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KARST FEATURES OF GUAM IN TERMS OF A GENERAL MODEL OF CARBONATE ISLAND KARST

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This paper describes the karst of Guam in terms of the Carbonate Island Karst Model (CIKM), a general model for the unique karst carbonate islands. The CIKM recognizes several processes and conditions unique to carbonate islands: 1) enhanced dissolution at the surface, base, and margin of the fresh-water lens; 2) the history of both vertical migration and stable positioning of these zones according to glacioeustatic and tectonic changes in relative sea level; 3) the size of the island's catchment area relative to its perimeter, which can vary with sea level change; 4) the hydrologic implications of the unique eogenetic environment of their young limestones; and 5) the position of the island's carbonate-basement contact relative to sea level and the island surface over time.

Guam's complex depositional and tectonic histories have endowed it with a unique legacy of karst features. The northern half is a Pleistocene karst plateau in Plio-Pleistocene limestone units that exhibit all the characteristic karst features of carbonate islands, from the simplest to the most complex. The epikarst is similar to that on other carbonate islands. Most closed depressions are broad and shallow, probably reflecting original depositional morphology, although vertical-walled collapse and banana-hole type features are also present. Caves include a few pit caves, some of which are very deep. Traversable stream caves occur where the limestone-basement contact is exposed on the flanks of volcanic outcrops. The most abundant caves are flank margin caves, which can be found all along the modern coast, and which occupy distinct horizons in the faces of the cliff line surrounding the plateau. Discharge features have been documented for three types of coastline around the northern plateau: (1) deeply scalloped embayments with broad beaches; (2) linear beaches fronted by fringing reefs; and (3) sheer cliffs with narrow or no benches, and only occasional small reefs. In the embayments, karst groundwater discharges by diffuse flow from numerous seep fields and as concentrated flow from springs along the beach. Seeps are found along the linear beaches, but we have not noted significant flow from springs or coastal caves. Along the cliff-dominated coast, karst groundwaters discharge in spectacular flows from dissolution-widened fractures, coastal caves, and submarine vents, most notably along the northwest coast.

The southern half of Guam is an uplifted volcanic highland containing a karst terrain on Mio-Pliocene limestone remnants in the interior. Because these units lie above the influence of the fresh water lens, sea water mixing, and sea level change, the karst is a classic tropical continental karst, with features that include contact springs issuing from well-developed caves, sinking streams with resurgences, and conical cockpit karst. Along the southeast coast, which is flanked by a continuous uplifted Pleistocene limestone unit, antecedent streams draining the interior have incised deep canyons. Dry valleys and large closed depressions in this unit appear to be associated with allogenic waters originating in the interior.

Guam is the largest and southernmost of the Mariana Islands (Fig. 1). It is 550 km^2 in area, 48 km long, and varies in width from 6-19 km (Fig. 2). The Mariana Islands are thought to have been first inhabited between 3000 and 2000 B.C. Spain colonized them subsequent to Magellan's landing in 1521 on either Guam or one of the islands to the north, his first landfall after crossing the Pacific Ocean. Spanish rule ended when the United States took possession during the Spanish-American War in 1898. The U.S. Navy administered the island until Japan captured it in 1941. Following liberation by U.S. forces in 1944, administration eventually shifted to the Department of Interior, but access was restricted for military security until 1962 (Rogers 1996). After the island was opened to commerce, the economy grew slowly but steadily until the Asian expansion of the 1980s brought an avalanche of capital investment and an economic boom. Guam's tourism-driven economy now supports 150,000 permanent residents plus over a million visitors a year.

Eighty percent of the island's drinking water is drawn from the karst aquifer in the limestone plateau of the northern half of the island (Jocson *et al*. 1999; Contractor & Jenson 2000). Mink & Vacher (1997) have summarized the results of previous hydrogeological studies of the northern aquifer. Such studies have been oriented, however, toward determining engineering parameters to support development rather than to gain more fundamental understanding of the karst geology. This paper is the first report from a two-year study aimed at inventorying and describing the karst on Guam in terms of a gener-

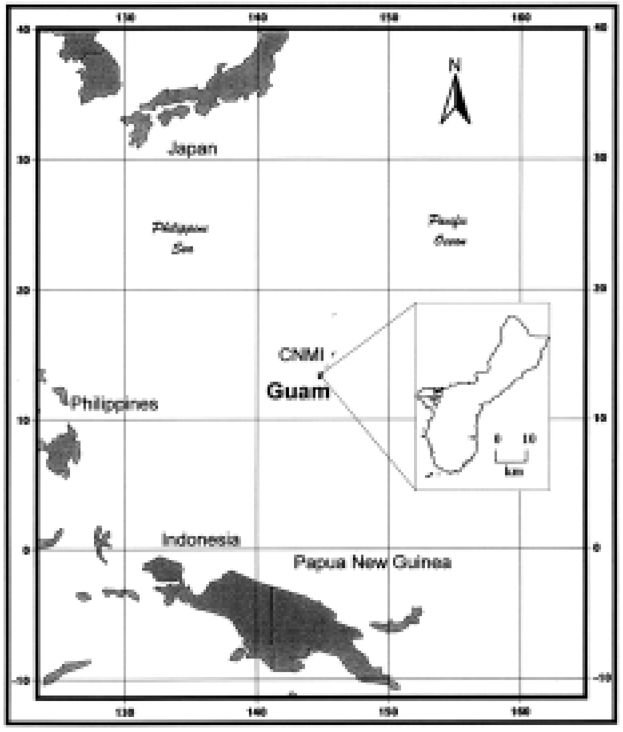

Figure 1. Location of Guam, Mariana Islands, in the western Pacific Ocean. CNMI stands for "Commonwealth of the Northern Mariana Islands" and includes the islands of Rota, Tinian, and Saipan (after Tracey *et al.* 1964).

al model of carbonate island karst (Mylroie *et al.* 1999; Mylroie & Jenson 2000).

THE CARBONATE ISLAND KARST MODEL

Small carbonate islands are a unique genetic environment, which produce a distinct karst (Mylroie & Vacher 1999). First, the carbonate units on islands have all spent some time in the island's fresh-water lens, where they have been exposed to the vadose-to-phreatic groundwater transition zone at the top of the lens (as in karst in general), and to the brackish transition zone between the fresh-water lens and the underlying marine groundwater (which is peculiar to coastal/island karst aquifers). Each is an especially aggressive dissolutional environment (Mylroie & Carew 1995). Second, carbonate islands worldwide have experienced Quaternary glacioeustatic sea-level changes. The fresh water lens, along with its upper and lower zones of aggressive dissolution, has similarly migrated, with the longest exposure durations associated with stratigraphic levels coinciding with eustatic sea-level maxima, minima, and stadial intervals. On tectonically active islands such as Guam, episodes of uplift and subsidence overprint glacioeustatic sea level migration, introducing further complexity. Third, the small catchment-to-perimeter ratio (for which catchment area is proportional to the square of the island radius, while the perimeter is only directly proportional)

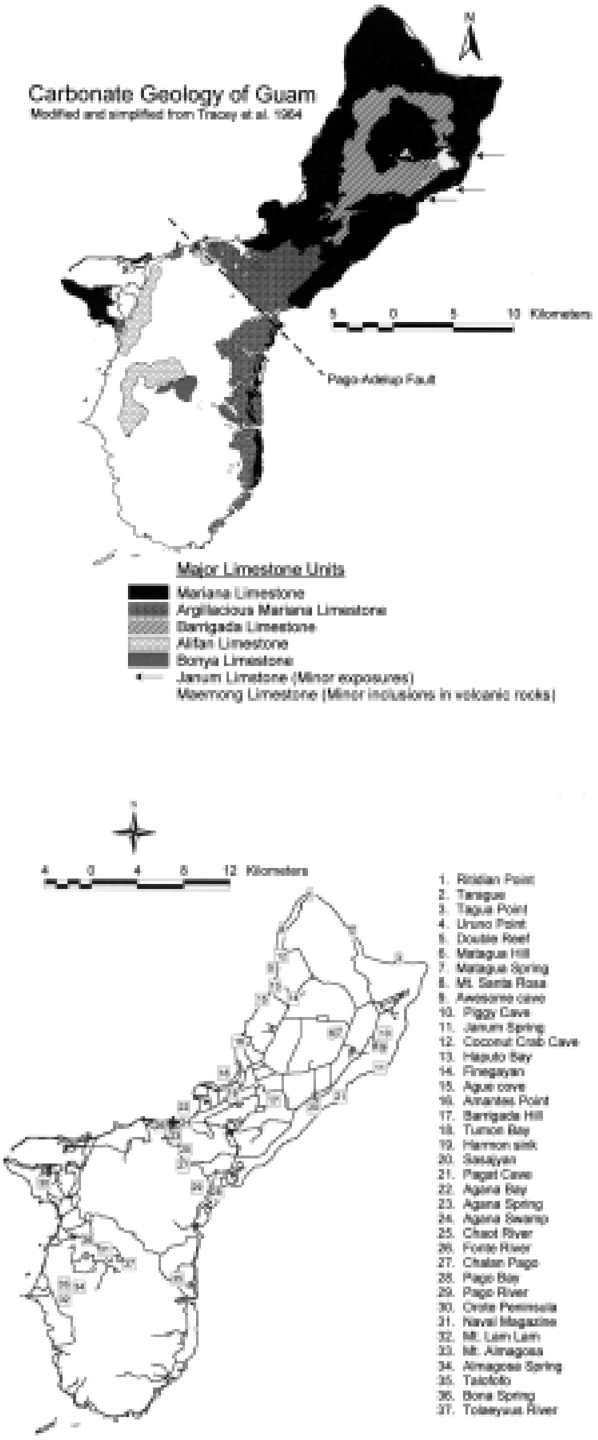

Figure 2. (a-top) Simplified geologic map of Guam (volcanic rocks in white). The Marianas units are Plio-Pleistocene; the Alifan, Bonya, Janum, and Maemong limestones are Miocene. The Holocene Merizo Limestone occurs as small, isolated patches primarily along the southeast coast. (b-bottom) Locations of features described in the text and figures. Major roads are shown for reference.

on small islands is hypothesized to facilitate diffuse discharge at any given rate of recharge, obviating—but not necessarily eliminating—the development of conduits to promote more efficient discharge (Mylroie & Vacher 1999). On large islands, on the other hand, the larger catchment-to-perimeter ratio favors the development of conduits. Moreover, the karst in the interior of islands such as Jamaica or Puerto Rico is likely to have been out of the influence of fresh/salt water mixing and glacio-eustasy for much of its history. Islands with interior carbonates thus exhibit forms similar to continental karst. Finally, the karst in most island environments, whether large or small, is *eogenetic, i.e.*, it has developed in young carbonate rocks that have never undergone deep burial, and thus have never been out of the reach of meteoric diagenesis (Mylroie & Vacher 1999). This situation implies that the rock began with and can retain high porosity, and that development of secondary porosity takes place concurrently with the ongoing occlusion of primary porosity. This has important implications for interception, storage, and transmission of groundwater, and the consequent evolution of karst landforms and aquifer properties.

Mylroie & Jenson (2000, in press) have integrated these observations with Mylroie & Carew's (1995, 1997) systematic geomorphic description of small carbonate islands studied in the Atlantic-Caribbean to propose the Carbonate Island Karst Model (CIKM) as a descriptive model for the unique karst of small carbonate islands. Initial research to develop a general model for carbonate island karst began in the Bahamas and Bermuda, which are relatively uncomplicated islands that have developed in tectonically stable settings (e.g. Mylroie *et al.* 1995). Subsequent observations from Isla de Mona, Puerto Rico (see Wicks 1998), a simple carbonate island that has been tectonically uplifted, extended the model to include the effects of relative sea-level change. Current work to extend the CIKM is focused on Guam (Jenson 1999; Taborosi 1999, 2000), which has not only been uplifted but has had complicated tectonic and depositional histories, with important consequences for the evolution of its karst features. Extending the CIKM to accommodate the unique characteristics of the karst on Guam takes it an important step closer to a fully general model of karst for small carbonate islands. Such a model is prerequisite to successful development and management of groundwater resources on small carbonate islands, especially in the face of their rapidly growing populations and economies (Falkland 1991).

Besides recognizing the unique attributes of island karst, the CIKM divides carbonate islands into three broad geomorphic types (Fig. 3) in terms of the position of the carbonate-basement contact with respect to sea level and the island surface. *Simple carbonate islands* contain only carbonate rocks on the surface and at a depth deep enough to interact with the fresh water lens. The Bahama Islands are an excellent example. *Carbonate cover islands* are defined by non-carbonate basement rocks that extend above sea level beneath the carbonate bedrock (but are not exposed at the surface), deflecting descending vadose water to the flank of the fresh water lens.

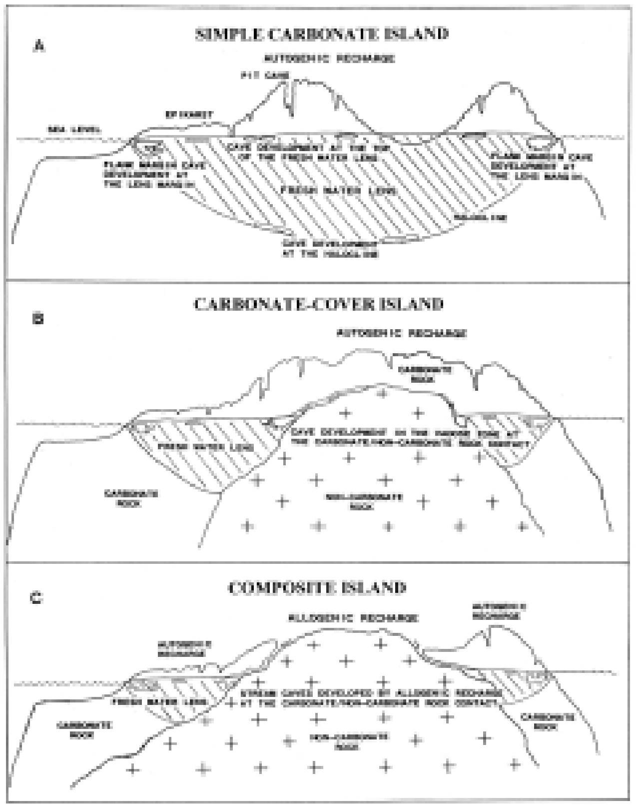

Figure 3. Geomorphic classification of carbonate islands, based on the position of the carbonate-noncarbonate contact with respect to sea level and the surface of the island (from Mylroie *et al*. 1999).

Islands can shift between simple and carbonate cover conditions with changes in relative sea level. Bermuda, for example, is a simple carbonate island during glacioeustatic sea-level highstands, but a carbonate cover island during lowstands (Mylroie *et al.* 1995). *Composite islands* contain carbonate and non-carbonate rocks exposed on the surface, in varying relationships and amounts. Barbados is a well-studied example. Islands in which volcanic rocks form the vast majority of the surface outcrop, with only limited carbonate exposures, as on some Hawaiian islands, are considered to be volcanic islands (Vacher 1997), outside of the CIKM classification scheme. The full range of differences in carbonate island aquifer characteristics occurs in the transition from a small, simple carbonate island to a large composite island. For a given island, sea level change may control the transition of island type. When sea level falls, an island will become larger as lagoons and forereef slopes become exposed. The fresh-water lens may also drop into the area of influence of basement rocks, forcing a simple carbonate island transition to a carbonate cover island. If a carbonate island has a minor basement rock inlier at a high elevation, a rise in relative sea level can decrease overall island size and carbonate outcrop area, making the basement outcrop a consequently more important component of the island's hydrology.

CLIMATIC AND GEOLOGIC CONDITIONS

CLIMATE AND HYDROLOGY

Guam is located at 13º28' north latitude, and has an equable mean annual temperature of 27º C. Rainfall averages 220-250 cm/yr, 70-80% of which arrives during the wet season from July to December. Trade winds bring dry conditions from January to May. During El Niño events, drought can be severe. Daily rainfall is highly variable, with important hydrological consequences. Some 20% of the mean annual rainfall arrives on days seeing less than 0.6 cm; it is thus unlikely to infiltrate past the root zone. At least another 20% arrives on days receiving 5 cm or more. Rapid rise and recovery of aquifer water levels immediately following such events, especially during the wet season, suggests that recharge from such heavy rainfall is transient. The proportion of rainfall contributing to the long-term equilibrium thickness of the fresh water lens thus seems likely to be no more than about 60% of the mean annual rainfall (Jocson *et al.* 1999; Contractor & Jenson 2000). Tropical cyclones, with an average recurrence of about one in three years, can bring up to 50 cm of rain in a single event. Although the hydrologic responses to these heavy storms are transient, cumulative effects on cave and karst evolution over geologic time could be significant. The nature of Guam's paleoclimate is unknown, including the degree to which Quaternary climate fluctuation affected rainfall and evapotranspiration. It should, therefore, be kept in mind that while the island's fresh-water lens is now equilibrated to current climatic conditions, the carbonate rock and the terrain formed on it might have gained their current characteristics under different (and varying) climatic conditions.

LIMESTONE GEOLOGY OF GUAM AND ITS RELATION TO THE CIKM

The seminal study on the geology of Guam is the work of Tracey *et al.* (1964). Reagan and Meijer (1984) made some revisions to the volcanic stratigraphy, but Tracey *et al.*'s report, with its 1:50,000 scale map, remains the primary reference (Fig. 2a). Early stage island-arc volcanism is recorded by Late Middle Eocene pillow lavas, breccias, and dikes. Subsequent volcanism in the Late Eocene to Middle Oligocene produced an overlying unit of breccias, tuffaceous sandstones, flows, and sills. These two units are unconformably overlain by a Late Miocene volcaniclastic unit containing occasional limestone fragments named the Maemong Limestone Member, indicating that a shallow carbonate depositional environment existed nearby. Overlying the Miocene volcanic unit are the Miocene Bonya and Alifan Limestones. These limestones now appear primarily as outliers on the high points of the underlying volcanic terrain of southern Guam, although small outcrops are mapped in northeastern Guam, near Mt. Santa Rosa, where the contemporaneous Janum Limestone, a rhythmically bedded argillaceous limestone deposited on its flank, is also exposed in the sea cliffs nearby.

On northern Guam, the most extensive limestone unit is the detrital Mio-Pliocene Barrigada Limestone, which lies atop the volcanic basement and comprises most of the bedrock. In much of the interior of northern Guam, the Barrigada Limestone extends to the plateau surface. Elsewhere, it grades laterally and upward into the Plio-Pleistocene Mariana Limestone, a reef and lagoonal deposit that occupies the largest surface area of any carbonate unit on Guam and dominates the perimeter of the northern plateau as well as the eastern edge of southern Guam. The Barrigada and Mariana Limestones are the major aquifers of northern Guam.

Guam has evolved in a tectonically active area. Episodes of uplift and subsidence, with associated normal faulting, have been ongoing prior to, during, and subsequent to carbonate deposition. Earthquakes are common, including a magnitude 8.1 event in August 1993. Recent uplift can be seen in the raised terraces of the Holocene Merizo Limestone, which is the final unit of the limestone succession on Guam. The predominant structural feature of the island is the NW-SE trending Pago-Adelup Fault, which separates the limestone plateau in the north from the primarily volcanic terrane in the south. (See Fig. 2 for the location of this and the rest of the features referred to in this report.) The northern plateau rises from near sea level adjacent to the fault to 190 m at the northernmost tip of the island. Volcanic outcrops form the summits of Mt. Santa Rosa and Mataguac Hill, rising to 252 m and 189 m, respectively, above the limestone plateau. The volcanic terrane in the south is deeply dissected hilly to mountainous uplands, with scattered limestone remnants. Mount Lamlam, the highest point on Guam at 405 meters (1,334 ft) a.s.l., is formed in the remnant of Alifan Limestone comprising much of the crest of the cuesta fronting the western coast of southern Guam.

The complex geologic history of Guam has produced an especially wide variety of karst landforms and caves. Guam combines, on a single island, features ranging from those characteristic of the simplest islands to those resembling continental landforms. At modern sea level, the volcanic basement lies well below the base of the fresh-water lens beneath about 80% of the northern limestone plateau. This portion of the plateau, thus, fits the simple carbonate island model (Fig. 3). Beneath the other 20% of the surface, however, the volcanic basement rises above sea level, thus fitting the carbonate cover model. Emery (1962) concluded that there were four submerged terrace levels around Guam, presumably marking prolonged relative sea level stillstands. Figure 4 shows the relative proportions of the plateau occupying simple vs. carbonate cover conditions for sea levels inferred to correspond with each of the terrace levels reported by Emery (neglecting any errors due to differential displacements of separate fault blocks). Finally, at Mt. Santa Rosa and Mataguac Hill in the northeastern corner of the plateau, about 1% of the basement is exposed at the surface, fitting the composite island model. Uplifted terraces are also common (Fig. 5).

The southern half of Guam is uplifted volcanic terrane upon which lies carbonate remnants, outliers, and occasional fragments of shallow-water carbonate deposits embedded in

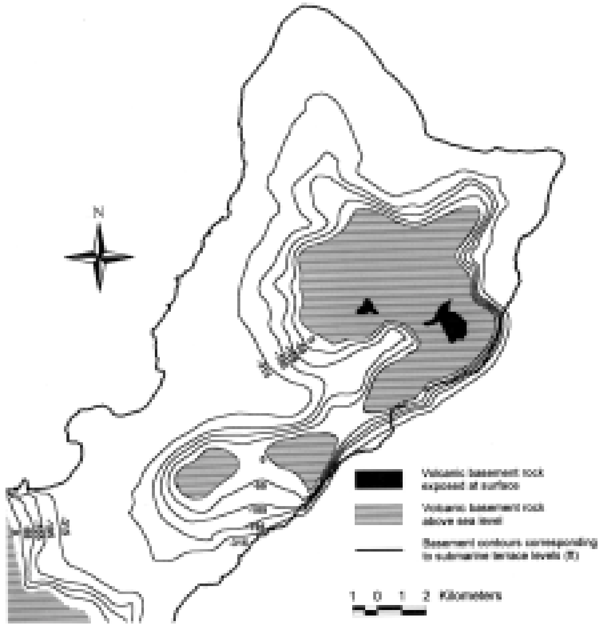

Figure 4. Contours (in feet) on volcanic basement rock corresponding to modern sea level and the four submerged terrace levels as mapped by Emery (1962).

Figure 5. Karrenfeld on marine terrace, with further uplifted terraces in the background, on the east side of Guam, south of Sasajavan.

the upper volcanic units. With the exception of the Mariana Limestone on the Orote Peninsula and the eastern coast of southern Guam, the base of the carbonate units in the south is now elevated above modern sea level, so that the units are removed from the direct influence of glacioeustasy and from the dissolution effects of fresh and marine water mixing. The karst of southern Guam is, thus, more analogous to that in larger islands such as Puerto Rico and Jamaica; as in these larger islands, the inland limestone units of southern Guam exhibit caves and karst landforms similar to those found in tropical continental settings.

KARST FEATURES ON GUAM

The karst landforms of Guam can be placed into two broad physiographic groups: those exemplary of carbonate island karst, which dominate the north, and those that imitate the karst of continental settings at similar latitude, which are found in the upland areas of the south. From the hydrologic and karst genetic perspectives, there are three logical subdivisions for karst features on carbonate islands regardless of physiographic provenance: surficial features, which are associated with catchment, infiltration, and surface dissolution from meteoric waters; subsurface features, which are involved in vadose and phreatic groundwater transport and dissolution; and coastal features, which are associated with groundwater discharge. We now describe the major types of karst features found on both northern and southern Guam in terms of these three groupings. For a complete and thorough description of caves and karst on Guam, with numerous maps and figures, the reader is referred to Taborosi (2000), a masters thesis written as the foundation for the karst inventory of Guam.

SURFACE FEATURES: EPIKARST & CLOSED DEPRESSIONS

The epikarst is the zone of dissolutional sculpturing (karren), weathered bedrock and soil products that develops from the surface downward for a few meters. Karren is a general term for dissolutional sculpturing in the millimeter to meter scale. Carbonate island karren is similar to that in interior continental settings, except that the salt spray of island and coastal environments produces the phytokarst of Folk *et al.* (1973) or the biokarst of Viles (1988) (Fig. 5). Below the salients of the karren, soil and weathered bedrock debris overlie solution fissures, holes and other shallow, small cavities in the bedrock to make up the epikarst. The most striking difference between island and continental epikarsts follows from the eogenetic character of the island rocks, which commonly produces an extensive chaotic surface of porous, dissolutionally modified rock fragments. The epikarst on Guam appears identical to that found on any number of carbonate islands in the Atlantic and Caribbean region (e.g., Bermuda, the Bahamas, Isla de Mona).

Closed depressions on carbonate islands can result from any combination of dissolution, natural construction, and human modification. Dissolution on young islands generally produces closed depressions of small to modest size, meters to tens of meters (Mylroie & Carew 1995; Wilson *et al.* 1995). Areas with autogenic recharge are unlikely to develop large, deep depressions because dissolution tends to be dispersed rather than focussed. Most large depressions on simple carbonate islands appear to be constructional, i.e., they are the result of depositional topography, or subsequent tectonic deformation (Mylroie & Carew 1997). In Bermuda and the Bahamas, for example, swales between eolianite ridges produce extremely large and deep closed depressions. Human activities such as quarrying and construction of stormwater ponding basins tend to accentuate pre-existing closed depressions because closed depressions are typically selected for such activities. On the other hand, depressions are also frequently filled to support construction or dispose of waste.

In the Barrigada and Mariana Limestones of northern Guam, closed depressions tend to be broad and shallow, suggesting origin by deposition and secondary structural modification. Streams are completely absent, except in the vicinity of Mt. Santa Rosa, Mataguac Hill, and Harmon Sink. Small ephemeral streams head on the volcanic outcrops at Mt. Santa Rosa and Mataguac Hill, where allogenic water sinking at the limestone contact has produced blind valleys that have evolved into locally significant dissolutional depressions. Harmon Sink, a deep elongate depression in a westward-trending valley terminating just inland of Tumon Bay (Fig. 2), is fed by autogenic water carried by an ephemeral sinking stream. The Harmon Sink stream system appears to be the single, though significant, exception to the otherwise general absence of deep closed depressions and stream courses on the limestone terrain of the northern plateau. Collapsed sinkholes can also be found on Guam, although they do not appear to be common. The few collapsed sinkholes that we have documented include some small cenotes 3-10 m deep in the Tarague area, a 25-m deep, vertical-walled sink in Chalan Pago (Carinos Pit), a 10-m deep sink in Barrigada (Appealing Cave), and a 3-m deep banana hole-type depression at Finegayan. The Chalan Pago and Barrigada pits are each associated with about 100 m of lateral passage development.

Immediately north of the Pago-Adelup Fault, the limestone area mapped (by Tracey *et al.* 1964) as the Argillaceous Member of the Mariana Limestone exhibits karst topography and hydrologic characteristics that set it apart from the rest of the northern plateau. Terrain is characterized by relatively large and deep, steep-walled, closed depressions and deeply incised rectilinear dry valleys following trends consistent with local fracture orientations. These valleys support ephemeral sinking streams that disappear into the valley floor before emptying into the Agana Swamp to the west, or Pago Bay to the east. The terrain is, thus, reminiscent of classic karst terrain in continental settings, in contrast to the rest of the limestone plateau. The reason for this contrast is not yet clear, but seems likely to be related to differences in the lithology (as suggested by Tracey *et al.* 1964) and/or stratigraphy arising from the area’s juxtaposition against the nearby higher volcanic terrain, which provided a source of non-carbonate terrigenous sediment during and following carbonate deposition. The armoring of the carbonate surface by volcaniclastic debris from the highlands to the south may also be responsible for the large number of sinking streams. This question is under active study (Mylroie *et al.* 1999).

The Bonya Limestone in southern Guam is entirely surrounded by volcanic rocks, and several streams flow through the area. These streams provide local base level and underdrain the limestone. As a result, large, deep closed depressions (50 m across, 20 m deep) have developed so close to one another that they are now separated by very narrow (down to less than a meter wide) ridges reflecting the original surface, to form terrain reminiscent of the cockpit karst of Jamaica. At least one of the base-level streams flows through the subsurface in large conduit passages. To the west, in the Mt. Almagosa area, some large closed depressions are found in the Alifan Limestone, probably associated with major internal conduits. Contact springs at the base of the Alifan Limestone augment stream flow that develops on the volcanic terrain of the mountain flanks. Large closed depressions are also located in southern Guam within the broad band of limestone mapped as Agana Argillaceous Member on the southeastern flank of the island (Fig. 2a). Such depressions in the vicinity of Talofofo include dry valleys. We propose that the observed large closed depressions could not have formed without the adjacent insoluble volcanic surfaces, and the colluvium derived from them, to perch surface water and isolate it from active contact with the limestone prior to the stream sink point.

CAVES

Systematic attempts to document the caves on Guam have begun only in recent years. Historically, indigenous people used sea-level caves containing fresh water as water sources, but not as dwellings. During the Second World War, Japanese garrisons modified caves for fortification, and stragglers took refuge in caves following the liberation. Live ordinance remains in many (Fig 6). Subsequent to the war, U.S. military personnel and other visitors made maps and sketches of caves, but none were published, and most maps left the island with their authors. The single best published source of information about caves on Guam is the comprehensive compendium by Rogers & Legge (1992), who list 74 caves based on systematic work that they did as part of the Pacific Basin Speleological Survey. In recent years, a local NSS-affiliated group, the

Figure 6. Live munitions from World War II exposed in a cave. Care must be taken to avoid these and other relics when working in caves on Guam.

Figure 7. Deep vadose shaft (45 m) behind Amantes Point, west coast of Guam.

Micronesian Cavers, has been making systematic efforts to locate and explore caves on Guam and elsewhere in the region. Currently, a scientific karst and cave inventory of Guam is being led by the Water and Environmental Research Institute of the Western Pacific, University of Guam (Taborosi 1999, 2000), as part of the work reported in this paper.

We discuss the caves of Guam here in terms of three field categories that are germane to carbonate islands: pit caves, stream caves, and flank margin caves. Pit caves (Mylroie & Carew 1995; Mylroie *et al.* 1995) carry vadose water from the epikarst into the subsurface, and can be very abundant locally on carbonate islands in general. A broad gradation of sizes can exist, from shallow and narrow pipes that barely penetrate the epikarst, to enlarged fissures, to classic vadose shafts. The deeper ones are effective vadose bypass routes for infiltrating water. Pit caves may intersect other voids at depth, including stream caves or flank margin caves (Mylroie & Carew 1995; Mylroie *et al.* 1995). In contrast to their occurrence on Caribbean islands (Harris *et al.* 1995), pit caves on Guam do not occur in clusters and are relatively rare. Tracey *et al.* (1964) noted the presence of cavernous development in the Mariana Limestone. This unit features well-developed pits along the cliffs at Amantes Point (45 m deep, Fig. 7) and Tanguisson (10 m deep) on the west coast, and at Talafofo Caves (35 m deep) on the east coast.

Traversable stream caves have developed on Guam along the contacts between limestone and the underlying volcanic units (Jenson *et al.* 1997) in both the north and the south. In northern Guam, several can be found on the flank of Mt. Santa Rosa. These are active caves fed by allogenic water from the volcanic slopes above the contacts. The primary discharge point for the water carried by the caves on the eastern flank of Mt. Santa Rosa is probably Janum Spring (discussed in "Discharge features" below). The upper levels of Awesome Cave, one of the more spectacular of the several Mt. Santa Rosa caves, exhibits a series of wide chambers, now undercut by a vadose streamway (Fig. 8). We propose that these are dissolutional features marking relative sea-level stillstands, during which vadose stream water mixed with the top of the fresh-water lens to create a broad dissolutional horizon. Alternatively, the broad chambers may represent collapse features formed as a result of vadose streamways meandering and undercutting the volcanic-limestone contact, as has been proposed for large chambers in Bermuda (Mylroie *et al.* 1995). In Awesome Cave, the well-developed phreatic dissolution features on the cave walls (cusps, rock pillars, etc.) argue for an *in situ* dissolutional origin in the fresh-water lens. Nearby Piggy Cave, however, has large collapse chambers that might follow the Bermuda model or merely be large phreatic dissolution chambers now undergoing collapse. In the Agana Argillaceous Member of the Mariana Limestone, at the opposite end of the plateau, we have identified no stream caves in the dry valleys we have explored so far. Relief is low, however, so whatever conduits may have developed during Pleistocene sea-level lowerings might now be below base level and inaccessible, perhaps clogged with sediment in the low gradient conditions currently present.

In southern Guam, stream caves occur in the Bonya Limestone and in the Alifan Limestone at Mt. Almagosa (Fig. 9). These caves have also formed at the contact with underlying volcanic rock, but are in limestone remnants positioned well above sea level, and thus unaffected by dissolution associated with fresh-water lens positions. These caves are, therefore, similar in origin and morphology, if not size, to similarly situated continental or large-island caves. In the Bonya Limestone, the perennial Tolaeyuus River (a.k.a. "Lost River") is fed by allogenic water from streams heading on the volcanic terrain above, plus discharge from Bona Spring, which rises on the contact between the Alifan Limestone and the underlying volcanic rock. In the basin, it disappears into a flooded cave and reemerges some 500 meters downstream. Almagosa Spring, one of the contact springs at the base of the Alifan Limestone, issues from a cave that is traversable for some 250 m. Flow is seasonally variable, but sufficient to have justified

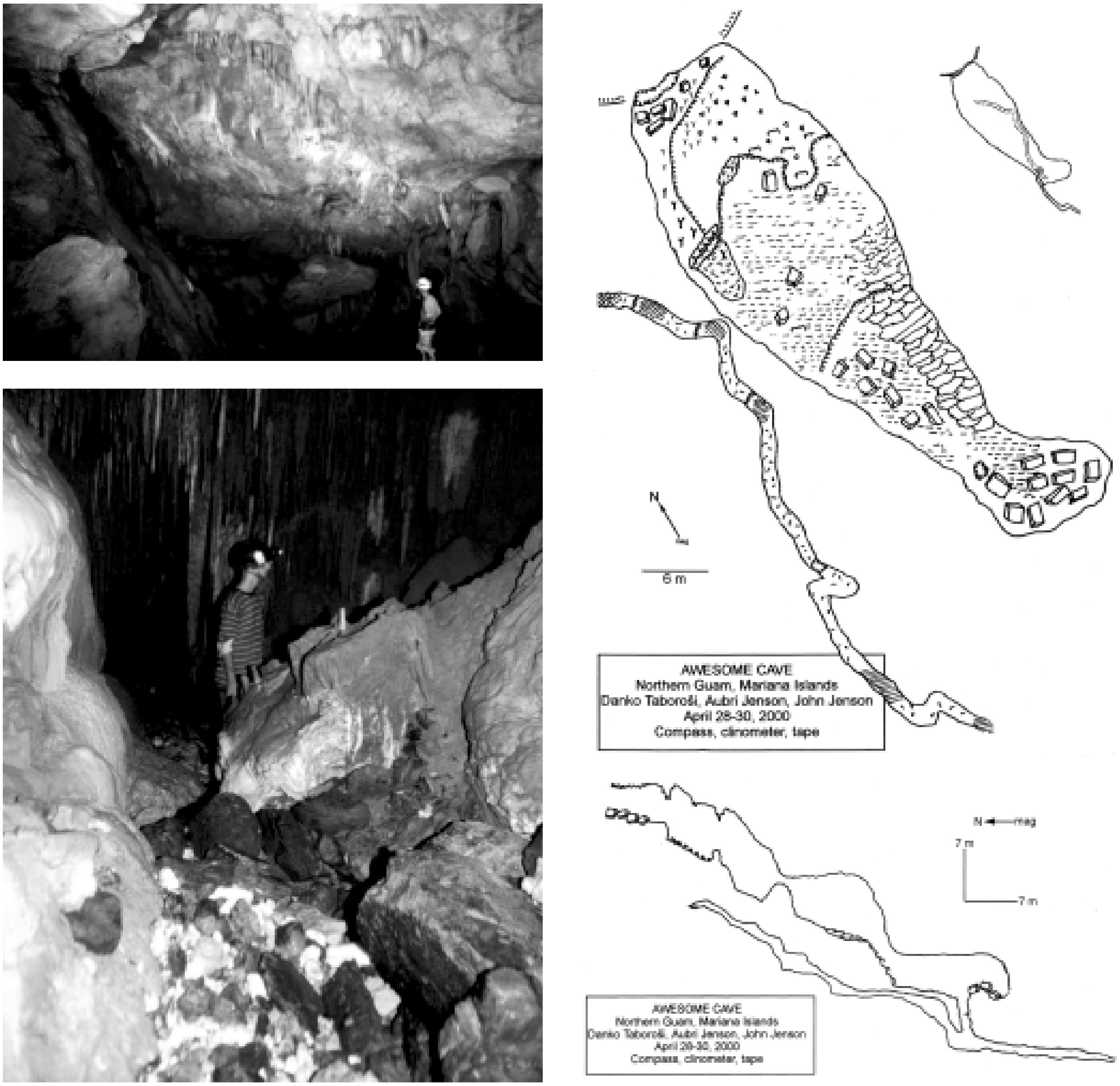

Figure 8. a-left top) Upper phreatic chamber of Awesome Cave, on the flank of Mt. Santa Rosa, northeast Guam. Note the dissolutional surfaces. b-left bottom) Typical vadose passage found at Mt. Santa Rosa, formed at the contact of the white limestone and the black volcanics, with incision into the volcanics. c-right) Map of Awesome Cave (Taborosi 2000) showing stacked phreatic chambers underdrained by vadose flow. The phreatic chambers formed within a fresh-water lens, fed by allogenic vadose flow, and were sequentially abandoned by tectonic uplift of the island.

development of the spring as a water source by the U.S. Navy.

Flank margin caves are characteristic carbonate island features that form at sea level in the distal margin of the freshwater lens. They have been well documented in the Caribbean (Mylroie & Carew 1995; Mylroie *et al.* 1995 and references therein). Because they are fed by diffuse groundwater flow, they reflect mixing chambers rather than conduits. Their presence indicates, in fact, that conduit flow was not operating in their immediate vicinity—or it would have captured the diffuse flow that helped develop the caves. Low, wide chambers oriented parallel to past shorelines are abundant on Guam. We have interpreted these as flank margin caves. Pagat Cave (Fig.

Figure 9. Cave in southern Guam, developed in the Bonya Limestone, which carries a base level stream at the limestone/volcanic contact and connects to deep cockpits.

10) at sea level on the northeastern coast of Guam, for example, is typical of flank margin caves, and shows overprinting by subsequent sea level events. It is currently half-filled with fresh water, yet the walls show evidence of vadose calcite deposition with later dissolution under phreatic conditions; stalagmites are found beneath the fresh water currently filling the lower regions of the cave. Given glacio-eustasy, and the uplift of the island, such a complex history is expected. During aerial reconnaissance of the island, we saw numerous cave openings on the cliffs along the periphery of the northern half of the island, as well as in the Talofofo area on the southeast coast (Fig. 11). Most of these voids were clearly at preferred horizons, indicating paleo-horizons of the fresh-water lens associated with a glacio-eustatic sea level stillstand, a period of tectonic quiescence, or both.

DISCHARGE FEATURES

In the karst region in the interior basin of southern Guam, water discharges from karst springs and resurgences into streams that determine the local base level, as in classical continental karst. The streams from the interior converge on trunks that flow east out of the basin across volcanic terrane until they intercept the limestone apron flanking the southeast coast. Because they are antecedent to the limestone, they have incised sheer canyon walls where they pass through. Between the trunk streams, small amounts of locally captured water discharge from the limestone.

In the northern plateau, fresh water discharges entirely from ubiquitous coastal springs and seeps, except at the southern end near the Pago-Adelup Fault. Here, the Fonte and Pago Rivers head on the volcanic terrain opposite the fault, then turn to run parallel or along it, discharging, respectively, into Agana Bay on the northwest and Pago Bay on the southeast. Immediately south of the Agana Swamp, the perennial Chaot

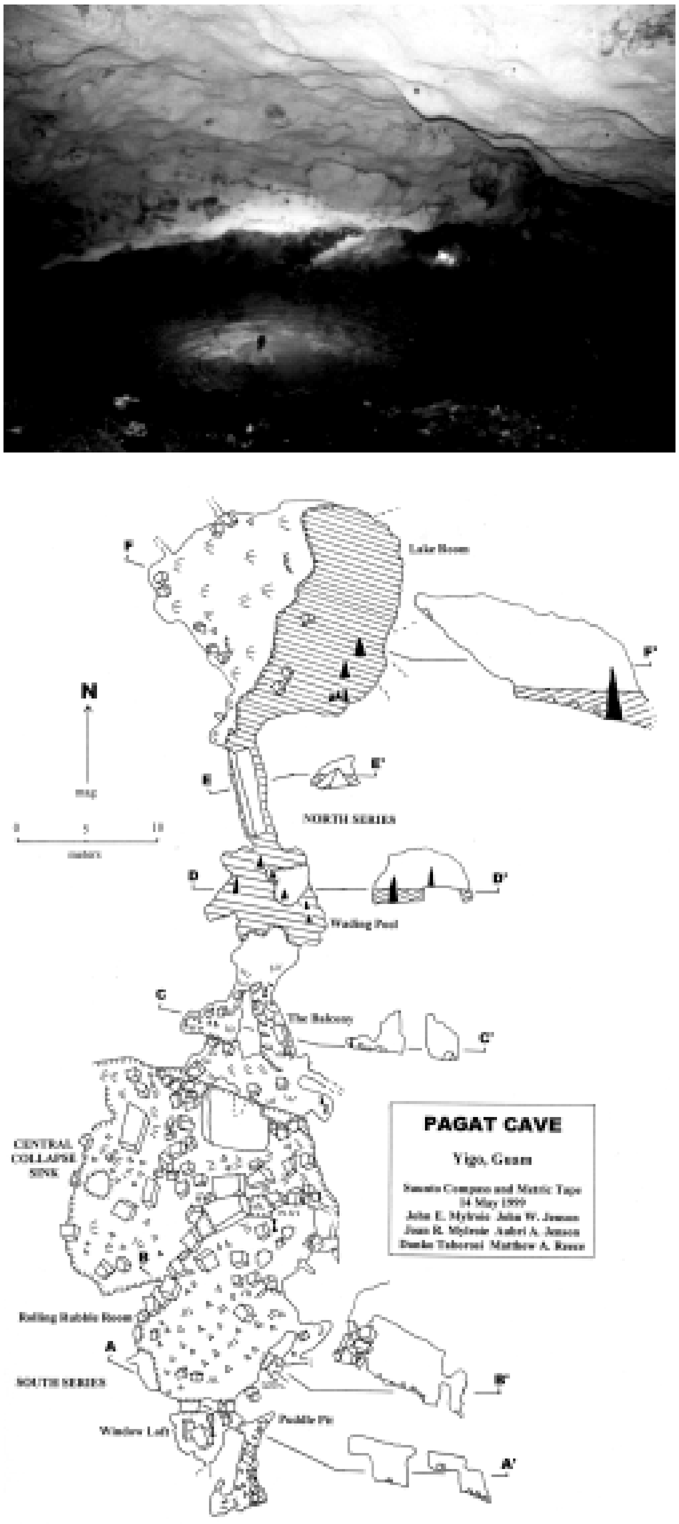

Figure 10. (a-top) Fresh water pool at sea level in the Lake Room of Pagat Cave, a typical flank margin cave located on the northeast coast of Guam. (b-bottom) Map of Pagat Cave showing development north-south, parallel to the coast line and the distal margin of a past fresh-water lens.

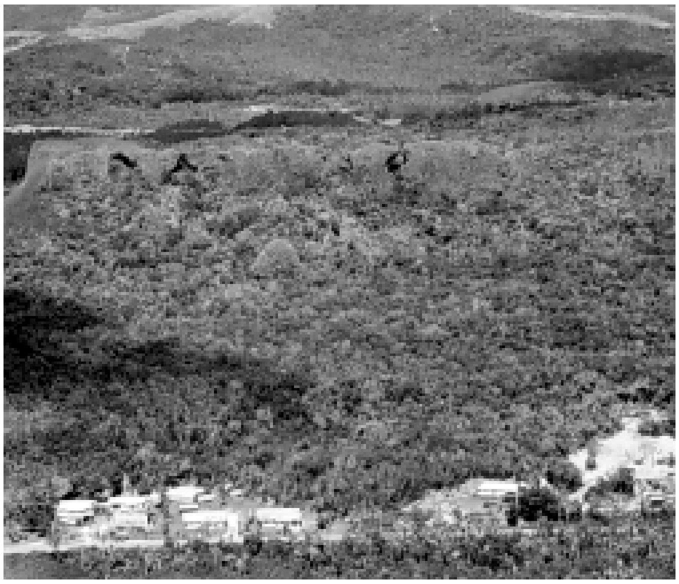

Figure 11. (a-top) Air photo of the Talafofo area, showing cave entrances in a cliff developed in Mariana Limestone; it is uncertain if these are flank margin caves or remnants of stream caves draining the volcanic uplands to the west. (b-bottom) Tarague cliffs on the north coast of Guam, showing breached flank margin caves containing abundant speleothems. The caves, while at a constant horizon, show the "beads-on-a-string" morphology produced by cliff intersection of adjacent cave chambers.

River heads and runs through a deeply incised valley in the Agana Argillaceous Member, first running inland, then turning back to discharge into the swamp. Agana Spring, which rises in the Agana Argillaceous Member and discharges at the south end of the Agana Swamp, is reported to have been a long-used local drinking water source, but from reports by local residents, flow fell to insignificance when pumping wells were installed on the terrain above. The only other inland spring on northern Guam is Mataguac Spring, in the northeast, on the flank of Mataguac Hill. It disappears into a small cave that is traversable for only some 30 meters.

Figure 12. Vista of Tumon Bay, looking southeast. Note the extensive beach, with the recessed cliff line trending from the foreground inland to the east and trending back west in the background.

Coastal groundwater discharge around the northern plateau is highly variable from one location to another, both in volume and style, as reported by earlier workers (Emery 1962; Matson 1993). We have examined the entire coastline on various occasions by foot or from boat or airplane. Our efforts have focused, however, on the 16-km sector along the northwest coast from Tumon Bay to Double Reef, which we have examined in detail on foot and by diving along the near-shore to locate sources of fresh-water discharge. This sector is accessible and representative of the coast as a whole in that it exhibits each discharge style found along the 80-km coastline of northern Guam. Significantly, it drains about 40% of the plateau while constituting only 20% of the coastline.

Jenson *et al.* (1997) described the coastline of northern Guam in terms of three distinct coastal morphologies. About 16% of the coastline is occupied by deeply scalloped embayments with broad interior beaches fronted by shallow platform reefs extending to the mouth of the bay (Fig. 12.). These include Agana Bay and Tumon Bay on the southwest coast, Pago Bay at the southeast corner of the plateau, and Haputo Bay, much smaller than the other three, on the northwest coast. In each of these embayments the cliffline is typically recessed 10s to 100s of meters behind the beachfront, and groundwater discharge is characterized by permanent seeps (Fig. 13) and springs (Fig. 14) distributed along the perimeter of the bay, with rarely more than about 100 meters between significant seeps or springs. Effluent is well exposed by the lowest tides, with the larger springs typically reworking the beach sand into meter-scale channels and deltas, as seen in figure 13. Jocson (1998) estimated low tide discharge for the largest Agana Bay and Tumon Bay springs to be about 0.2 m^3s^{-1}. On the east side of the island, nearly opposite Tumon Bay, is Sasajyan, a scalloped area where the cliff line lies about 1.5 km inland and is fronted by a sloping surface (4-5% grade) rising from a few

Figure 13. Large seep field behind Pacific Island Club complex in Tumon Bay. Estimated flow is about 30 L/sec (Jocson 1998). Sand channels and small deltas are built and destroyed with each tidal cycle.

Figure 14. Wet Willies Spring. Estimated flow is about 50 L/sec (Jocson 1998).

meters at the shoreline to 50-60 meters near the base of the cliff line. Its size and shape are reminiscent of Tumon Bay, suggesting it could be an uplifted embayment of similar origin, although this question has yet to be investigated.

The second type of coastal morphology is sandy beaches following linear coastline with fringing reefs, which provide the sand and protect the beach from the surf (Fig. 15). These occupy about 24% of the total coastline, mostly in a continuous stretch from Uruno Point clockwise around Ritidian Point to Tagua Point at the northwestern corner of the island. The cliffline is generally recessed 10s to 100s of meters behind the shoreline. We have observed numerous seeps along the beaches but, with one exception partway between Ritidian and Taraque Points, we have not found significant concentrated flow from either caves or sea-level coastal springs in this environment.

Figure 15. Linear beach along north coast of Guam, between Tarague Beach and Ritidian Point; lowest cliff near beach in center of the photograph contains the cave entrances shown in figure 11b.

About 60% of the total coastline is sheer cliffs with narrow to no benches, which support no beaches and only occasional small reefs (Fig. 16). Rock along the coast is typically strongly indurated, and we have found no evidence of distributed, diffuse seepage in this zone. Discharge appears rather to be associated with dissolution-widened fractures, flowing caves, and submarine vents. The largest of the dissolution-widened fractures are up to about 2 or more meters wide, are traversable a few 10s of meters into the cliff face, and discharge an estimated 0.1 m^3s^{-1} (Fig. 17-19). The largest single discharge observed on the coast of the plateau so far is at Coconut Crab Cave, which Jocson (1998) estimated to be at least 0.25 m^3s^{-1}. Finally, we have observed a few small submarine discharges at ~4-6 m depth along this zone, and three larger vents at ~10 m depth. Flux is difficult to measure from these, but our initial impression of discharge from the large vents, based on visual observation while diving to observe the cold plume issuing

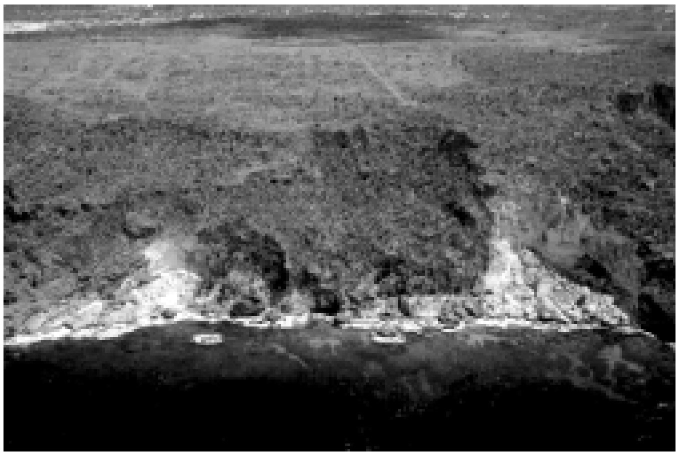

Figure 16. Rocky coastline with no beach along northeast Guam, near Janum.

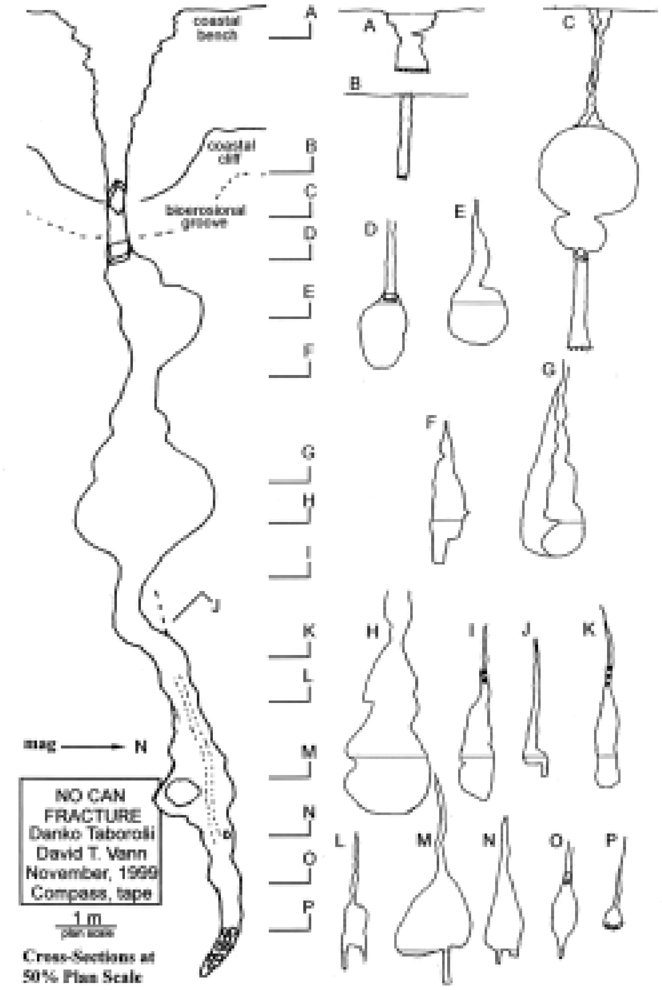

Figure 17. a-left top) Entrance to No Can Fracture. b-left bottom) Phreatic tube, back end of No Can Fracture. c-right above) Map of No Can Fracture (Taborosi 2000).

from the vents, is that flux from each may be comparable to the discharge from Coconut Crab Cave (the term "cold" is relative, as the springs discharge water at a temperature of 26-27ºC, while the shallow lagoon can easily exceed 30ºC as a result of solar heating).

The Pacific (eastern) coastline of the northern plateau is notably devoid of beaches and reefs, and the total discharge is limited by the restricted size of the groundwater catchment area bounded by the basement ridge (Figs. 2 and 4) running from the Barrigada Hill area to Mt. Santa Rosa. Here, some 35% of the coastline drains only about 10% of the plateau. Discharge is difficult to observe because of the usually heavy surf from the easterly Trade Winds and lack of footing beneath the cliffs, but observations so far suggest that discharge is sparse and relatively small over most of this stretch of coastline. The important exception is Janum Spring, which is well known locally and supported an ancient settlement on the adjacent terrace. The cavern at the mouth of the spring collapsed during the 1993 earthquake, so that the discharge point is now covered with rubble and is unobservable. Authors Jenson and Wexel, however, observed an extensive plume of reddish discharge from Janum Spring during a local heavy rainfall while working in the Mt. Santa Rosa area, suggesting that Janum Spring is the mouth of a trunk by which water discharges from a cave system descending the eastern flank of Mt. Santa Rosa.

CONCLUSIONS

Guam represents as complete a site for the investigation of island karst as exists anywhere in the world. In the south, it has

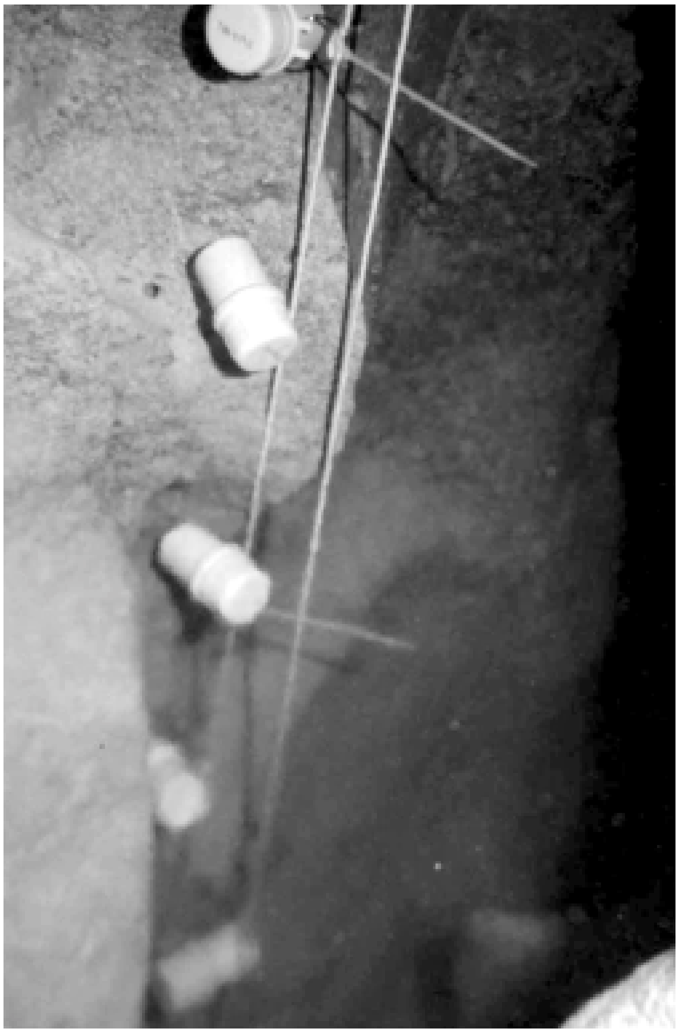

Figure 18. Halocline in No Can Fracture. White objects are waterproof casings holding temperature probes, note that lower ones appear fuzzy as they are below the halocline. The entire view is under water. Photo by J. Carew.

Figure 19. Large fracture cave on the coast, a few hundred meters south of No Can Fracture. These features are common along the northwest coast of Guam.

interior elevated limestones that contain karst identical to that of inland, tropical continental situations. In the north, it contains the karst characteristic of simple carbonate islands, carbonate cover islands, and composite islands (Fig. 19). The southern half of Guam therefore can be characterized in terms of established karst ideas derived from continental settings. However, the northern half of the island, which contains the vast majority of the island's water reserves, must be viewed in terms of the unique characteristics of the Carbonate Island Karst Model (CIKM) in order for those water resources to be successfully conserved and utilized.

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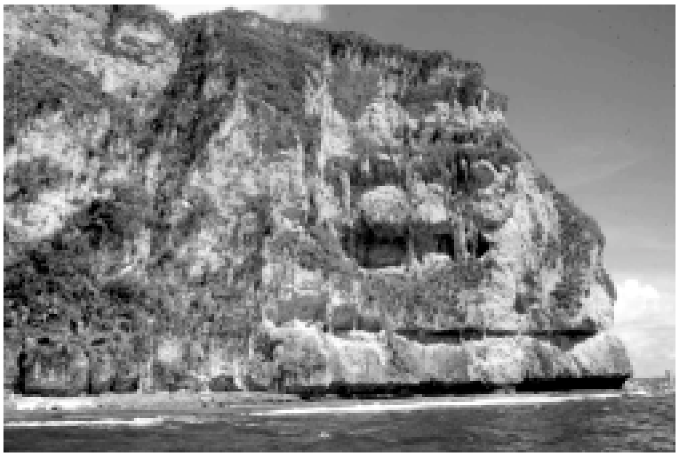

Figure 19. Cliff at Amantes Point, showing stacked cave levels, now breached with speleothems exposed. A modern bioerosion notch is visible at sea level. As uplift occurs, cliff erosion first removes evidence of older bioerosion notches, then further erosion exposes the flank margin caves within the cliff.

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