-level highstand, the Merizo Limestone was deposited at ~2 m above modern sea level and later elevated to ~4 m by tectonic uplift. The Tarague Limestone contains wave-cut and bioerosion notches associated with the Mid-Holocene sea-level highstand. It also contains flank-margin caves at elevations of 4 and 7 m. These caves formed during post-MIS 5e sea-level highstands, most likely either MIS 5c or MIS 5a, or both, and were subsequently tectonically uplifted to their current position. The one cave found at 4 m could have formed during the Mid-Holocene sea-level highstand. The present-day elevations of these sea-level indicators point to a ~1.8 m uplift since Mid-Holocene and a long term average uplift rate of ~0.2 mm/yr over the past 120 ka.

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