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KARST DEVELOPMENT ON TINIAN, COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS: CONTROLS ON DISSOLUTION IN RELATION TO THE CARBONATE ISLAND KARST MODEL

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Tinian, located in the western Pacific Ocean, is an Eocene volcanic edifice mantled by younger algal and coralline limestones. Carbonate rocks are eogenetic, producing an island karst terrane as predicted by the Carbonate Island Karst Model. Surface karst features include epikarst, closed depressions, and freshwater discharge sites. Subsurface karst features include three morphologically distinct cave types: mixing zone, fissure, and contact. Controls on cave development inferred from morphology are supported by non-parametric statistical analyses. Mixing zone cave development is controlled by freshwater lens position, fissure cave development is controlled by structural deformation, and contact cave development is controlled by lithologic boundaries. Horizons of mixing zone caves preserve at least three previous sea level positions, but differential rates of uplift between fault blocks prevent correlation of horizons across the entire island. Tinian karst development demonstrates the functionality of the Carbonate Island Karst Model and illustrates how portions of individual islands may exhibit each of the ideal island categories to some extent.

Tinian lies across a six-km channel at the southwest end of Saipan in the Mariana Archipelago in the western Pacific Ocean, approximately 3000 km east of the Asian landmass (Fig. 1). The islands are formed along the Mariana Arc, 160 km west of the Mariana Trench, created by subduction of the Pacific Plate to the east under the Philippine Plate to the west. Of the 17 Mariana Islands, only the southern six islands (Guam, Rota, Aguijan, Tinian, Saipan, and Farallon de Medinilla) are overlain by carbonate rocks, while the northern 11 are exclusively volcanic (Cloud *et al*. 1956).

Most freshwater consumed on Tinian is extracted from shallow skimming wells in the karst aquifer. The unpublished Military Geology of Tinian (Doan *et al*. 1960) remains the most detailed geologic survey of the island and includes a 1:25,000 scale geologic map with cross-sections showing island lithology and structure. Gingerich and Yeatts (2000) investigated the freshwater lens and found that the top of the lens is generally less than 0.6 m above sea level and thins to less than 12 m total thickness in the vicinity of the island's municipal wells. Karst studies on the island have begun only recently (Stafford *et al*. 2002, 2003a,b; Stafford 2003). This paper is the first formal report on karst development on Tinian, with description and analyses based on the Carbonate Island Karst Model (Mylroie & Jenson 2001, 2002; Jenson *et al*. 2002).

FIELD SETTING

Tinian is the third largest island in the Marianas with a surface area of 102 km², 51.2 km of coastline, and a maximum elevation of 187 m. It is composed of Eocene volcanic rocks mantled by Miocene and Plio-Pleistocene coralline and algal limestone and Holocene raised beach and reef deposits. Located at 15.01° N latitude (Fig. 1), it has a wet-dry tropical climate with a distinct rainy season (July-September) and dry season (February-March). Annual precipitation averages 200 cm, and temperature ranges from 20° C to 32° C. Dense woody vegetation occupies carbonate regions, while grass dominates non-carbonate regions (Doan *et al*. 1960; Tracey *et al*. 1964; Gingerich & Yeatts 2000).

The Eocene volcanic tuffs and breccias that comprise the basement are exposed on less than 3 km² of the island surface. Volcanics have been extensively weathered, with only relict structures and textures remaining. Foraminifera observed in weathered tuffs indicate that pyroclastic deposits were probably ejected from a submarine vent. The carbonate rocks that

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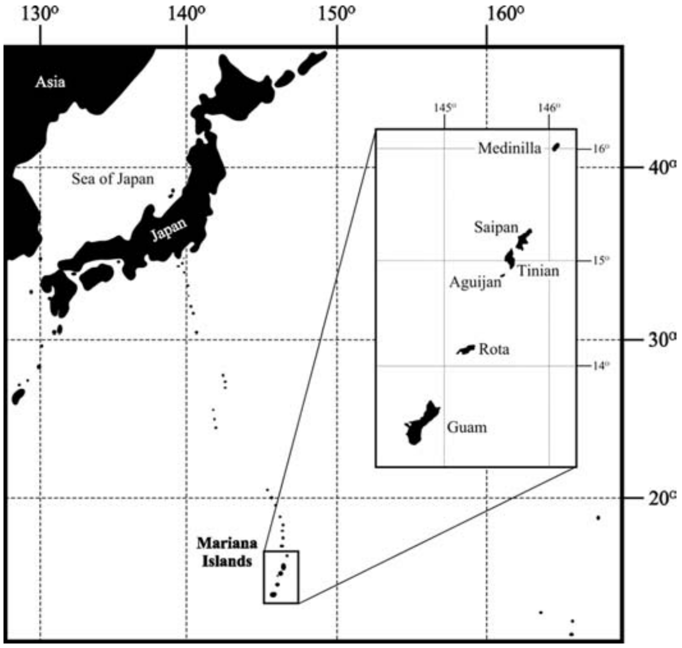


Figure 1. Location of study area, with carbonate islands of the Marianas expanded.

Cenezoic	Quaternary	Holocene	Recent sands, reefs, alluvium and colluvium
		Pleistocene	Mariana Limestone
	Tertiary	Pliocene	
		Miocene	Tagpochau Limestone
		Oligocene	No Recognized Units
		Eocene	Tinian Pyroclastic

Figure 2. Tinian geologic column (adapted from Doan *et al.* 1960).

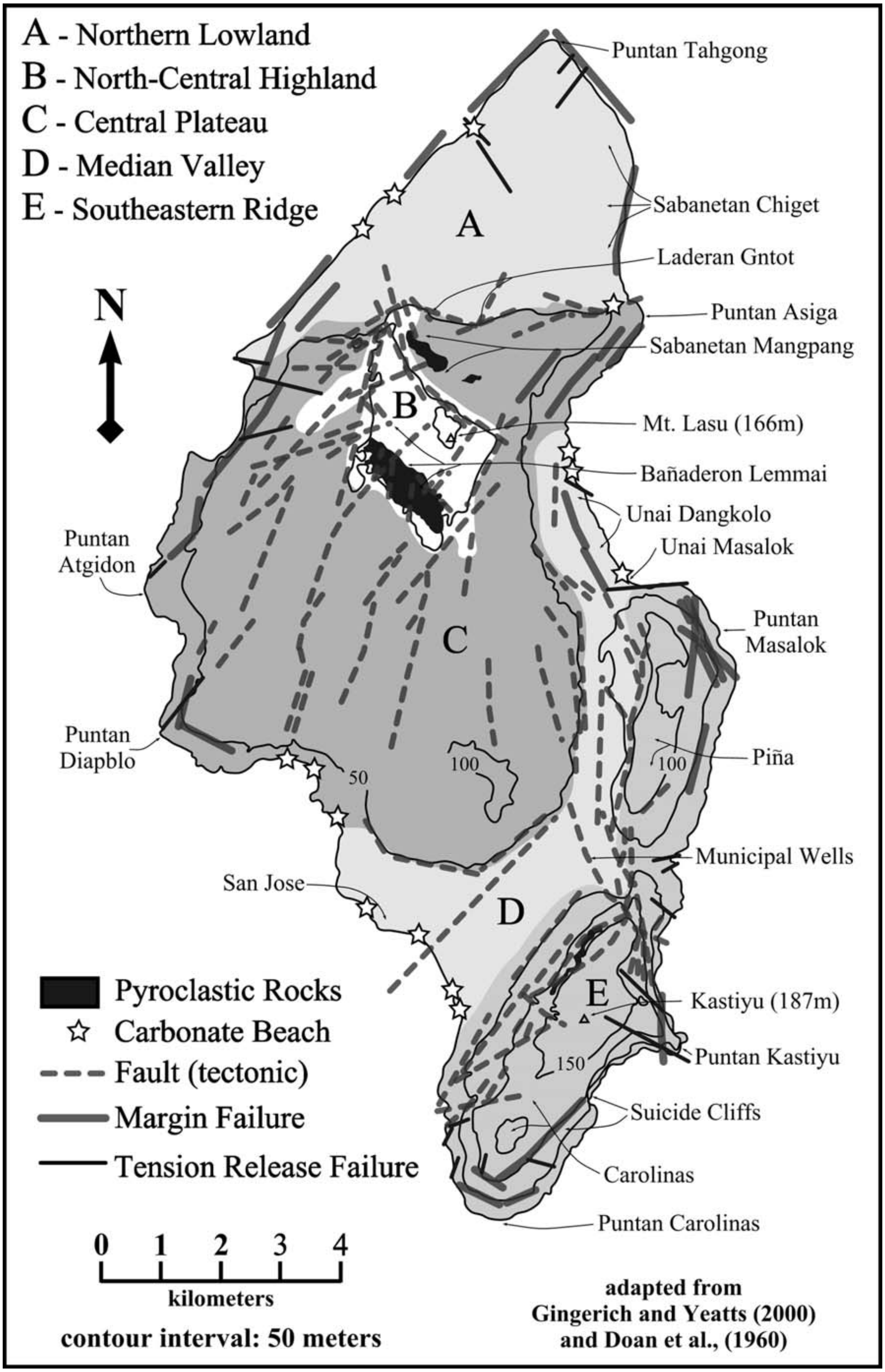
mantle the volcanics are subdivided into three units (Fig. 2): Miocene Tagpochau Limestone, Plio-Pleistocene Mariana Limestone, and Holocene raised beach and reef deposits (Doan *et al*. 1960). The Tagpochau Limestone covers approximately 16% of the land surface and is composed of three contemporaneously deposited facies: detrital, argillaceous, and sandy. The Mariana Limestone covers approximately 82% of the island surface and is composed of seven facies based primarily on constructional and detrital compositions: constructional coralline, constructional algal, detrital coralline, detrital shelly, detrital Halimeda, detrital argillaceous, and detrital undifferentiated. Holocene raised beach and reef deposits overlie the Mariana Limestone in coastal regions, where developing sands, gravels, and reefs cover less than 1% of the island surface (Burke 1953; Doan *et al*. 1960; Siegrest 1988). Primary porosities remain high in limestone units because they have not undergone extensive burial and diagenesis that would increase cementation and compaction.

Tinian's geomorphology is primarily controlled by three factors: 1) original volcanic deposition, 2) original carbonate deposition, and 3) structural deformation, primarily brittle failure. Although obvious karst landforms such as sinking streams and large dissolutional closed depressions are rare, the overall effect of karst can be seen in the lack of surface streams, the many open cave entrances, and numerous small sinks and epikarst morphology not evident at topographic scale. Tinian's current coastline is mostly erosional with scarps and cliffs strongly controlled by structure (Fig. 3). Structural modification is seen in three contexts (Doan *et al*. 1960): 1) regional faulting associated with island arc tectonism, 2) brittle failure parallel to scarps and cliffs associated with margin failures, and 3) brittle failure near-perpendicular to scarps and cliffs associated with tension-release structures that form at right angles to margin failures. Although minor in the Marianas, passive isostatic subsidence may also induce additional brittle failures (Dickinson 2000).

High-angle faults have separated Tinian into five distinct physiographic provinces (Fig. 3): Northern Lowland, North-Central Highland, Central Plateau, Median Valley and Southeastern Ridge (Doan *et al*. 1960). The Northern Lowland forms a broad region covering the northern third of the island. The North-Central Highland contains most of the non-carbonate outcrops and forms the second highest plateau with a maximum elevation of 166 m. The Central Plateau, isolated by scarps, is located directly south of the Northern Lowland and extends from the east to west coast of Tinian around the North-Central Highland. The Median Valley is a fault-bounded, broad depression that separates the Central Plateau from the Southeastern Ridge. The Southeastern Ridge is developed on two large fault blocks forming the Piña and Carolinas ridges, and includes the highest peak on the island, Kastiyu, at 187 m.

CARBONATE ISLAND KARST

The Carbonate Island Karst Model is the current model for hydrologic development in island and coastal settings where eogenetic carbonate rocks (i.e., young rocks that have not been buried beyond the range of meteoric diagenesis) are present (Mylroie & Vacher 1999; Vacher & Mylroie 2002; Mylroie & Jenson 2002). It was originally designed to explain karst devel-



adapted from Gingerich and Yeatts (2000) and Doan et al., (1960)

Figure 3. Map of Tinian showing important locations, physiographic provinces, igneous outcrops, brittle failure features, and beaches (constructional coastlines) (adapted from Doan *et al*. 1960).

opment in the Bahamas and Bermuda, and later expanded based on observations in the Pacific. Karst on small carbonate islands and coasts composed of young limestones is unique from karst in continental settings because of the extensive interaction between fresh and saline groundwater in young, highly porous carbonate rocks. On carbonate islands, a freshwater lens develops as a result of the density difference between fresh and saline waters, as defined by the Ghyben-Herzberg-Dupuit Principle (Raeisi & Mylroie 1995; Mink & Vacher 1997).

The Carbonate Island Karst Model was created to define the unique interaction of fresh and saline groundwater in diagenetically immature rocks (Mylroie & Jenson 2001, 2002; Jenson *et al*. 2002; Stafford *et al*. 2003a). The main elements of the model are (Fig. 4):

1. The freshwater/saltwater boundary creates mixing dissolution and organic trapping horizons.
2. Quaternary glacio-eustacy has moved the freshwater lens vertically.
3. Local tectonics and glacio-eustatic sea-level events may overprint one another.
4. Carbonate islands can be divided into four categories based on basement/sea-level relationships:
    a. Simple Carbonate Islands,
    b. Carbonate Cover Islands,
    c. Composite Islands,
    d. Complex Islands.
5. The karst is eogenetic.

Eogenetic karst of the Carbonate Island Karst Model was defined by Vacher and Mylroie (2002, p. 183) as “the land surface evolving on, and the pore system developing in, rocks undergoing eogenetic, meteoric diagenesis.” Eogenetic carbonate rocks have not been extensively compacted or cemented and retain much of their primary depositional porosity. True island karst only develops in young carbonate rocks on coasts and small islands where the rocks are affected by sea-level variations, but have not been deeply buried. Island karst defined by the Carbonate Island Karst Model is distinctly different from karst development found on continents and the interior of larger islands, such as Puerto Rico, where karst development mimics continental settings and has been called “karst on islands” as opposed to “island karst” (Vacher & Mylroie 2002, p. 183–184).

Glacio-eustacy, tectonic uplift and subsidence cause the freshwater lens to migrate vertically within eogenetic rocks as sea-level changes, with important implications on the distribution of porosity and hydraulic conductivity in the aquifer. The four island types reflect the fundamentally different environments for the evolution of karst created by the structural and stratigraphic characteristics of the island, including the relationship between the rock units and sea-level (Fig. 4) (Jenson *et al*. 2002; Mylroie & Jenson 2002). Simple Carbonate Islands (Fig. 4a) are end members defined by observations in the Bahamas, where no non-carbonate rocks interfere with the freshwater lens and groundwater recharge is completely autogenic. Carbonate Cover Islands (Fig. 4b) introduce impermeable, non-carbonate rocks below the land surface that deflect the freshwater lens as observed in Bermuda during glacioeustatic sea-level lowstands. Composite Islands (Fig. 4c) place non-carbonate rocks at the land surface, which introduces allogenic waters into the system, while the freshwater lens is partitioned by impermeable rocks, a common occurrence in the Mariana Islands. Complex Islands (Fig. 4d) introduce the interfingering of carbonate/non-carbonate facies and faulting, which brings rocks of differing lithology into contact when they were not before, partitioning the freshwater lens as seen on Saipan (Mylroie *et al*. 2001; Jenson *et al*. 2002).

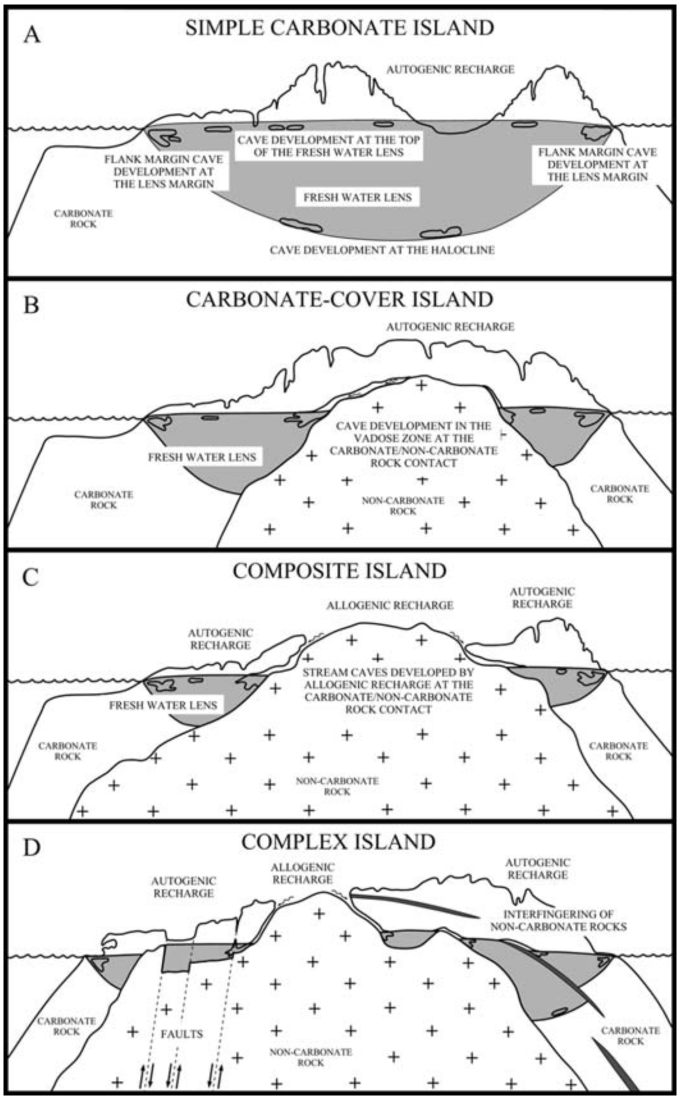


Figure 4. Carbonate Island Karst Model illustrating the 4 categories of carbonate islands that exist, based on variations in basement/sea-level relationships (adapted from Mylroie *et al*. 2001).

Karst development on Tinian

Karst development on Tinian is reported here in terms of surface and subsurface features. Surface features include epikarst, closed depressions, and freshwater discharge features. Subsurface features include three general cave types: mixing zone, fissure and contact. For a thorough description of Tinian karst development, including statistical analyses and detailed maps, the reader is directed to Stafford (2003).

Surface karst features

Epikarst occurs in all carbonate rocks on Tinian and can be observed at all elevations with morphological variations associated with coastal proximity. In areas proximal to coasts, where limestone is constantly wetted by sea-spray, karren forms extremely jagged, centimeter to meter-scale pinnacles, variously defined as phytokarst (Folk *et al*. 1973), biokarst (Viles 1988), and littoral eogenetic karren (Taboroši *et al*. 2004). The rugged coastal karren on Tinian is attributed to a polygenetic origin that includes the interaction of meteoric water with salt spray, salt weathering, dissolution by meteoric waters, and biological weathering. When joints and fractures are present, coastal epikarst develops into enlarged planar features and shallow solution pans (kamenitzas). In more inland regions, where soil is present, surface karren features become more subdued, suggesting that salt weathering and the interaction of salt spray and meteoric water is largely responsible for the unique karren forms in coastal settings, although some of the variation likely results from soil processes. Inland karren generally expresses little relief but in highly fractured regions, closely-spaced, meter-scale canyons produce a highly irregular surface (Taboroši *et al*. 2004).

Closed depressions on Tinian are localized and represent three genetic types: dissolutional, constructional, and human made and modified (Mylroie *et al*. 2001). Interpretation of closed depressions can be problematic, because specific features may be polygenetic, having been one type of depression that was subsequently modified by dissolution, tectonics, or human activity (Mylroie *et al*. 1999). Twenty closed depressions greater than ten meters in diameter were identified on Tinian: seven dissolutional, eight constructional, and five anthropogenic.

Dissolutional depressions are associated with carbonate/non-carbonate contacts where allogenic waters from ephemeral streams in small valleys have increased dissolution along the contact between carbonate bedrock and non-carbonate basement. Two such depressions exhibited small caves at the recharge sites, while another two contained ponded water. Constructional depressions were present in regions more distal to volcanic terranes and showed no evidence of associated allogenic recharge. They appear to be either primary depressions formed during original carbonate deposition, or secondary structural basins from faulting. In the Northern Lowland, a large closed depression that contains a freshwater pond approximately two meters above sea-level appears to be a primary depositional feature. On the other hand, a large closed depression in the Median Valley, where the Tinian Municipal Well is located, is bounded by faults, which suggests a tectonic origin. Anthropogenic depressions are the result of the excavation of quarries, borrow pits and landfills. Only one active quarry remains on Tinian, while several abandoned quarries may be relicts from construction projects associated with World War II.

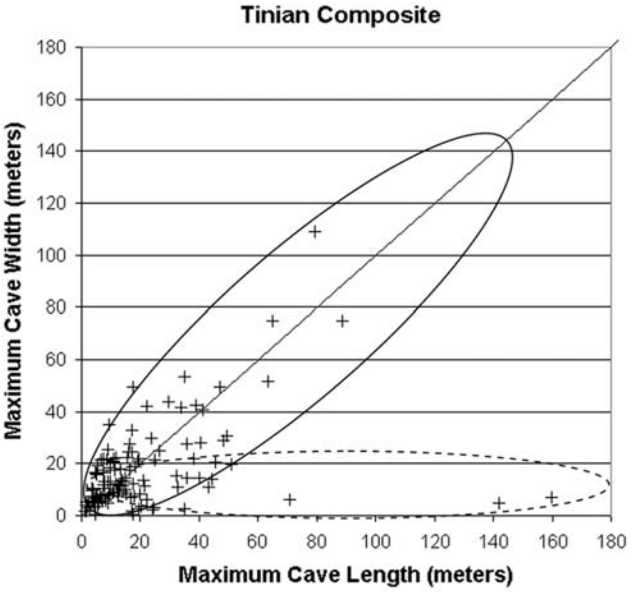


Figure 5. Plot of maximum width to length ratios for caves on Tinian. Note that that two distinct populations of caves exist. One population is approximately elliptical (circled with solid line) and one population is linear (circled with dashed line). This indicates that two distinctively different populations of cave development exist on Tinian.

Coastal discharge features identified on Tinian at low tide include seeps and springs. Seeps are diffuse discharge features that emerge through carbonate sands along beaches, whereas springs are focused discharge features that occur along bedding planes and fractures on scarped coastlines (Jenson *et al*. 1997; Mylroie *et al*. 1999, 2001). Although coastal conditions prevented a complete examination of the entire coastline, seeps were observed at three beaches on Tinian, and fourteen springs, commonly associated with fissure caves, were located along coastal scarps. Additional springs and seeps are expected to exist in coastal regions that were not accessible because of high wave energies.

Subsurface karst features

The central objective of the field study was to evaluate the occurrence, morphology, and field relationships of the island's caves with respect to structural features and other elements that control cave development. Simple analyses of length to width ratios of surveyed caves indicates that at least two dis-

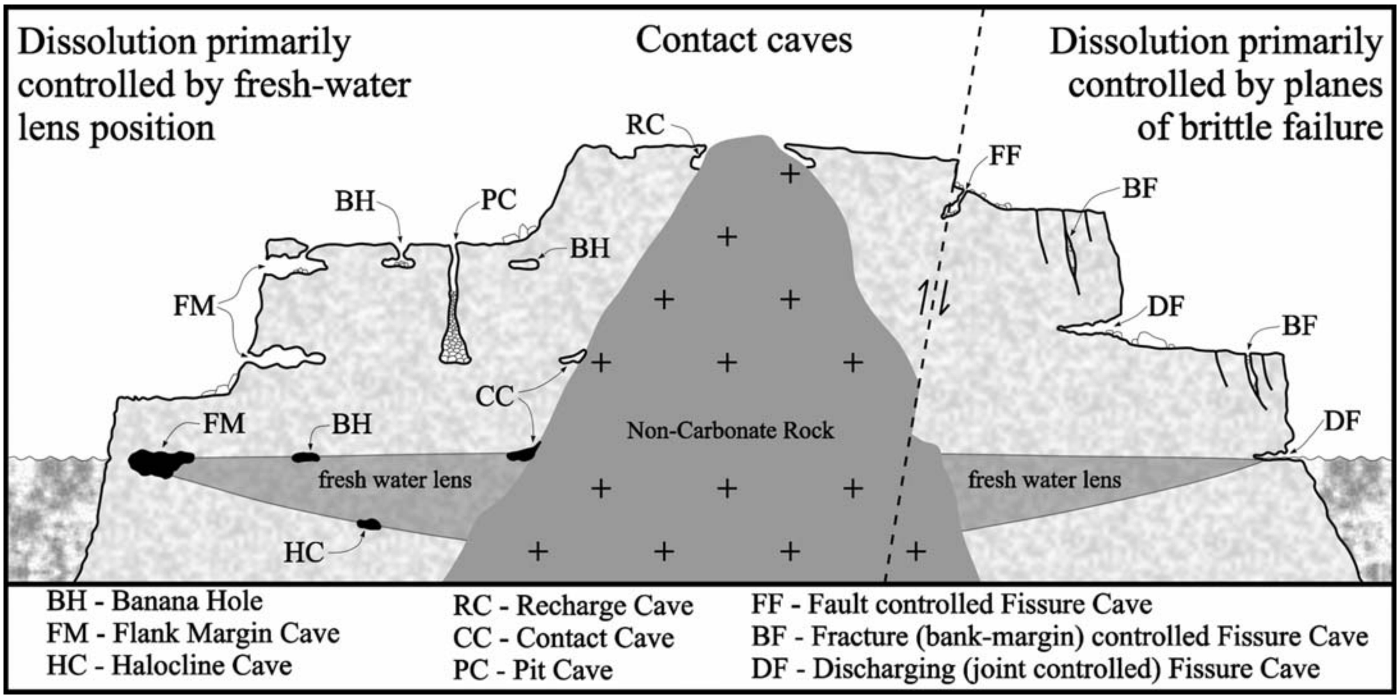


Figure 6. Schematic diagram illustrating the types of subsurface karst development on carbonate islands. Note that not all cave types occur on all carbonate islands.

Table 1. Caves surveyed on Tinian, including surveyed lengths and examples.

Cave Type	# of Caves Surveyed	Total Surveyed Length (m)	Example
Mixing Zone Caves	67	6132	
Water Table Caves	2	90	CUC Cave (Fig. 8a)
Flank Margin Caves	65	6042	Liyang Dangkolo (Fig. 8b)
Fissure Caves	13	1943	
Fault Caves	2	213	Plunder Cave (Fig. 8c)
Margin Failure Caves	6	1194	Danko's Misery (Fig. 8d)
Tension-release Caves	5	536	Cetacean Cave (Fig. 8e)
Contact Caves	2	34	
Stream Caves	2	34	Lasu Recharge Cave (Fig. 8f)

tinct populations of caves exist on Tinian of differing genetic origin (Fig. 5). Subsurface karst development on Tinian occurs as three morphologically distinct cave types (Stafford *et al.* 2002): mixing zone caves, fissure caves and contact caves (Fig. 6). Our fieldwork on Tinian resulted in an inventory of 86 caves or cave complexes (Table 1): 68 mixing zone caves, 16 fissure caves, and 2 contact caves. Based on reports from island residents, this is believed to include most of the accessible caves and adequately represents subsurface karst development on Tinian. No doubt there remain many unbreached caves and caves whose entrances are obscured by dense vegetation. It is reported that some caves were sealed with explosives or bulldozers during and after the battle to secure the island in 1944. Cave morphologies suggest that development of each cave type is controlled by variations in water chemistry, geologic structure, and lithology.

Mixing zone caves are the most common cave type on Tinian (Table 1), as on other carbonate islands of the Marianas. They are a type of hypogenic cave (Palmer 1991) that forms where waters of different original chemistry mix at the vadose/phreatic contact, freshwater/saltwater contact, or the margin of the freshwater lens, giving rise to three respective

Figure 7. Liyang Dangkolo is an archetypical flank margin cave in the Marianas. Note the larger chamber in the foreground that divides into smaller passages in the background, which is typical of mixing zone dissolution on carbonate islands.

subcategories: water table caves, halocline caves, and flank margin caves (Mylroie & Carew 1988; Mylroie *et al*. 1995a,b). Mixing zone caves form interconnected, globular chambers (Fig. 7). They are hydrologically interconnected and provide reliable indicators of former relative sea level because of their association with the freshwater lens position (Carew & Mylroie 1995; Mylroie *et al*. 1995a,b).

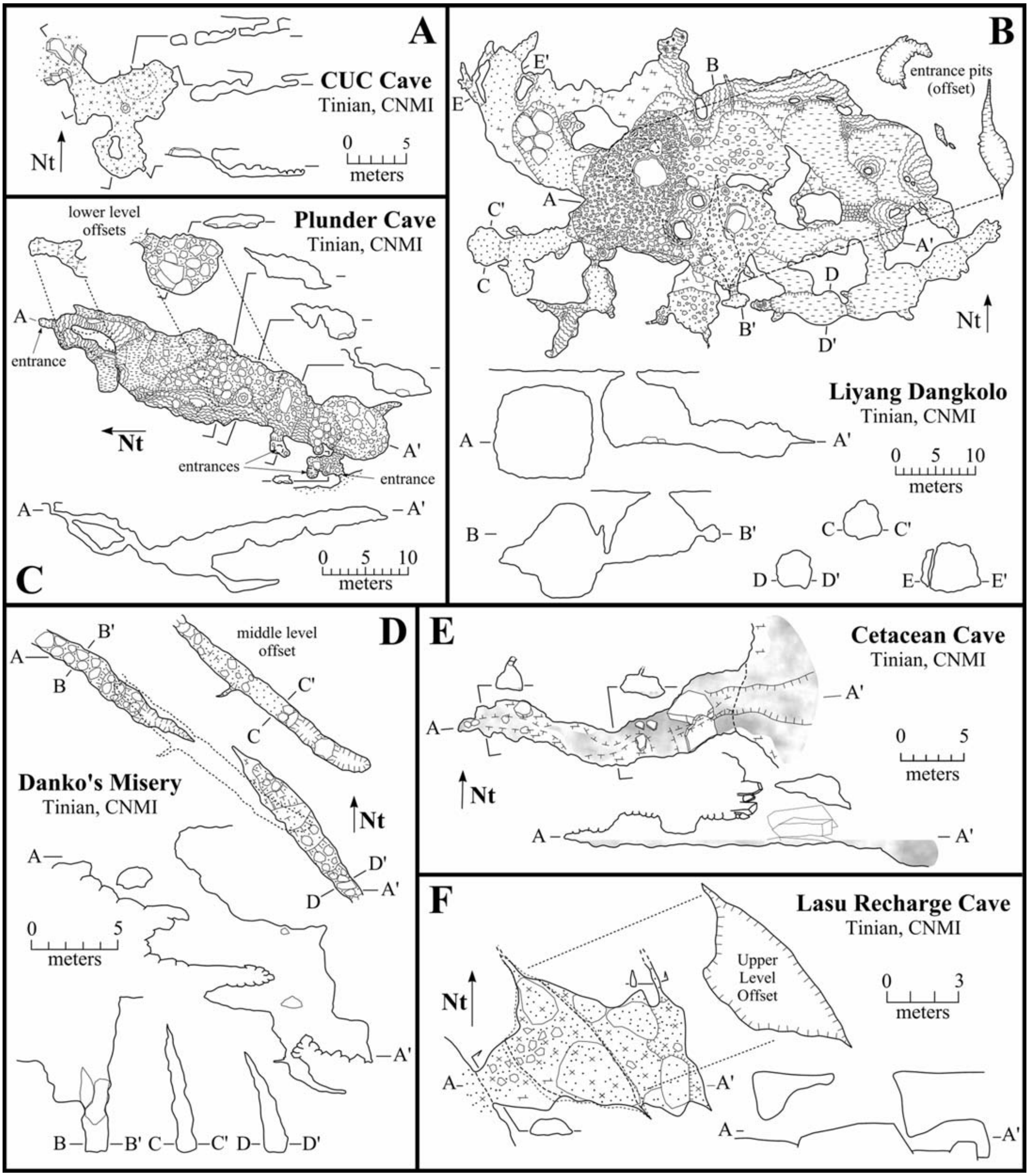
Small lenticular to oblate chambers, termed water table and halocline caves, have been reported to develop at the top and bottom of the lens (Mylroie & Carew 1995). Halocline caves form at the bottom of the lens where speleogenesis is enhanced by the decay of organics trapped at the water-density boundary and by the mixing of fresh and saline groundwater. Water table caves, commonly referred to as banana holes when breached at the land surface (Harris *et al*. 1995), are the result of increased dissolution induced by the mixing of vadose and phreatic waters, and the decay of organics trapped at the surface of the freshwater lens (Mylroie & Carew 1988). Small, lenticular features on Tinian (Fig. 8a) are interpreted as water table caves, because caves formed at the top of the modern or paleo-freshwater lens are more likely to be expressed by collapse at the land surface. However, if surface denudation completely removes the shallowest water table caves, then it is difficult to determine whether the caves formed at the top or bottom of the lens because multiple horizons of halocline and water table caves result from sea level change. Water table caves are rare on Tinian, but common on some carbonate islands. In the Bahamas, where the majority of the land surface is less than 10 m above sea level, only minor surface denudation is required to breach a water table cave (Harris *et al*. 1995); however, carbonate rocks crop out at 187 m on the Southeastern Ridge of Tinian, which could require significant denudation to breach caves formed at the top of the modern and other paleo-freshwater lens positions.

Figure. 8 (next page). Examples of the six morphological cave types observed on Tinian A) CUC Cave is a small banana hole feature on Tinian. Note that the cave map shows a globular central chamber that is generally less than 1 m tall. B) Liyang Dangkolo is a large flank margin cave. Note the large central chamber with smaller, interconnected passages extending from it. C) Plunder Cave is a fissure cave developed along a fault. Note the linear nature of the cave, which has been horizontally widened from mixing dissolution from intercepting the freshwater lens. D) Danko's Misery is a fissure cave developed parallel to a scarp apparently along a margin failure. Note that the cave is extremely linear and descends near vertically with several levels separated by breakdown floors. Larger features associated with scarp and margin failures have similar morphologies but reach greater depths and extend over larger distances. E) Cetacean Cave is a fissure cave developed perpendicular to the coastline at sea level apparently along a tension-release structure. Note the linear nature of the cave and horizontal widening from the mixing of fresh and saltwater as a result of freshwater discharge from the inland portion of the cave. F) Lasu Recharge Cave is a contact cave located in a large, dissolutional, closed depression at a non-carbonate/carbonate contact. Allogenic water enters the cave from the west, traverses a short distance through the cave and descends through a small fracture to the north on the eastern edge of the cave. Note that the majority of the cave has no ceiling due to collapse.

Flank margin caves are the most common and largest caves on Tinian (Table 1). They are reported to form at the distal margin of the freshwater lens where the mixing of fresh and saline waters and organic trapping horizons are in close proximity as the freshwater lens thins (Mylroie & Carew 1995). Flank margin caves tend to be globular with large, interconnected chambers. Small flank margin caves on Tinian consist of a single main chamber with several small alcoves radiating outward. Larger caves have more complicated morphologies and more extensive interconnected passages (Fig. 8b). These caves are commonly found along cliffs and scarps at consistent horizons (Fig. 9), because their position at the margin of the freshwater lens makes them highly susceptible to breaching from cliff retreat and erosion (Mylroie *et al*. 1999).

Fissure caves are the second most common cave type on Tinian (Table 1). They are linear features that appear to develop along faults, fractures, and joints (Stafford *et al*. 2003b). The planar surfaces created by brittle deformation provide paths for increased flow of groundwater, which results in preferential dissolution of vadose fast-flow routes that can locally distort the freshwater lens morphology (Aby 1994; Mylroie *et al*. 1995c). On Tinian, we have identified three distinctly different fissure caves, each associated with a different type of brittle deformation: faults, margin failures, and tension-release fractures.

Fissure caves associated with faults form linear features that descend at moderate slopes and show horizontal widening,



most likely from collapse of the hanging wall (Fig. 8c). Although no direct evidence of offsetting is visible in these caves, possibly because of extensive breakdown and calcite deposits covering the walls and ceilings, they do align closely with regional fault orientations reported by Doan and co-workers (1960).

Fissure caves that develop parallel to scarps and coastlines form laterally extensive features that descend near-vertically with relatively narrow widths (Fig. 10). We interpret these as associated with margin failures. They form the deepest caves on Tinian, can intersect the fresh-water lens, and contain

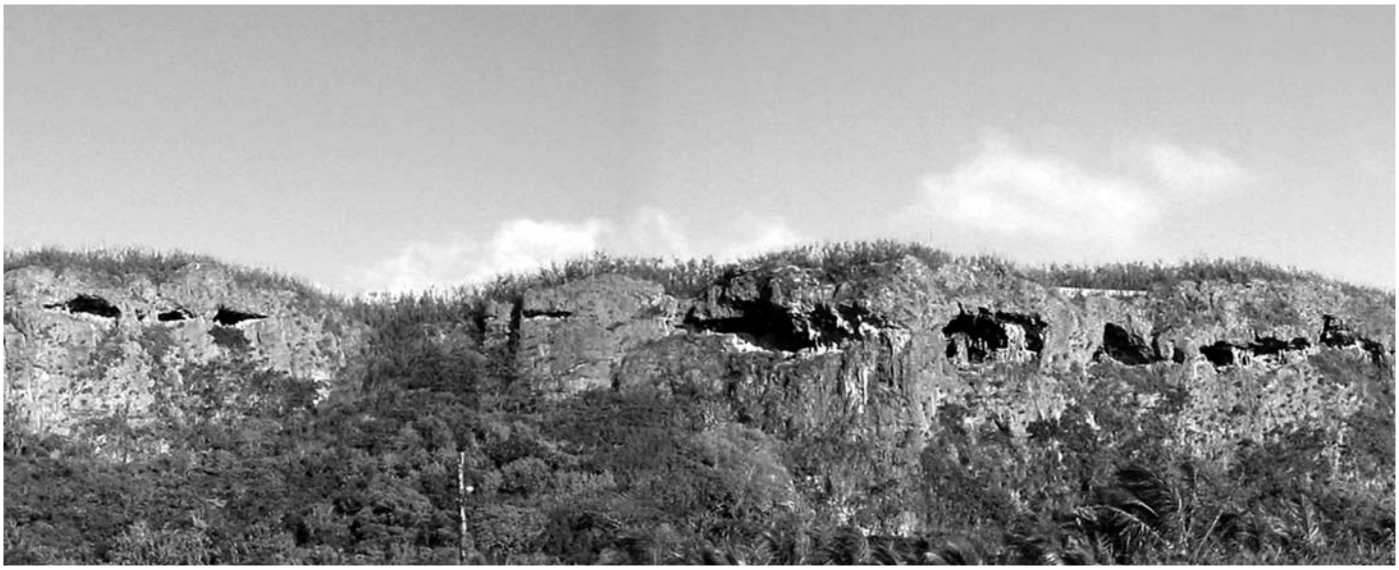


Figure 9. Suicide Cliffs on Tinian is an excellent example of mixing zone cave development along consistent horizons defined by previous sea-level stillstands. Note that most entrances are approximately 2.5 m tall.

extensive breakdown, which forms the majority of the floor and ceiling when present (Fig. 8d). Large portions of the caves are often unroofed but show evidence of being closed for significant periods in the past, based on the presence of calcite speleothem deposits on the walls.

Fissure caves oriented perpendicular and sub-perpendicular to scarps and coastlines (hence near-perpendicular to margin failures) are interpreted to be associated with tension-release structures. These features can extend inland for over 30 m with distinct joints or fractures located along the central axis of the ceilings and floors (Fig. 8e). When found at sea-level, they commonly discharge freshwater from their inland portions and show evidence of horizontal widening from the mixing of fresh and saline water. When found inland along scarps, they frequently show morphological evidence of past freshwater discharge and are interpreted as paleo-discharge features.

Contact caves, often referred to as stream caves, form at the carbonate/non-carbonate contact where allogenic water descending off surface igneous outcrops is funnelled into the subsurface. These features are generally associated with dissolutional closed depressions and are fed by perennial streams (Mylroie *et al*. 2001). Only two small contact caves were identified (Table 1). Mount Lasu Recharge Cave (Fig. 8f) shows evidence of rapid recharge with significant detritus accumulation in the vicinity of the cave, but little sediment coating the cave walls. Allogenic water enters the cave and after a short distance descends through a fracture less than ten centimeters wide. Although these features are rare on Tinian because of limited volcanic exposures, they have a significant role in subsurface recharge of allogenic waters.

STATISTICAL ANALYSES OF CAVE DEVELOPMENT

Previous studies of island karst suggest that mixing dissolution is the primary origin for cave development in eogenetic rocks on carbonate islands. In continental settings, variations in geologic structure and lithology provide primary controls for dissolution in diagenetically mature rocks (White 1988; Palmer 1991). Barlow and Ogden (1982) and Nelson (1988) showed that in continental settings cave development is significantly similar to regional brittle failure features when Kolmogorov-Smirnov statistical comparisons of cave passage orientations and regional geologic structure were evaluated. A similar study was conducted on Tinian (Stafford 2003) to investigate the possible relationships between cave development, geologic structure, and freshwater lens position.

Non-parametric, statistical comparisons for populations of orientation data from mixing zone caves and fissure caves were evaluated with respect to orientations for structural, coastline and scarp orientations (Stafford 2003). Populations of orientation data were evaluated using Kolmogorov-Smirnov statistical analyses because they are not normally distributed and because non-parametric analysis enable the comparison of two populations of data that contain large differences in the number of data samples within individual populations. Biases can be introduced into statistical comparisons based on the origin of data; therefore, orientation data was length-weighted into two length classes when available in order to reduce the amount of error introduced by using only one sample set for each population of data. Statistical comparisons were only considered to be similar if they showed a high degree of similarity amongst all length classes evaluated ($p < 0.01$) (i.e., 99% confidence). The use of non-parametric statistical analyses does not prove that the two populations of data are the same, but instead can only be used to show that they are not from dif-

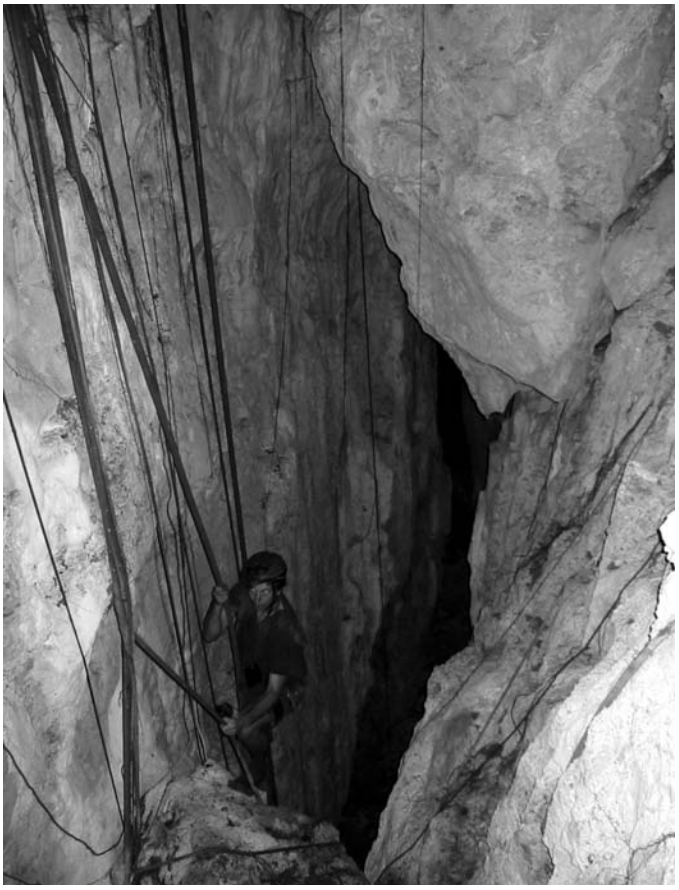


Figure 10. Typical fissure cave passage associated with scarp and margin failures. Note that the cave descends near vertically and has a floor and ceiling composed primarily of breakdown.

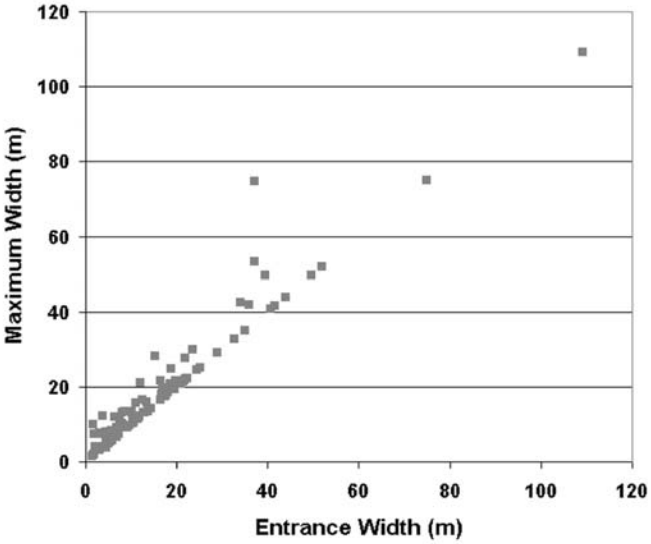


Figure 11. Diagram showing the relationship between mixing zone cave entrance width and maximum width. Note that a large portion of the caves plot with a ratio of one, indicating that the entrance width and the maximum width are the same because of significant scarp retreat.

ferent populations. If the two populations of data being tested show similarity and are not from different populations then it is inferred that they represent the same population.

Structural orientations for faults were measured from the unpublished geologic map of Tinian (Doan *et al*. 1960) and length-weighted into 50 and 100 m segments to apply greater significance to larger features, while joints (Doan *et al*. 1960) and smaller fractures of indeterminate length measured in the field were only measured for orientation (Table 2). Coastline and scarp orientations were measured from a digital elevation model of Tinian with a 10 m cell size (United States Department of the Interior Geological Survey 2001a,b,c,d,e) and length-weighted into 50 and 100 m segments (Table 2), similar to fault orientation measurements. In order to statistically evaluate cave development, individual cave passage orientations from the two primary cave types (Table 1), whose origin was inferred from morphology (mixing zone caves and fissure caves), were measured from surveyed features and length-weighted into 5 and 10 m segments to apply greater significance to larger passages (Table 3). Contact caves were not evaluated because only two features were identified in the survey area. Statistical evaluations were performed at the island scale, physiographic province scale and at small-scale sites (i.e., 1 km^2 sites) to determine if similarities existed between cave development and differing dissolutional controls at local or regional scales.

Statistical comparisons showed a high degree of similarity for orientations of cave development with structural (i.e., faults, fractures and joints) and geographic features (i.e., scarps and coastlines) at the island and physiographic province scales (Table 4). This high degree of similarity is likely a result of the complex depositional and tectonic regime of the Marianas, which complicates elimination of variables not significant in cave development. At the island and province scales, both coastline and scarp orientations as well as brittle failure features exhibited too large a range in orientations to accurately compare them with orientations of cave development. Distinct similarities were found between populations of orientations at the small-scale sites, however (Table 4). Within the small-scale sites, mixing zone cave orientations were found to be significantly similar to coastline and scarp orientations, consistent with control by freshwater lens position; however, brittle failure appears to significantly influence mixing zone cave development by intercepting diffuse lens flow. Fissure cave orientations showed significant similarity to brittle failure orientations including faults, margin failures and tension release structures at the small-scale sites, but did not show significant similarities with coastline and scarp orientations except where margin failures were parallel to scarps.

These results are consistent with the hypothesis that fissure cave development is controlled by brittle deformation, while mixing zone cave development is controlled by the position of the freshwater lens, but influenced by regional brittle deforma-

Table 2. Number of orientation measurements of geologic and geomorphic features used in statistical analyses. Fault, scarp and coastline orientations were subdivided into 50 m and 100 m segments, while fractures with limited vertical extent were not subdivided.

Region	faults[a] (50 m)	faults[a] (100 m)	fractures[a,b] …	scarps[c] (50 m)	scarps[c] (100 m)	coasts[c] (50 m)	coasts[c] (100 m)
Island							
Tinian	3322	1661	457	1264	645	939	501
Province							
Northern Lowland	324	162	104	0	0	206	113
Central Plateau	944	472	141	335	169	250	134
North-Central Highland	394	197	0	150	79	0	0
Median Valley	686	309	131	56	29	169	94
Southeastern Ridge	618	309	83	723	368	320	160
Small-Scale Sites							
Limestone Forest	53	29	40	32	20	24	12
Unai Dangkolo	26	11	44	0	0	22	9
Puntan Diablo	26	11	18	27	15	33	16

[a] Source: Doan *et al*. 1960

[b] Source: Stafford 2003

[c] Source: United States Department of the Interior Geological Survey 2001a,b,c,d,e

Table 3. Number of orientation measurements of cave passages (composite, fissure, and mixing zone), with orientations subdivided into 5 m and 10 m increments (Stafford 2003).

Region	composite (5 m)	composite (10 m)	fissure (5 m)	fissure (10 m)	mixing zone (5 m)	mixing zone (10 m)
Island						
Tinian	1277	614	297	135	980	480
Province						
Northern Lowland	13	11	2	2	11	9
Central Plateau	326	134	24	12	302	122
North-Central Highland	30	8	0	0	30	9
Median Valley	524	256	100	44	424	212
Southeastern Ridge	384	205	171	77	213	128
Small-Scale Sites						
Limestone Forest	91	34	68	24	23	10
Unai Dangkolo	263	134	46	23	217	111
Puntan Diablo	98	54	13	7	85	47

Note: Low sample populations (i.e., n<6) were not evaluated because the sample size was too small for Kolmogrov-Smirnov statistical analyses. For a complete list of all orientation measurements see Stafford 2003.

tion. Therefore, statistical analyses of cave orientations support genetic interpretations of cave morphology (Stafford 2003).

Fresh-water lens migration

Distinct horizons of mixing zone caves throughout Tinian reflect previous freshwater lens positions related to relative sea-level positions (Fig. 9). Most mixing zone caves on Tinian are small compared to the large flank margin caves seen on other carbonate islands, such as Isla de Mona (Frank *et al*. 1998). The smaller caves reflect shorter periods of stable sea-level position, limiting the development of larger dissolutional voids. The short development time available for flank margin cave formation resulted in small, globular chambers that commonly did not grow large enough to intersect (Fig. 9) and form the type of complex flank margin caves found in other carbonate island settings.

Figure 11 shows that the vast majority of the breached

Table 4. Simplified non-parametric data matrix of statistical analyses.

Region	Fissure Caves	Mixing Zone Caves
Island-Scale		
Brittle Failure Orientations	similar	similar
Scarp and Cliff Orientations	similar	similar
Coastline Orientations	similar	similar
Province-Scale		
Brittle Failure Orientations	similar	dissimilar
Scarp and Cliff Orientations	dissimilar	similar
Coastline Orientations	similar	similar
Small-Scale Sites		
Brittle Failure Orientations	similar	dissimilar
Scarp and Cliff Orientations	dissimilar	similar
Coastline Orientations	dissimilar	similar

Note: Comparisons between cave orientations and brittle failure, scarp and coastline orientations were only considered similar if $p < 0.01$. For detailed results of statistical analyses, see Stafford 2003.

flank margin caves have entrance widths that are approximately equal to their maximum widths, indicating that the caves have been eroded at least halfway. Early erosion nicks into the globular cave chamber such that the entrance is much smaller than the maximum width of the cave. As erosion proceeds to the halfway point, and beyond, the entrance width will be the maximum width of the cave. If crystalline stalagmites were collected from these caves and U/Th dates could be obtained from them, it would be possible to establish boundary conditions for rates of cliff retreat and surface denudation. Because mixing zone caves form in the phreatic zone at sea level, they must be uplifted in order for speleothems to develop in them. Therefore, future research using speleothem dates from breached flank margin caves at differing terrace levels, which exhibit differing degrees of breaching, can be used to predict rates of cliff retreat because flank margin caves are generally ellipitical and any caves that exhibit an entrance width equal to the maximum width were originally at least 50% larger.

The effects of glacio-eustacy coupled with tectonic uplift of the Mariana Arc account for the absence of large mixing zone caves, where continual uplift has reduced the duration of sea-level stillstands. Although differential rates in uplift exist across Tinian and individual mixing caves are smaller than on some other carbonate islands, a North-Central Highland transect (Fig. 12) confirms the presence of at least four sea-level stillstands (three paleo horizons and the current horizon) that reflect freshwater lens migration.

CONCLUSIONS

Tinian displays well-developed island karst that reflects a polygenetic origin, both in surface and subsurface development, with multiple horizons of development associated with previous sea-level stillstands. Karst development is largely controlled by freshwater/saltwater interaction, but geologic structure and lithology greatly influence and often control the location and orientation of cave development. Genetic interpretations of morphology are supported by statistical analyses; however, at specific sites, mixing zone caves are influenced by brittle deformation and fissure caves show horizontal widening when intersecting the freshwater lens.

High-angle faults separate Tinian into distinct physiographic provinces, indicating that individual categories of islands in Carbonate Island Karst Model cannot be easily applied to the entire island. Significant fresh-water discharge along faults separating the Northern Lowland and Southeastern Ridge from the three central provinces (Central Plateau, North-Central Highland and Median Valley) suggest that three largely separate hydrologic regions exist on Tinian. Therefore, the three regions should be treated separately with respect to the model, as each region best fits a specific category: the Northern Lowland acts as a Simple Carbonate Island, the Southeastern Ridge acts as a Carbonate Cover Island, and the three central provinces act together as a Composite Island. Tinian provides an excellent example of the functionality of the Carbonate Island Karst Model but it demonstrates that the model often must be applied to island regions and not to the entire island.

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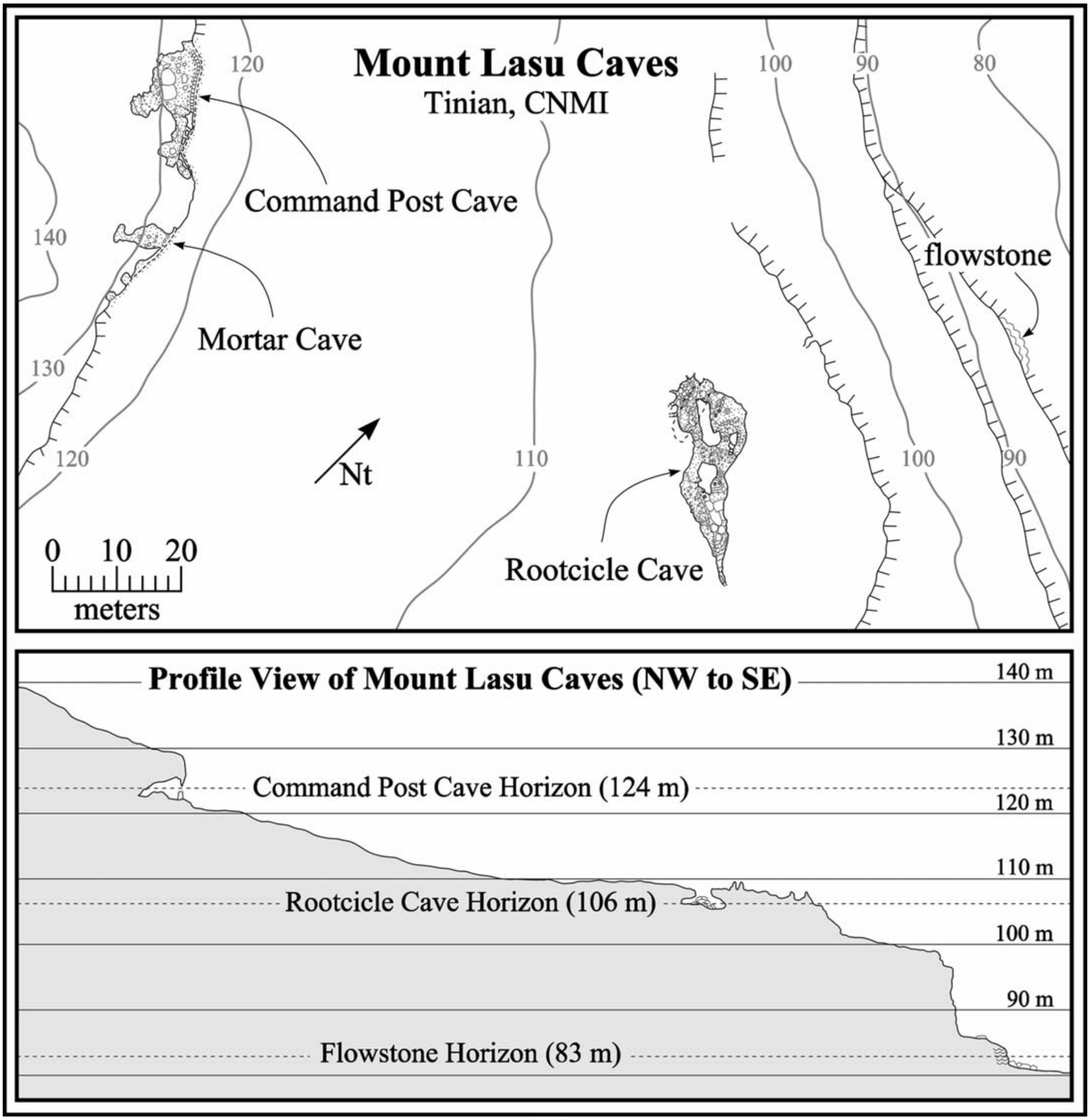

Figure 12. Overland transect of the Mount Lasu Caves provides evidence of three paleo freshwater lens positions, as indicated by two horizons of cave development and a third horizon indicated by speleothems present on a lower scarp.

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REFERENCES

Aby, S.B., 1994, Relation of bank-margin fractures to sea level change, Exuma Islands, Bahamas: Geology, v. 22, p. 1063–1066.

Barlow, C.A., & Ogden, A.E., 1982, A statistical comparison of joint, straight cave segment, and photo-lineament orientations: NSS Bulletin, v. 44, p. 107–110.

Burke, H.W., 1953, The Petrography of the Mariana Limestone, Tinian, Mariana Islands [PhD Dissertation]: Stanford University, 111 p.

Carew, J.L., & Mylroie, J.E., 1995, Quaternary tectonic stability of the Bahamian Archipelago: evidence from fossil coral reefs and flank margin caves: Quaternary Science Reviews, v. 14, p. 145–153.

Cloud, P.E., Jr., Schmidt, R.G., & Burke, H.W., 1956, Geology of Saipan, Mariana Islands, Part 1, General Geology, 280-A: U.S. Geological Survey Professional Paper, U.S. Government Printing Office, Washington, D.C., 126 p.

Dickinson, W.R., 2000, Hydro-isostatic and tectonic in influences on emergent Holocene paleoshorelines in the Mariana Islands, Western Pacific Ocean: Journal of Coastal Research, v. 16, no. 3, p. 735–746.

Doan, D.B., Burke, H.W., May, H.G., Stensland, C.H., & Blumenstock, D.I., 1960, Military Geology of Tinian, Mariana Islands: Chief of Engineers, U.S. Army, 149 p.

Frank, E.F., Mylroie, J.E., Troester, J., Alexander, E.C., & Carew, J.L., 1998, Karst development and speleologenesis, Isla de Mona, Puerto Rico: Journal of Cave and Karst Studies, v. 60, no. 2, p. 73–83.

Folk, R.L., Roberts, H.H., & Moore, C.C., 1973, Black phytokarst from Hell, Cayman Islands, British West Indies: Geological Society of America Bulletin, v. 84, p. 2351–2360.

Gingerich, S.B., & Yeatts, D.S., 2000, Ground-Water Resources of Tinian, Commonwealth of the Northern Mariana Islands, Water-resources Investigations Report 00-4068: U.S. Department of the Interior, 2 sheets.

Harris, J.F., Mylroie, J.E., & Carew, J.L., 1995, Banana holes: Unique karst features of the Bahamas: Carbonates and Evaporites, v. 10, no. 2, p. 215–224.

Jenson, J.W., Jocson, J.M.U., and Siegrist, H.G., 1997, Groundwater discharge styles from an uplifted Pleistocene island karst aquifer, Guam, Mariana Islands, *in* Beck, B.F., & Stephenson, J.B. (eds.), The Engineering Geology of Karst Terraines: Balkema, Springfield, Missouri. p. 27–32.

Jenson, J.W., Mylroie, J.E., Mylroie, J.R., & Wexel, C., 2002, Revisiting the carbonate island karst model: Geological Society of America Abstracts with Program, v. 34, no. 6, p. 226.

Mink, J.F., & Vacher, H.L., 1997, Hydrogeology of northern Guam, *in* Vacher, H.L., & Quinn, T. (eds.), Geology and Hydrogeology of Carbonate Islands, Developments in Sedimentology 54: Elsevier Science, p. 743–761.

Mylroie, J. E., & Carew, J. L., 1988, Solution conduits as indicators of late Quaternary sea level position: Quaternary Science Reviews, v. 7, p. 55–64.

Mylroie, J.E., & Carew, J.L., 1995, Karst development on carbonate islands, *in* Budd, D.A., Harris, P.M., & Staller, A. eds., Unconformities and Porosity in Carbonate Strata: American Association of Petroleum Geologists, p. 55–76.

Mylroie, J.E., Carew, J.L., & Vacher, H.L., 1995a, Karst development in the Bahamas and Bermuda, *in*: Curran, H.A., & White, B., eds., Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda: p. 251–267.

Mylroie, J.E., Panuska, B.C., Carew, J.L., Frank, E., Taggart, B.E., Troester, J.W., & Carrasquillo, R., 1995b, Development of flank margin caves on San Salvador Island, Bahamas and Isla de Mona, Puerto Rico, *in* Boardman, M., ed., Proceedings of the Seventh Symposium on the Geology of the Bahamas: Bahamian Field Station, San Salvador, Bahamas, p. 49–81.

Mylroie, J.E., Carew, J.L., & Moore, A.I., 1995c, Blue hole: Definition and genesis: Carbonates and Evaporites, v. 10, no. 2, p. 225–233.

Mylroie, J.E., Jenson, J.W., Jocson, J.M.U., & Lander, M., 1999, Karst Geology and Hydrology of Guam: A Preliminary Report, Technical Report #89: Water and Environmental Institute of the Western Pacific, University of Guam, Mangilao.

Mylroie, J.E., & Vacher, H.L., 1999, A conceptual view of carbonate island karst, *in* Palmer, A.N., Palmer, M.V., & Sasowsky, I.D., eds., Karst Modeling, Karst Waters Institute Special Publication 5: Karst Waters Institute, Inc., Charles Town, WV, p. 48–57.

Mylroie, J.E., & Jenson, J.W., 2001, The carbonate island karst model applied to Guam: Theoretical and Applied Karstology, v. 13-14, p. 51–56.

Mylroie, J.E., Jenson, J.W., Taboroši, D., Jocson, J.M.U., Vann, D., & Wexel, C., 2001, Karst features of Guam in terms of a general model of carbonate island karst: Journal of Cave and Karst Studies, v. 63, no. 1, p. 9–22.

Mylroie, J.E., & Jenson, J.W., 2002, Karst flow systems in young carbonate islands, *in* Martin, J.B., Wicks, C.M., & Sasowsky, I.D., eds., Hydrogeology and biology of post-Paleozoic carbonate aquifers, Karst Waters Institute Special Publication Number 7: Karst Waters Institute, Inc., Charles Town, WV, p. 107–110.

Nelson, J.W., 1988, Structural and Geomorphic Controls of the Karst Hydrogeology of Franklin County, Alabama [MS Thesis]: Mississippi State University, MS, 165 p.

Palmer, A.N., 1991, Origin and morphology of limestone caves: Geological Society of America Bulletin, v. 103, p. 1–21.

Raeisi, E., & Mylroie, J.E., 1995, Hydrodynamic behavior of caves formed in the fresh-water lens of carbonate islands: Carbonates and Evaporites, v. 10, no. 2, p. 207–214

Siegrest, H.G., 1988, Miocene reef carbonates of the Mariana Islands: American Association of Petroleum Geologists Bulletin, v. 72, no. 2, p. 248.

Stafford, K.W., 2003, Structural Controls on Megaporosity in Eogenetic Carbonate Rocks: Tinian, CNMI [MS Thesis]: Mississippi State University, MS, 340 p.

Stafford, K.W., Mylroie, J.E., & Jenson, J.W., 2002, Karst Geology and Hydrology of Tinian and Rota (Luta), CNMI: Technical Report No. 96: Water and Environmental Institute of the Western Pacific, University of Guam, Mangilao, 31 p.

Stafford, K.W., Mylroie, J.E., Mylroie, J.R., & Jenson, J.W., 2003a, Tinian, CNMI: A carbonate island karst model evaluation: Geological Society of America Abstracts and Programs, v. 35, no. 1, p. 3.

Stafford, K.W., Mylroie, J.E., Taboroši, D., Mylroie, J.R., Keel, T.M., & Jenson, J. W., 2003b, Structurally controlled eogenetic karst: Mariana Islands: Geological Society of American abstracts with programs, v. 4, no. 7, p. 452.

Taboroši, D., Jenson, J.W., & Mylroie, J.E., 2004, Karren features in island karst: Guam, Mariana Islands: Zeitschrift fur Geomorphologie.

Tracey, J.I., Jr., Schlanger, S.O., Stark, J.T., Doan, D.B., & May, H.G., 1964, General Geology of Guam, 403-A: U.S. Geological Survey Professional Paper, U.S. Government Printing Office, Washington, D.C., 104 p.

United States Department of the Interior Geological Survey, 2001a, 1697184.DEM.SDTS.TAR.GZ: National Mapping program of the U.S. Geological Survey, ftp://sdts.er.usgs.gov/pub/sdts/datasets/raster/dem/.

United States Department of the Interior Geological Survey, 2001b, 1697335.DEM.SDTS.TAR.GZ: National Mapping program of the U.S. Geological Survey, ftp://sdts.er.usgs.gov/pub/sdts/datasets/raster/dem/.

United States Department of the Interior Geological Survey, 2001c, 1697336.DEM.SDTS.TAR.GZ: National Mapping program of the U.S. Geological Survey, ftp://sdts.er.usgs.gov/pub/sdts/datasets/raster/dem/.

United States Department of the Interior Geological Survey, 2001d, 1697337.DEM.SDTS.TAR.GZ: National Mapping program of the U.S. Geological Survey, ftp://sdts.er.usgs.gov/pub/sdts/datasets/raster/dem/.

United States Department of the Interior Geological Survey, 2001e, 1697338.DEM.SDTS.TAR.GZ: National Mapping program of the U.S. Geological Survey, ftp://sdts.er.usgs.gov/pub/sdts/datasets/raster/dem/.

Vacher, H.L., & Mylroie, J.E., 2002, Eogenetic karst from the perspective of an equivalent porous medium: Carbonates and Evaporites, v. 17, no. 2, p. 182–196.

Viles, H.A., 1988, Biogeomorphology: Basil Blackwell, Oxford, United Kingdom.

White, W.B., 1988, Geomorphology and Hydrology of Karst Terrains: Oxford University Press, New York, 464 p.