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THE CAVES OF ROTA, COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS

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ABSTRACT

Rota, like the other carbonate islands in the Mariana Arc, was created primarily by Late Eocene to Early Oligocene volcanism. It is extensively mantled by Miocene through Holocene limestones, but also has significant exposures of volcanic rock. The complex interactions among the eogenetic limestone, low permeability volcanic rock, tectonic uplift and subsidence, and eustatic sea-level changes have created an assemblage of caves on Rota similar to, yet distinct from the documented cave assemblages on other nearby islands in the Mariana Arc, including Guam, Aguijan, Tinian, and Saipan. Consistent with the Carbonate Island Karst Model, Rota has a large number of flank margin caves, the result of mixing dissolution under diffuse flow conditions at the edge of the fresh water lens. It also has a few caves developed along the contact between limestone and underlying volcanic rocks. However, compared to the other islands we have surveyed in the Mariana Arc, Rota has a striking number of well-developed mixing zone fracture caves. Mixing zone fracture caves develop where fresh water discharging from fractures mixes with seawater to create zones of enhanced dissolution, in which the cave wall is extended laterally. These mixing-enhanced dissolution zones appear to have migrated headward as the fracture was widened by dissolution. Although these caves form in the distal portion of the fresh-water lens, they differ from flank margin caves in that their morphology is dominated by vertical fractures with zones of lateral widening, rather than the typically spheroidal to oblate shape of flank margin caves. Rota has three areas with networks of solutionally modified fractures. Although caves have been found on Rota from sea level to within a few meters of the summit at 496 m, fewer caves have been found at higher elevations. This could be due to the longer history of destruction of older and higher caves by dissolution and mass wasting. It may slo be an artifact of the greater difficulty of exploring the thick jungle cover at higher elevations.

INTRODUCTION

The purpose of this investigation was to locate and map a significant portion of the caves and karst features of Rota island and to evaluate these features in the context of the Carbonate Island Karst Model (Mylroie et al., 2004). This report summarizes the findings of field investigations of 122 karst features on the Island of Rota, Commonwealth of the Mariana Islands (CNMI). We are confident that we have characterized the types and relative occurrence of each, although the large number of caves, the rugged terrain, and the dense vegetation preclude an exhaustive quantitative survey and rigorous analysis of the variation and distribution of cave types and related karst features.

As predicted by the Carbonate Island Karst Model (CIKM), there are numerous flank margin caves along the modern and ancient perimeters of the island, and a few stream caves along the contact between the volcanic basement and overlying limestone units. Pit caves, of which we documented but one on Rota, are rare, as they are on the rest of the Mariana Islands. Rota, however, is distinguished by the significant number of relatively large caves apparently developed from fresh water discharging at sea level from vertical fractures.

SETTING

Physiography and Geology

The Mariana Islands (Figure 1), in the western Pacific Ocean, consist of fourteen islands in two parallel arcs, both of which sit atop the Mariana Ridge (Karig, 1971). The eastern, paleo-volcanic chain is expressed at the surface as the islands of Guam, Rota, Aguijan, Tinian, Saipan and Medinilla. The chain on the western edge of the Mariana Ridge is expressed at the surface as the nine, volcanically active, northern islands. Rota (Figure 2) lies E 145° 12′, N 14° 10′on the eastern side Mariana Ridge about 80 km north of Guam, the southernmost island in the chain. It has a surface area of ~85 km^2, a coastal perimeter of ~52 km, and is oriented roughly northeast-southwest. Rota, like the rest of the Mariana Islands, has a wet-dry tropical climate with the wet season running from July to September, and the dry season from February to March. Average annual rainfall is ~200 cm. Temperatures on Rota rarely go below 25°C or above 32°C and average ~27°C (USDA, 1994).

Figure 2 is a generalized topographic map of Rota, along with the locations of the caves discussed here. The southwest end of Rota is dominated by the *Sabana*[1], the top of which is an irregular plateau about 4 km east-west and 2.5 km north-south in size. The highest point on Rota, *Mt. Sabana*, rises to 496 m (USGS, 1999). East and west of the *Sabana*, the land drops in a series of irregular limestone terraces. The northwest flank of the *Sabana*, *Uyulan Hulo*, contains a large area of outcropping volcanics covered with scattered limestone remnants. Unlike the other known volcanic outcrops on Rota, it is covered with forest. The northeast flank of the Sabana, *As Mundo*, is bounded by a scarp at the northwest end and a series of irregular terraces at the southeast end.

The south flank of the *Sabana*, *Talakhaya*, is bounded by a scarp which overlooks a broad slope formed on weathered volcanic terrain. This area contains the only surface streams on the island. A discontinuous band of limestone lies at about 100 m elevation on the *Talakhaya*, and a continuous band extends from sea level up to about 40 m elevation.

The *Sinapalo* region, at the eastern end of Rota is dominated by a mid-level plateau (100 – 200 m). Along the north side of the *Sinapalo* region, the terrain slopes gradually to sea level. From the northeast end of the island and all along the southern side of the *Sinapalo* region, the plateau is bounded by steep cliffs that drop to a coastal terrace of variable-width.

At the west end of Rota, the *Taipingot Peninsula* ("Wedding Cake") is connected to the southwest end of the *Sabana* Region by a 0.5 km wide isthmus at *Songsong*. The *Taipingot* reaches an elevation of 143 m (USGS, 1999).

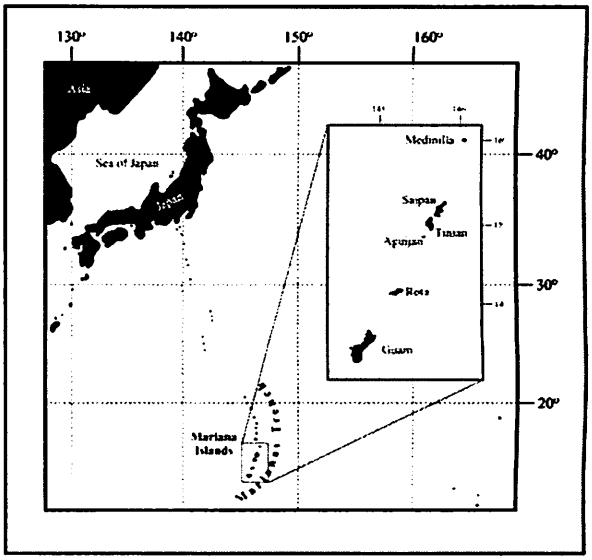

Figure 1. Location of the Mariana Islands

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[1] Local place names are taken from the USGS topographical map of Rota (1999) and are italicized for clarity.

The first and only extensive report on the geology of Rota was written in Japanese by Sugawara and translated into English by the United States Army (1939 [1949]). Although no English translation of the maps accompanying Sugawara's report is available, some faults are clearly depicted. Sugawara's approach was primarily to define the physiography of Rota based on the prominent series of terrace levels that are obvious almost all the way around the island. Based on his understanding of depositional facies, he also defined a series of depositional units. These units followed the visible terraces, which he describes as constructional. The positions of the terraces are variable and reflect complex interaction between glacio-eustasy and local tectonics.

In the absence of a previous exhaustive mapping of Rota, and to support our field study of the karst, as reported here, we have drawn from the work of Sugawara (1939 [1949]), Stafford (2003), Stafford et. al (2002) and Doan et. al (1960) on Tinian; Tracey et. al (1964) on Guam; Cloud et. al (1956) on Saipan; and Karig (1971) on the geologic history of the Mariana Arc, in order to posit the following rough, hypothetical history of the geology of Rota.

During the Eocene, island arc volcanism, which had been producing pillow basalts and submarine pyroclastic flows since the early Tertiary, created a seamount that reached into

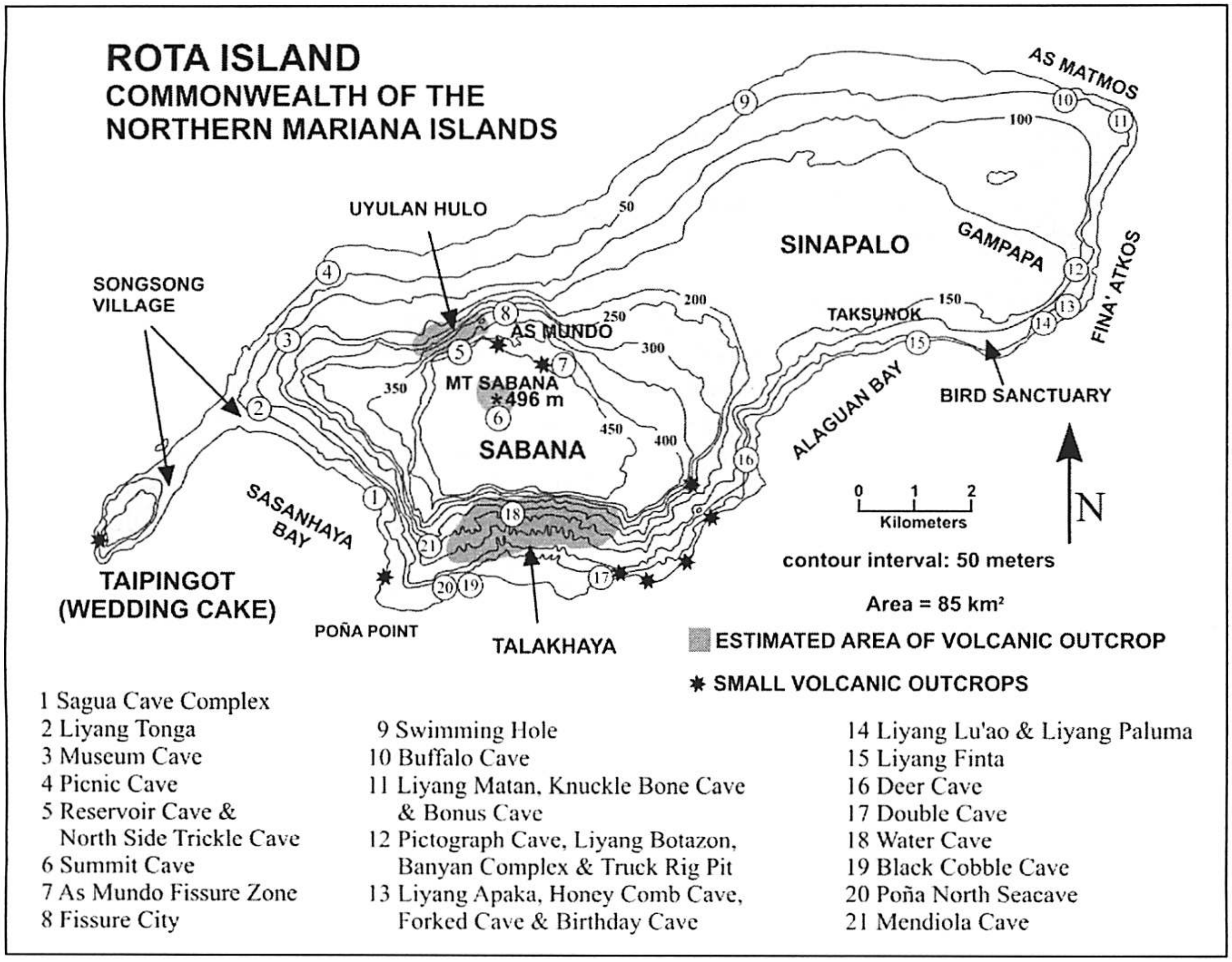

Figure 2. Rota (Luta) Island, Commonwealth of the Northern Mariana Islands.

the photic zone. Coral and calcareous algae colonized the seamount, despite sporadic volcanism that continued at least to the Early Oligocene and possibly to the mid-Miocene. This interaction resulted in an interfingering of volcanics and volcanoclastics with limestone. Uplift and subsidence, driven by the volcanism and plate motion, produced a complex set of faults, some of which are masked by younger limestone deposits and some of which are expressed on the surface. Net uplift, exceeding 500 m, left Rota mantled with eogenetic limestone to within 20-30 m of the summit on the *Sabana*. The limestone of Rota is forms of irregular terraces that reflect the position of sea-level stillstands.

Around much of its perimeter, Rota is fringed by Holocene reef limestone that was exposed by tectonic uplift. Estimates of the maximum amount of Holocene uplift range from 3.1 m (Dickinson, 2000), to 3.5 m (Kayanne et al., 1993). Weathering and erosion of this recently exposed limestone has produced a jagged surface and rugged coast.

Historical and Political Setting

Rota was settled by the Chamorro people around 1500 BCE. Magellan landed somewhere in the Marianas in 1521. Spanish missionaries began the "reduction" of the islands in 1668 (Coomans, 1997). In 1898, the United States took Guam during the Spanish–American War. Since then, Guam has been politically separate from the other the islands in the Mariana Arc. In 1899, Spain sold the northern Marianas to Germany, which maintained control of them until Japan occupied them in 1914 at the beginning of World War I. Japan controlled them until the end of World War II when they were liberated by the United States in 1944. The Japanese mined phosphate-rich soil on the *Sabana* (Rodgers, 1948) and cleared land for sugar cane. When US forces landed on Saipan and Tinian in 1944, Rota, which had only a small garrison, was spared invasion, but it was eventually surrendered along with the rest of the Mariana Islands. In 1947, the United Nations created the Trust Territory of the Pacific Islands, under which the United States administered the northern Mariana Islands along with other islands in the Pacific. In 1978, following a plebiscite in the northern Mariana Islands, the United States ratified a covenant that established the Commonwealth of the Northern Mariana Islands (CNMI), under which the citizens of the CNMI have US citizenship, but retain self-governance with regard to taxation, immigration, and labor laws. Rota, the southernmost island in the CNMI, is one of its three municipalities, along with Saipan, and Tinian. Several federal agencies, including the US Postal Service, National Park Service, US Geological Survey, and US Department of Agriculture provide services in the CNMI.

THE CAVES AND KARST FEATURES OF ROTA

Rota's complex geologic history of deposition, tectonic emergence and submergence, glacio-eustasy, and weathering and erosion in a tropical climate, has resulted in caves of various types occurring across a wide range of elevations. Recent investigations of Saipan, Guam, and Tinian by the authors and colleagues (Mylroie and Jenson, 2001; Mylroie et al., 2001; Stafford, 2003; Stafford et al., 2002; Stafford et al., 2003; Taboroši, 2000; Taboroši and Jenson, 1999), and earlier brief investigations by Rogers and Legge (1992) suggested that Rota had many flank margin caves, some sea caves, some contact caves between the limestone and the underlying volcanic basement rock, and some caves developed along bedrock fractures.

Mixing Zone Caves

Eighty five of the 122 caves surveyed on Rota were formed in the mixing zone at the edge of the fresh water lens. Fifty three of those are flank margin caves and the remaining thirty two are mixing zone fracture caves.

Flank Margin Caves. Consistent with the CIKM (Mylroie, 2004) we found flank margin caves at elevations from present sea level to 320 m. Flank margin caves on Rota range from small isolated remnants of caves to extensive horizons of interconnected caves. The length of each cave, in meters, will be given in parentheses after the first mention of the cave name.

The most spectacular group of documented flank margin caves on Rota is the Sagua Cave Complex (1,168 m) (Figure 3 & #1, Figure 2). It consists of multiple flank margin caves exposed at sea level along ~800 m of cliff face below *Sagua*, on *Sasanhaya Bay*. Many of the individual caves have skylights and/or multiple entrances. To date, the Sagua Cave Complex is the longest documented semi-continuous horizon of flank margin caves in the Marianas.

In terms of culture and hydrology, Water Cave (Matan Hanum) (32 m) (reported as Water Fall Cave by Rogers and Legge, 1992), (# 18, Figure 2) is the most significant cave on Rota since it is the source of most of the fresh water entering the municipal system. Water Cave apparently is a flank margin cave that coincidentally developed at the contact between the volcanic basement rock and the overlying limestone. This now stands at an elevation of about 320 m on the *Talakhaya*. The topography of the volcanic-limestone contact concentrates the flow of water from the *Sabana* above, which then emerges from vents in the east wall of the Water Cave. There are also several smaller springs along the contact just outside the Water Cave and numerous springs along the contact east and west of Water Cave.

Although there are a few at modern sea level, most of the flank margin caves on Rota stand well above sea level. This reflects the rapid uplift of the island. Picnic Cave (25 m), along the road near the Veterans Memorial on the northeast coast (#4, Figure 2), for example, stands less than a meter above sea level in a limestone "hill" along the coast. It more closely resembles the low-lying flank margin caves of the Bahamas than any other documented cave on Rota.

Liyang Tonga (65 m) (#2, Figure 2), (Rogers and Legge, 1992), is a large flank margin cave with considerable human modification, including concrete slabs and stone

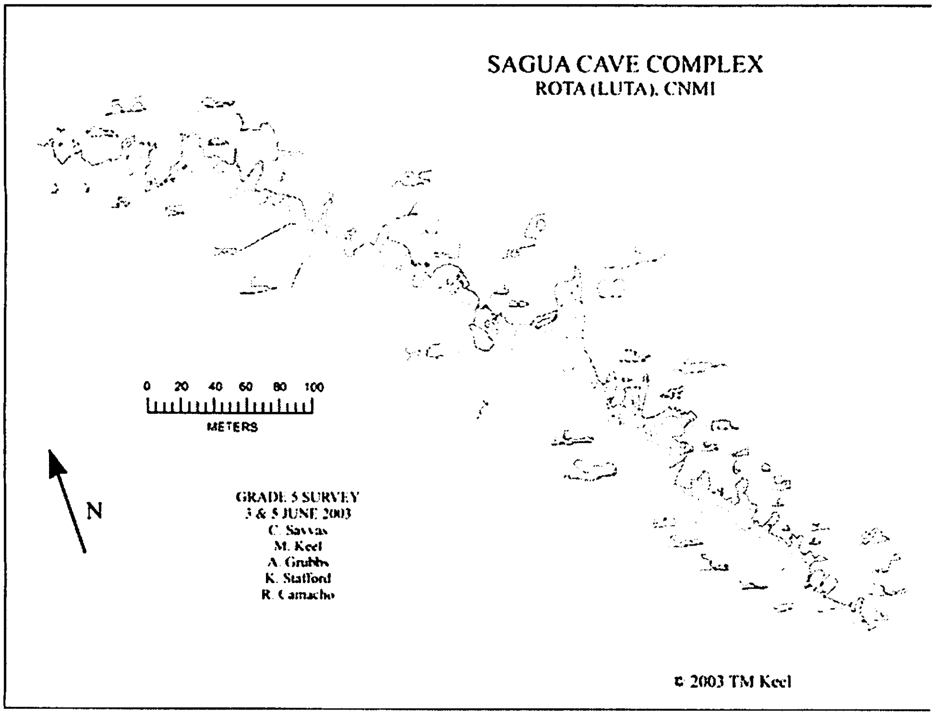

Figure 3. Sagua Cave Complex

stairs. Almost the entire west wall of Liyang Tonga has been removed by cliff failure. The tall narrow entrance on the south side of Liyang Tonga and its proximity to known mixing zone fracture caves (Liyang Ganas and Nanong Katiyu) suggest that its development has been influenced by the presence of a fracture (see Fracture Caves below). Similarly, the Museum Cave (55 m) on the northwest coast (#3, Figure 2) apparently developed as a flank margin cave but was influenced by the fracture that is visible in the ceiling along the length of the cave.

Black Cobble Cave (27 m) on the northeast flank of *Poña Point* (#19, Figure 2) is apparently a flank margin cave that developed along an interfingering bed of volcanics.

The Swimming Hole (28 m) on the northeast coast (#9, Figure 2) (Rogers and Legge, 1992), is probably a collapsed flank margin cave. Since fresh water presently discharges at the Swimming Hole, it may be analogous to the caletas of the Yucatan, Mexico (Back et al., 1984).

Rota has several large horizons of apparent flank margin caves that because of time constraints and difficulty of access have not been surveyed. There is a flank margin cave horizon stretching several hundred meters along the cliff face at *As Matmos*, on the east end of the island. Buffalo Cave (45 m) (#10, Figure 2) is a segment of the *As Matmos* horizon that was surveyed. There are several horizons of flank margin caves in the cliffs along *Alaguan Bay*. The most prominent, with several large entrances, stretching across several hundred meters, is in the cliff face below *Taksunok*, just west of the *Bird Sanctuary*.

Mixing zone fracture caves. Although similar caves had been documented on other islands in the Mariana Arc (Stafford, 2003), on Rota, we were surprised to discover a significant number of linear caves developed along fractures roughly normal to the cliff faces. For reasons explained in the Summary and Conclusions section, we decided to call this distinct cave type "mixing zone fracture caves."

On Rota, we found mixing zone fracture caves at elevations from sea level up to ~140 m, a maximum length of ~100 m and heights to 25 m. They are typically oriented normal to the cliff face with the genetic fracture prominent in the ceiling. On some parts of Rota, mixing zone fracture caves are found in clusters of up to four caves over a few tens to hundreds of meters laterally. These apparently formed during the same sea-level still stand. At the base of the cliff in the *Bird Sanctuary*, Liyang Paluma (38 m) and Liyang Lu'ao (70 m) are within about 40 m of each other (#14, Figure 2 and Figure 4).There is another cluster of four mixing zone fracture caves at the base of the cliff, south of *Fina' Atkos*, in the north end of the *Bird Sanctuary*. Liyang Apaka' (60 m), Honey Comb Cave (20 m), Forked Cave (35 m), and Birthday Cave (14 m) are all within about 40 m of each other (#13, Figure 2).

At the eastern tip of Rota, near *As Matmos*, there are three large mixing zone fracture caves that may constitute a cluster, but which are more widely spaced than caves in some other clusters. Liyang Matan (130 m), Knuckle Bone Cave (85 m) and Bonus Cave (110 m) (#11, Figure 2) are the largest documented mixing zone fracture caves on Rota. The entrances to Liyang Matan and Knuckle Bone Cave are incised into the cliff face by a few tens of meters, probably due to collapse of the outer part of the cave roof. This collapse was probably promoted by the existence of the two parallel fractures along which each of these caves is developed. These caves would be significantly longer if the distance from the drip line to the cliff face was included. One of the fractures along which Knuckle Bone Cave is developed, lies along a lineament visible on satellite imagery.

Liyang Ganas (45 m) and Nanong Kastiyu (25 m) (Rogers and Legge, 1992) are in the cliff face just east of Liyang Tonga (#4, Figure 2), in *Songsong Village*. These are near-parallel mixing zone fracture caves containing historical human modifications, including a man made tunnel connecting them.

Although not apparently found in clusters, there are several other significant mixing zone fracture caves on Rota. For its size, Pictograph

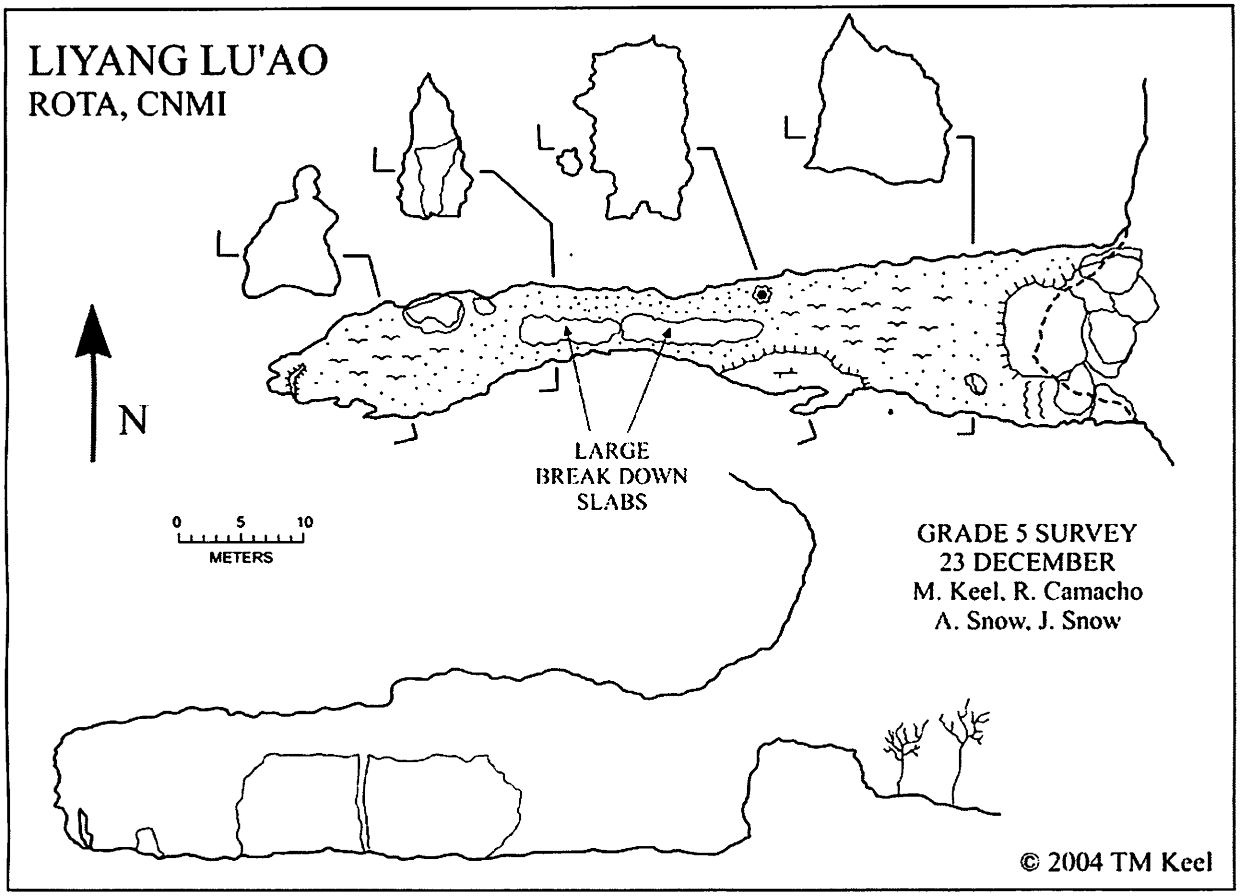

Figure 4. Liyang Lu'ao

Cave (60 m) (#12, Fig. 2), at *Gampapa*, is a significant mixing zone fracture cave.

The canyon extending from the cave entrance appears to be collapsed cave passage, giving this feature a length in the range of 100 m, close to the maximum length of fracture caves on Rota. Liyang Botazon (90 m), at the prominent coastal notch at *Fina' Atkos*, is unique among the documented mixing zone fracture caves on Rota in that it opens at the present sea level and has storm tossed boulders and plastic net floats at the back of the cave, about 100 meters from the shore line. The prominent canyon above Liyang Botazon, which cuts steeply across several cliff lines and extends up to the wide bench below Pictograph Cave, suggests that development of this feature has been along a significant fault, although no evidence of displacement has been documented. Deer Cave (90 m) (#16, Figure. 2) is a large, isolated fracture cave developed along two parallel fractures at the base of the cliff at *Payapai*.

Near *Taksunok*, Liyang Finta (#15, Figure 2) is apparently mixing zone fracture cave that is also expressed on the cliff top above it. The many broken and re-cemented speleothems and the rubbly facies below Liyang Finta, in which Basement Cave is developed, suggest that this fracture is, in fact a fault and that there has been movement since the development of Liyang Finta.

Fissure Caves

Fissure caves are vertical or steeply dipping fractures that have been solutionally modified by descending meteoric water. To date, none of the fissures documented on Rota to date show any indication of stream flow. The most significant fissure caves are located in concentrations referred to herein as "fissure zones". The three documented fissure zones are the As Mundo Fissure Zone, Fissure City and the Banyan Complex. The As Mundo Fissure Zone (#7, Figure 2) is ~450 m long and ~200 m wide and is located about 700 m southeast of *As Mundo* and is a dense network of solutionally modified fractures that generally trend NW-SE. Some fissures are oriented diagonal or perpendicular to the trend. Many of the fissures reach 10+ m depth and some have roofed sections. The relatively small areas between fissures are mostly covered with pinnacle karst. The As Mundo Fissure zone contains some of the most rugged terrain on Rota, earning it the field name, "Fissure Hell". The determination of where one fissure ends another starts was somewhat arbitrary. Tea Kettle Fissure (95 m) consists of a large, open sinkhole-like section that leads to a narrow roofed section >13 m deep. Henry Fissure Cave (60 m) (Figure 5) is a narrow winding fissure that leads to a 15 m roofed section at the west end. The depth of Henry Fissure Cave ranges from 2 m to 12 m. The size and complexity of the As Mundo Fissure Zone limited the number of features that we could reasonably map.

Fissure City (#8, Figure 2), located, east of *Uyulan Hulo,* and is ~400 m long and ~150 m wide. It is oriented roughly northeast-southwest. The large closed depression depicted east of *Uyulan Hulo* (USGS, 1999) is at the northeast end of Fissure City. Fissure City has a very rugged pinnacle karst terrain with fissures that tend to more discrete than in the As Mundo Fissure Zone.

Due to the size and complexity of Fissure City, only a limited number of features were

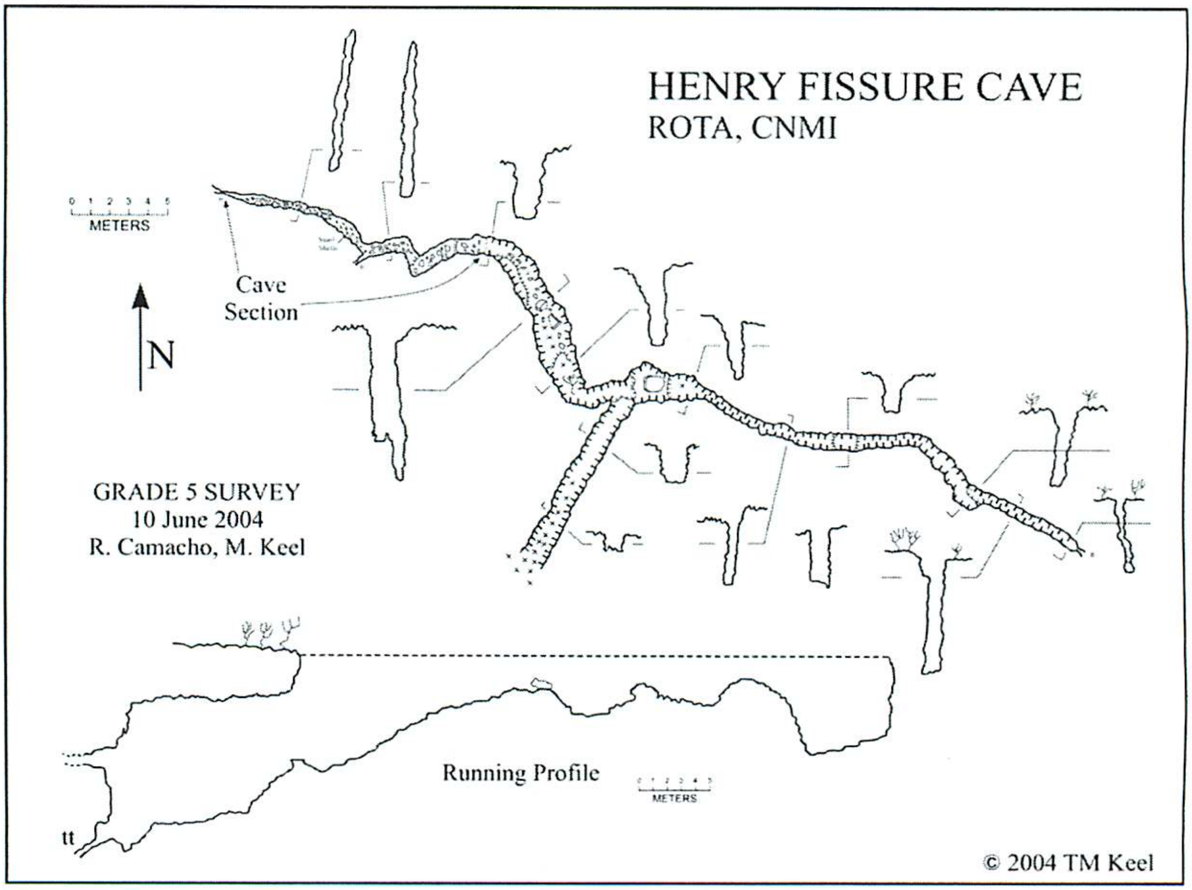

Figure 5. Henry Fissure Cave

mapped. Fissure City Cave (35 m), located at the north end of the large closed depression (USGS, 1999), is the largest feature mapped, and to date, at 30 m, is the deepest documented cave on Rota. The fracture along which it is developed clearly continues below the passable part of the cave. There are several other fissures at the bottom of the same closed depression that were not mapped. Just to the north of this same closed depression is Root Wall Cave (40 m), developed along a complex set of fractures.

The Banyan Complex is in the bench below Pictograph Cave (#12, Figure 2). It is strikingly different from the other two documented fissure fields. The Banyan Complex appears to have developed along a conjugate fracture set related to the apparent nearby fault thought responsible for the prominent coastal notch at *Fina' Atkos* (USGS, 1999). Most of the fractures in the Banyan Complex are less than 1 m wide and there are only a few small caves developed. The lateral extent of the Banyan Complex has not been determined.

Sea Caves.

There are numerous, generally small, sea caves on Rota, mostly along the south coast. Most of these sea caves remain undocumented. The largest documented sea cave, Double Cave (60 m) (#17, Figure 2) consists of two large open chambers. The distribution of debris indicates that storm waves apparently reach all the way to the back walls of these chambers. Poña North Sea Cave (16 m) (#20, Figure 2), just north of *Poña Point* is located ~3 m above present sea level.

Contact Caves

Water Cave, discussed previously, originated as a flank margin cave, but because it is located at the volcanic-limestone contact on the *Talakhaya* it has developed the characteristics of a contact cave as well. There are three contact caves on the *Sabana*. The largest, by far, is Summit Cave (25 m) (#6, Figure 2), located at the bottom of sinkhole on the south side of the summit of *Mt. Sabana*. Summit Cave is a significant insurgence; water flowing into it descends through the floor of the largest room. But, there is no accessible stream passage. Discus Cave and Rota Rooter Cave, located in a large closed depression north of the *Sabana* Peace Memorial, are both very small. Neither acts as an insurgence. But, significant insurgences are located within a few meters of each.

There are two small contact spring caves at the base of the scarp on the northwest flank of the *Sabana* at *Uyulan Hulo*. North Side Trickle Cave (10 m) and Reservoir Cave (15 m) (#5, Figure 2) were discharging 1-2 liters per minute in the 2004 wet season. Neither shows evidence of having significant discharge at any other time of the year.

Mendiola Cave (#21, Figure 2), near Haofña, is a large (36 m), sloping, open chamber with a very small stream of rapidly flowing water at the bottom. Although no volcanic rock crops out in the cave, the presence of the stream suggests that the contact was influential in the development of Mendiola Cave.

Pit Caves

Pit caves are rare in the Mariana Islands (see Stafford, 2003), and Rota is no exception. Truck Rig Pit (7 m deep), adjacent to the parking area for Pictograph Cave (#12, Figure 2), is clearly developed along a fracture that has the same ~60° strike at Pictograph Cave. Since its morphology was unlike the documented mixing zone fracture caves or fissure caves, and we classified it separately as a pit cave due to its vertical entrance. To date, It is the only pit cave documented on Rota.

SUMMARY AND CONCLUSIONS

The development of flank margin caves on Rota, as outlined in the CIKM, reflect the complex interaction of mixing dissolution with local uplift and eogenetic limestone. The large horizons of flank margin caves reflect relatively long sea-level still stands. Flank margin caves were found from sea level to about 320 m elevation. The development of flank margin caves on Rota is not significantly different from that on the other limestone mantled islands in the Mariana Arc.

The abundance of mixing zone fracture caves on Rota was not expected. This cave type had been documented by Stafford (2003) on Tinian, but not in the numbers nor developed to the extent that we found them on Rota. Perhaps on Rota the number of caves developed along fractures is a reflection of the history of tectonic uplift that has make Rota the highest of the limestone mantled islands of the Mariana Arc.

The morphology and location of mixing zone fracture caves led us to conclude that they form at and just below sea level where fresh water discharging from a fracture (fault or joint) mixes with salt water. Differences in salinity and CO_2 concentration between the mixing waters create a zone of aggressive dissolution (Bögli, 1980; Palmer, 1991; Plummer, 1975) that widens the fracture. The zone of aggressive dissolution is thought to migrate headward in the fracture analogous to the headward erosion of a waterfall. Although the main passages are generally linear with near-parallel walls, the ends of several caves have a dissolutional fretwork ("boneyard") appearance that suggests an aggressive dissolutional environment. Since little geologic structure has been mapped on Rota, it is difficult to interpret with confidence the nature of the fracture along which any given fracture cave is developed.

The vertical extent of some mixing zone fracture caves on Rota is probably the result of continued freshwater discharge as local tectonics and glacio-eustasy changed sea level or the result of simultaneous discharge of freshwater along several vertical meters of the fracture. The size of some of the mixing zone fracture caves indicates that the discharges that formed them were active for a considerable time. Although we have not explored below sea level along a significant part of the coast, some sea-level fractures on Rota are probably acting as discharge paths from the freshwater lens and mixing zone fracture caves are probably forming presently.

There may be significant vertical and horizontal distortion of the freshwater lens associated with actively discharging fractures that have implications for any future attempts to exploit the fresh water lens.

There seems to be a trend of larger mixing zone fracture caves being found singly or widely spaced with smaller mixing zone fracture caves sometimes found in clusters.

Although fissure caves had been previously documented on other islands in the Mariana Arc, they had not been reported in large complex fields of fissures. The genesis of fissure zones is more problematic than that of the other karst feature on Rota. They are obviously developed by the solutional modification of near vertical fractures. The genesis of the original fractures is difficult to determine; they could be the product of fault zones or the result of cliff margin failure. In the case of the fissures at *Uyulan Hulo*, there is the possibility that motion of a large block of limestone facilitated by the underlying weathered volcanics may be responsible for the fractures.

The interaction of glacio-eustasy, local uplift and subsidence, fracturing and faulting, the bedrock-basement contact, mixing dissolution, mass wasting, and wave erosion with the eogenetic limestone of Rota have created a variety of caves at a variety of elevations. Caves are found at elevations from sea level (and probably some below sea level) to within 30 m of the summit of the island.

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