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DISSOLUTION CONTROLS RELATED TO THE CARBONATE ISLAND KARST MODEL ON TECTONICALLY ACTIVE CARBONATE ISLANDS: TINIAN AND AGUIJAN, COMMONWEALTH OF THE NORTHERN MARIANA ISLANDS

Kevin W. Stafford
Department of Earth and Environmental Science
New Mexico Institute of Mining and Technology
Socorro, NM 87801

John E. Mylroie and Joan R. Mylroie
Department of Geosciences
Mississippi State University
Mississippi State, MS 39762

John W. Jenson
Water and Environmental Institute of the Western Pacific
University of Guam
Mangilao, Guam 96923

Danko Taboroši
School of Environmental Earth Science
Hokkaido University
Sapporo, Japan 060-0810

ABSTRACT

Tinian and Aguijan, located along the Mariana Arc in the western Pacific Ocean, are composed of Eocene volcanic edifices mantled by younger algal and coralline limestones. Non-carbonate rocks crop out on Tinian, but not on Aguijan. Eogenetic carbonate rocks, such as those in the study area, develop island karst as predicted by the Carbonate Island Karst Model, including surface features (*i.e.* epikarst, closed depressions, and discharge features) and subsurface features (*i.e.* caves). Fieldwork and statistical analyses of cave orientations was conducted in order to evaluate controls on dissolution on Tinian and Aguijan with respect to the Carbonate Island Karst Model.

Epikarst development near coastlines produces jagged, irregular features, while inland karren are generally more subdued. Closed depressions are dissolutional at non-carbonate/carbonate contacts, while similar features distal to volcanic terrains are anthropogenic or constructional (depositional). Discharge features are present along coastlines in the form of seeps and springs.

Three morphologically distinct cave classes occur: contact, mixing zone, and fissure. Focused allogenic recharge forms contact caves at non-carbonate/carbonate contacts. Hypogenic mixing zone caves form interconnected, globular chambers in relation to the fresh-water lens position. Linear, fissure caves develop along faults, margin failures and associated tension-release structures (*e.g.* joints). Non-parametric statistical comparisons of cave orientations do not show significant differences between mixing zone caves and fresh-water lens position nor between fissure caves and brittle failure features, supporting interpretations based on morphology.

Tinian is divided into three hydrologically separate regions that fit different Carbonate Island Karst Model categories. The northern, central and southern regions of the island respectively

correspond to Simple, Composite and Carbonate-Cover island types. Based on its karst features, Aguijan best fits the Carbonate-Cover Island category. Mixing zone dissolution dominates karst formation on both islands, but lithology and brittle failure provide significant controls on the process.

INTRODUCTION

Tinian and Aguijan are located in the western Pacific Ocean (Figure 1), approximately 3000 kilometers east of the Asian landmass. They were formed along a volcanic arc (Mariana Arc) created by Pacific Plate subduction to the west under the Philippine Plate. With the exception of Guam, the southernmost island, the Mariana Islands are governed by the Commonwealth of the Northern Mariana Islands (CNMI). Guam is a politically separate U. S. territory. Of the 17 islands of the Marianas, only the southern six (Guam, Rota, Aguijan, Tinian, Saipan, and Farallon de Medanilla) have carbonate rocks mantling the volcanic basement rocks, while the northern islands remain volcanically active (Cloud et al., 1956). Currently, Tinian has a population of approximately 2000 people, while Aguijan is uninhabited (Bormann, 1992).

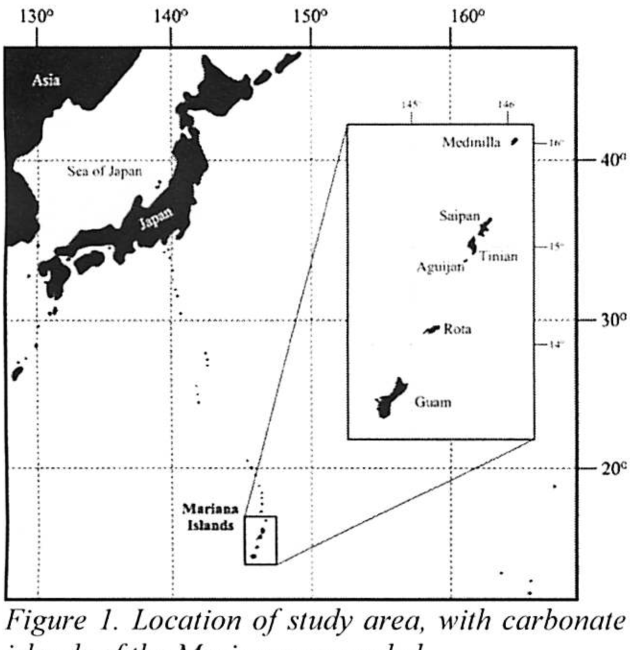

Figure 1. Location of study area, with carbonate islands of the Marianas expanded.

Despite that fact that the majority of the freshwater consumed on Tinian is pumped from shallow wells in the karst aquifer, there has been little past research has focusing on the hydrology and geology of Tinian and Aguijan,. The work of Doan et al. (1960) and Tayama (1936) remain the most detailed geologic surveys of Tinian and Aguijan, respectively. Recent work on Tinian and Aguijan has been limited to investigations of the freshwater lens morphology near Tinian's municipal wells (Gingerich and Yeatts, 2000), ecological and archeological studies (Butler, 1992) and current karst studies (Stafford et al., 2005, Stafford, 2003; Stafford et al., 2002). This paper is the first report that describes both Tinian and Aguijan with respect to controls on dissolution and the Carbonate Island Karst Model.

STUDY AREA

Tinian is located at 15.01° N latitude. It has a surface area of 102 km^2 and a maximum elevation of 187 m, while Aguijan is a smaller island located approximately 9 km southwest of Tinian (Figure 1), with a surface area of 7.2 km^2 and a maximum elevation of 157 m. Tinian is an Eocene volcanic edifice mantled by Miocene and Plio-Pliestocene coralliferous and algal limestone facies and Holocene raised beach and reef deposits (Figure 2) (Doan et al., 1960). Although, no detailed geologic map exists for Aguijan, its close proximity and similar geomorphology to Tinian suggest a similar geologic history. Island vegetation is characterized by dense woody species in carbonate regions and grass species in non-carbonate regions. The climate is wet-dry tropical with a distinct rainy season (July-September) and dry season (February-March). Annual precipitation averages 200 cm and temperature ranges from 20° to 32° C (Gingerich and Yeatts, 2000; Doan et al., 1960).

Depositional terraces that reflect previous sea-level stillstands dominate island geomorphology. Tinian is separated into three distinct physiographic provinces by high-angle normal faults (Figure 3): 1) Northern Lowland, 2) Southeastern Ridge, and 3) a central region which comprises the North-Central Highland, Central Plateau and the Median Valley (Doan et al., 1960). Aguijan has not been separated into distinct regions, but is composed of three major depositional terraces (Figure 4) similar to the Southeastern Ridge of Tinian.

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).

Based on previous geologic studies of Tinian (Doan et al., 1960), the islands are composed of a basement of Eocene volcanic tuffs and breccias that are covered by younger limestones. Non-carbonate rocks crop out on less than 2 km^2 of Tinian, while no surface exposures were seen on Aguijan. Carbonate rocks are composed of algal and coralliferous facies divided into three units: Miocene Tagpochau Limestone, Plio-Pleistocene Mariana Limestone and Holocene raised beach and reef deposits. The Mariana Limestone is the dominant unit on the islands, with the Tagpochau Limestone limited to higher elevations and the Holocene deposits limited to coastal benches (Doan et al., 1960; Tayama, 1936). Limestones exhibit high primary porosities and do not appear to have undergone extensive burial and diagenesis, which would have increased cementation and compaction.

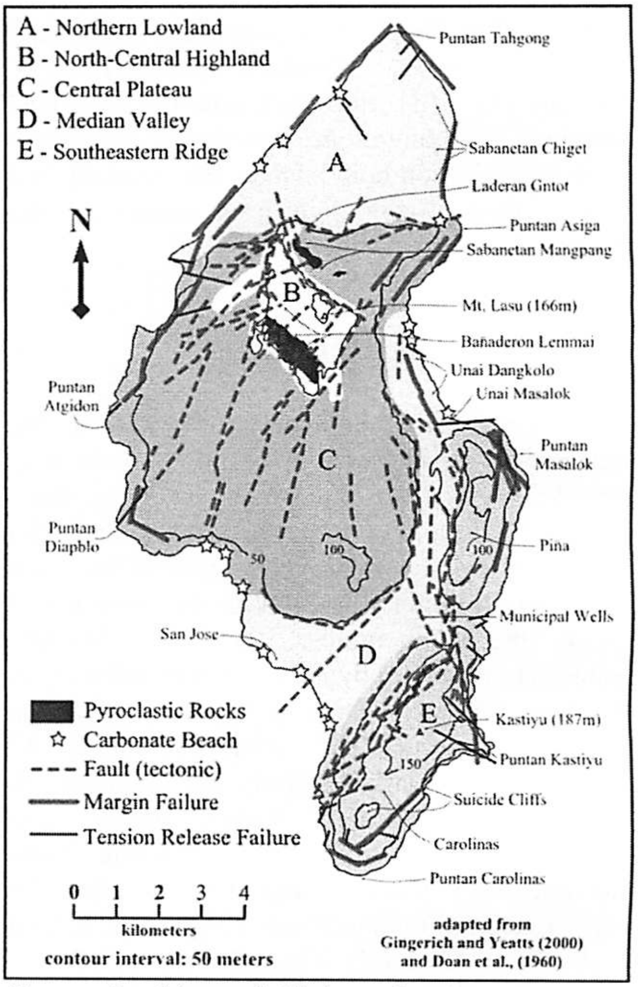

Figure 3. Map of Tinian showing important geographic, physiographic, and geologic features (adapted from Doan et al., 1960).

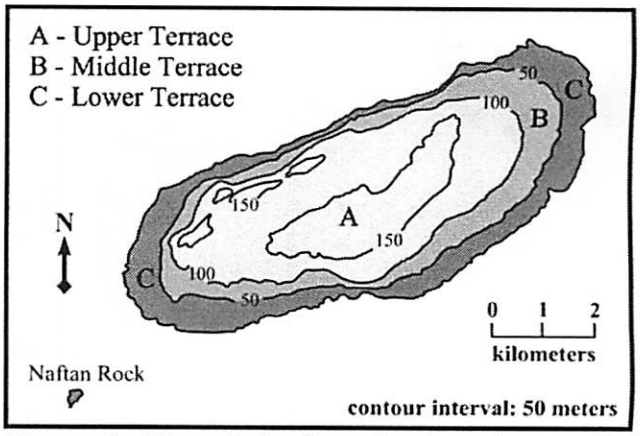

Figure 4. Map of Aguijan showing three major depositional terraces.

Island geomorphology is controlled by three primary factors: 1) the original volcanic depositional regime, 2) the original carbonate depositional regime, and 3) structural deformation, primarily brittle failure. The majority of Tinian's coastline and Aguijan's entire coastline are erosional with scarps and cliffs strongly controlled by brittle failure. Island uplift in the Marianas has resulted in three general types of structural deformation: 1) regional faulting associated with island arc tectonism, 2) brittle failure parallel to scarps and coastlines associated with margin failures, and 3) brittle failure near-perpendicular to scarps and coastlines associated with tension release structures that form perpendicular to margin failures. Additional brittle failures may result from passive, isostatic subsidence, but these are rare in the Marianas (Dickinson, 2000).

METHODS

Fieldwork on Tinian and Aguijan was carried out in May 2002, December 2002 and May 2003. It consisted of an inventory of cave and karst features as well as structural and geomorphic features. Caves were surveyed in accordance with standards established by the National Speleological Society (Dasher, 1994) using a Suunto compass, Suunto inclinometer and fiberglass tape, and field sketches were made. Structural orientations of planes of brittle failure were measured in areas where joints or fractures extended for several meters and cut through more than one bedding plane in outcrops or caves. The data were used to produce maps of all surveyed caves in the study area.

Non-parametric statistical analyses of cave orientations were compared with structural orientations and geomorphic orientations for Tinian. Cave maps were used to delineate primary orientations of passages, which were length-weighted to give greater significance to larger caves. Structural orientations of faults reported by Doan et al. (1960) were measured and length-weighted to give greater significance to larger features. Because they could not be traced over long distances due to dense vegetation, joints and fractures measured in the field were not length-weighted but evaluated as individual measurements. Geomorphic orientations of scarps and coastlines were measured from digital elevation models in order to predict the margin of modern and ancient freshwater lens positions shown by terrace levels, which were also length-weighted. Data from orientation measurements were evaluated using Smirnov-Kolmogrov statistical comparisions to determine possible relationships between cave development and structural and geomorphic features.

The reader is directed to Stafford (2003) for a detailed description of karst development on Tinian and Aguijan, a master's thesis that includes detailed maps and statistical analyses for the caves surveyed in the study area.

EOGENETIC ISLAND KARST

Karst development on small carbonate islands and coastlines containing rocks that have not been buried beyond the range of meteoric diagenesis (*i.e.* eogenetic rocks) is different from karst development in continental settings and large islands. Vacher and Mylroie (2002, p. 183) define eogenetic karst as "the land surface evolving on and the pore system developing in, rocks undergoing eogenetic, meteoric diagenesis." Eogenic island karst only develops in young rocks on small carbonate islands and coastlines that are affected by glacio-eustatic sea-level fluctuations, but have not been buried beyond the range of meteoric diagenesis. The Carbonate Island Karst Model (CIKM) is the current hydrologic model for island karst development, which includes five main components (Mylroie et al., 2004):

1. The karst is eogenetic.
2. The freshwater/saltwater boundary creates mixing dissolution and organic trapping horizons.
3. Glacio-eustacy has moved the fresh-water lens up and down during the Quaternary.
4. Local tectonics can overprint glacio-eustatic sea-level events.

5. 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

In the model, simple carbonate islands contain no non-carbonate rocks that interfere with the fresh-water lens morphology and groundwater recharge is completely autogenic (*e.g.* Bahamas). Carbonate-cover islands contain subsurface, impermeable, non-carbonate rocks that interrupt the fresh-water lens and shunt vadose water along the contact, while recharge remains completely autogenic (*e.g.* Bermuda during glacio-eustatic lowstands). Composite islands contain both carbonate and non-carbonate rocks at the land surface that partition the freshwater lens and provide both allogenic and autogenic recharge (*e.g.* Barbados and Guam). Complex islands exhibit interfingering of carbonate/non-carbonate rocks and faulting (which brings rocks of differing lithology into contact), lens partitioning, and both allogenic and autogenic recharge (*e.g.* Saipan). For a detailed description of the Carbonate Island Karst Model, see Mylroie et al. (2004).

TINIAN AND AGUIJAN KARST DEVELOPMENT

Karst development in the study area can be divided into two general categories: surface and subsurface features. Surface karst features include epikarst, closed depressions and fresh-water discharge. Subsurface karst features include three general cave types that are morphologically distinct: 1) mixing zone, 2) fissure and 3) contact. Detailed studies of cave development were conducted on Tinian by evaluating non-parametric, statistical comparisons of cave orientations with brittle failure features and fresh-water lens position.

Surface Features

Surface karst features on Tinian and Aguijan are of three basic types: 1) epikarst, 2) closed depressions and 3) fresh-water discharges. Epikarst is well developed on both islands and can be observed at all elevations. Closed depressions and fresh-water discharge features were only observed on Tinian.

Epikarst development is extensive in the study area with karren morphology variations related to coastal proximity. In coastal areas, limestone is constantly wetted by sea-spray which produce karren with extremely jagged, centimeter to meter scale pinnacles (Figure 5a) that have been termed eogenetic karren (Taboroši et al., 2004), biokarst (Viles, 1988) and phytokarst (Folk, 1973). This unique coastal karren has been attributed to a polygenetic origin involving the mixing of salt spray and meteoric water, dissolution by meteoric waters, salt weathering, and biological weathering. When joints and fractures are present, coastal karren forms also include enlarged planar features and shallow solution pans (kamenitzas) (Taboroši et al., 2004). In inland regions, epikarst is more subdued and less jagged, but can form meter-scale canyons in highly fractured regions (Figure 5b), suggesting that the interaction of salt weathering and the mixing of salt spray and meteoric water are largely responsible for the unique characteristics of coastal karren. However, some of the variation observed in inland karren is likely the result of soil processes since soil profiles here are better developed than in coastal regions.

Closed depressions in the Marianas exhibit three genetic types: 1) dissolutional, 2) constructional, and 3) human made or modified (Mylroie et al., 2001). No significant closed depressions were identified on Aguijan but 20 depressions greater than 10 m in diameter were located on Tinian. Seven dissolutional depressions were found proximal to volcanic outcrops in the central region of Tinian, where allogenic streams originating on non-carbonate terrains focus recharge at the non-carbonate/carbonate contact. Two of the depressions at the contact contain small caves,

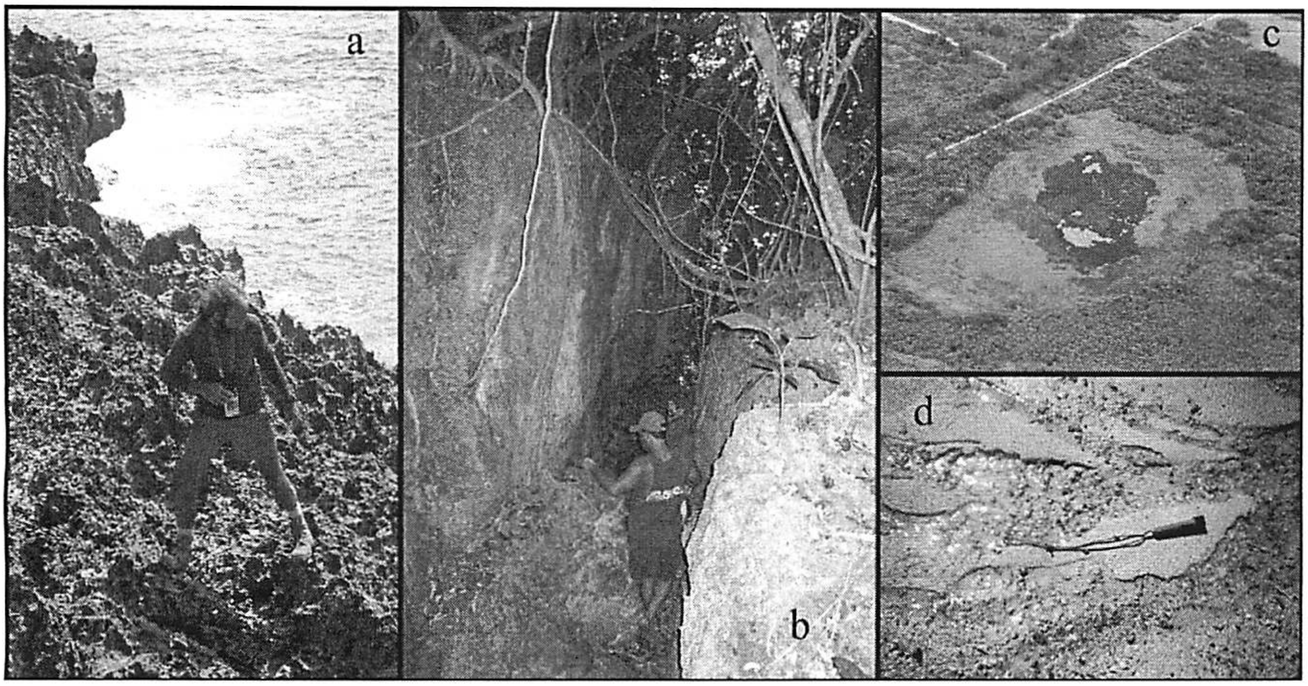

Figure 5. Surface karst features include: a) eogenetic coastal karren, which has centimeter to meter scale pinnacles; b) meter-scale canyons developed in highly fractured inland regions; c) Hagoi, a constructional closed depression with ponded freshwater; and d) coastal seeps through carbonate sands.

while another two contain pools of standing freshwater. Eight constructional depressions were identified in regions more distal to volcanic outcrops and showed no evidence of allogenic recharge. Those at low elevations contain pools of freshwater (Figure 5c). Constructional closed depressions appear to be the result of original carbonate deposition or in some cases produced by tectonic activity that created graben-like features, such as that seen in the large depression in the Median Valley where the municipal wells are located. The remaining five depressions are anthropogenic and included landfills, borrow pits and quarries. Only one quarry is currently active. The others appear to be relicts from World War II construction projects. Interpretation of closed depressions can be problematic, because features may be polygenetic, one type of depression could subsequently be modified by human activity, dissolution, or tectonics (Mylroie et al., 1999).

Discharge features are found in coastal regions and include both seeps (diffuse discharge) and springs (focused discharge). Modern discharge features were only recorded on Tinian because steep scarps and strong surf prevented detailed coastal studies on Aguijan. It is likely that Aguijan has discharge features similar to Tinian. The conclusion is supported by paleo-discharge features identified on higher terrace levels. These indicate that coastal discharge occurred during previous sea-level stillstands, and suggest that, although the area to perimeter ratio of Aguijan is small, it is still large enough for the development of concentrated coastal discharge. On Tinian, seeps were observed flowing from carbonate sands (Figure 5d) on three beaches, and fourteen springs were located on coastal scarps. Many springs were associated with fissure caves and exhibited significant discharge along fractures. It is expected that more features exist on Tinian since approximately half of coastline was not investigated due to time constraints and coastal surf conditions during fieldwork.

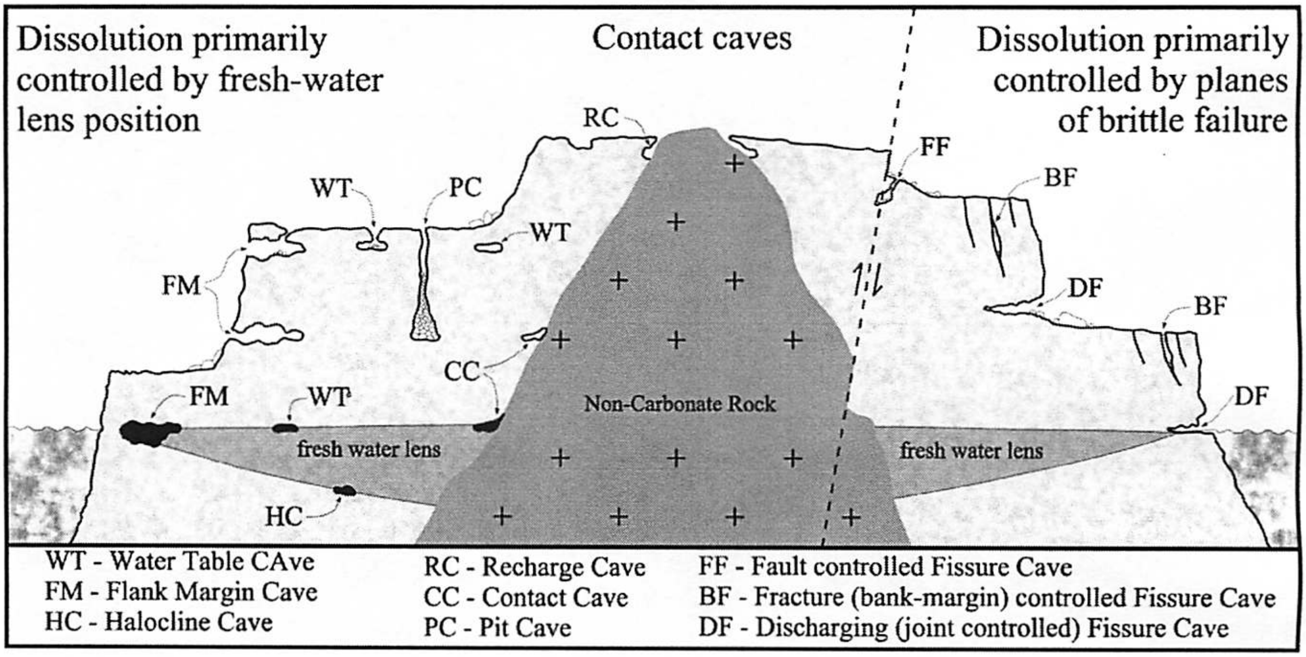

Figure 6. Conceptual diagram showing primary cave types observed in island karst, with primary controls on dissolution associated with water chemistry, lithology and geologic structure represented on the left, middle and right portions of the diagram, respectively. Note that not all cave types occur on all carbonate islands.

Subsurface Features

Subsurface karst development in the Marianas can be divided into three morphological cave classes (Stafford, 2003): 1) mixing zone, 2) fissure, and 3) contact. Cave morphologies suggest that development reflects differing primary controls on dissolution, including water chemistry, geologic structure, and lithology (Figure 6). Fieldwork conducted on Tinian and Aguijan resulted in an inventory of 113 caves or cave complexes: 89 mixing zone, 21 fissure, 2 contact, and one, Liyang Atkiya, which does not conveniently fit any current category. Residents in the study area report that the inventory includes the majority of known caves on the islands. However, an explorational bias does exist in the database because it is likely that additional features exist but were not inventoried due to lack of entrances (unbreached caves), dense vegetation, safety concerns, etc. Analysis of length to width ratios of caves suggests that at least two distinct types of caves exist, supporting classification of features based

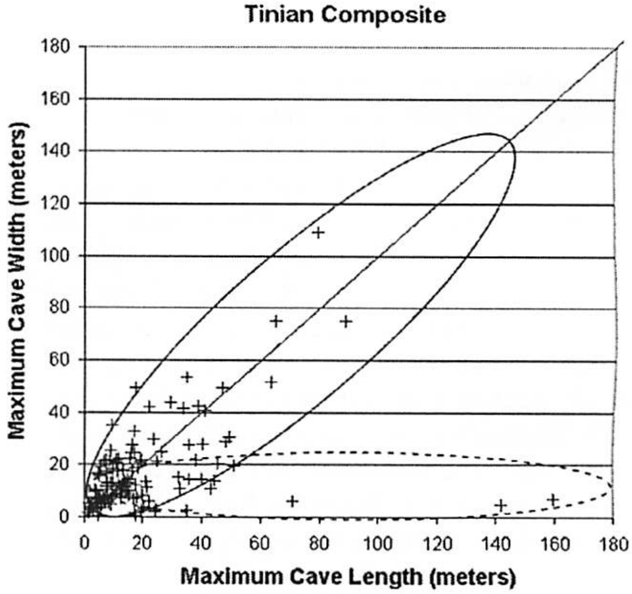

Figure 7. Plot of maximum width to length ratios of Tinian caves. Note that two different cave morphologies appear to exist: 1) a population that is approximately elliptical (circled with a solid line) and 2) a population that is linear (circled with a dashed line). This suggests that two distinctively different groups of cave development exist on Tinian.

on morphology (Figure 7).

Mixing zone caves are the most common cave type in the study area and, based on morphology, have been defined as forming in association with the fresh-water lens positions (Mylroie and Carew, 1995; Mylroie et al., 1995a). Three types of mixing zone caves exist: 1) water table (WT), 2) halocline (HC), and 3) flank margin (FM), which form respectively at the three edges of the fresh-water lens, the top, the bottom, and the distal margin (Figure 6). Recently, it has been suggested that caves involving mixing of seawater with the fresh-water lens (halocline and flank margin caves) should be placed in a category called "halo-phreatic" caves (Vacher, 2004). Mixing zone caves are hypogenic and have a consistent morphology of interconnected, globular chambers. They are excellent indicators of sea-level changes induced by glacio-eustacy and island uplift, because their formation is linked to the fresh-water lens position, which is controlled by sea level (Carew and Mylroie, 1995; Mylroie et al., 1995a,b).

Water table caves form at the top of the fresh-water lens where ther is vadose/phreatic

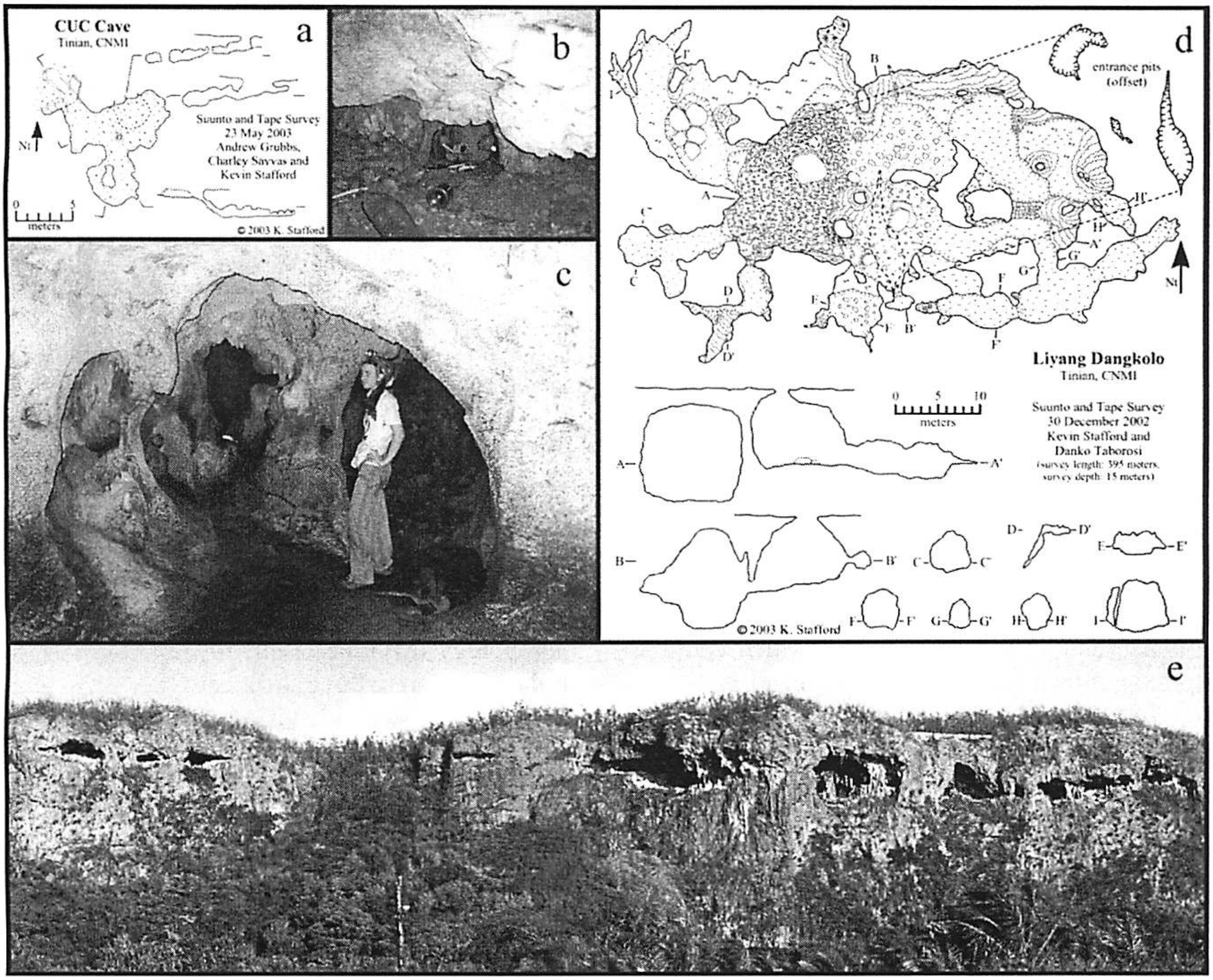

Figure 8. Subsurface karst development, mixing zone caves. Water table caves (a,b) form at the top of the fresh-water lens, forming small chambers (a) with limited vertical extent (b). Flank margin caves develop at the margin of the fresh-water lens, forming interconnected, "globular" passages (c) with complex cave morphologies (d). Horizons of flank margin caves such as those observed at Suicide Cliffs (e) on Tinian represent previous sea-level stillstands.

mixing and decomposition of organics trapped at the top of the lens (Harris et al., 1995). These caves, referred to as banana holes when breached (Harris et al., 1995), are small shallow chambers with little vertical extent. They are uncommon on Tinian and Aguijan (Figure 8a,b), with only four features identified.

Halocline caves form at the bottom of the fresh-water lens where freshwater/saltwater mixing and there is decomposition of organics trapped at the density horizon. There features are morphologically similar to water table caves. Halocline caves have been hypothesized on Tinian and Aguijan, but none have been unequivocally identified in the field area (Stafford, 2003). It is possible that some halocline caves may be incorrectly identified as water table caves, but the likelihood of water table caves is far greater considering that they form at the top of lens, in locations closer to the land surface and susceptible to breaching by collapse. It is likely that halocline caves and additional water table caves exist in the study area that remain unbreached because the lens position when they formed was sufficiently deep below the land surface. In the Bahamas, breached water table caves are common, but the majority of the land surface is less than ten meters above sea level, requiring only minor surface denudation to breach features formed in association with a paleo-freshwater lens position six meters higher than today (Harris et al., 1995). The land surface reaches a maximum of 187 m on Tinian and 157 m on Aguijan, which could require significant surface denudation to breach caves formed at the top and bottom of previous lens positions.

Flank margin caves form at the margin of the fresh-water lens where mixing dissolution and organic trapping horizons located at the top, bottom, and edge of the lens are close to each other, promoting greater dissolution (Mylroie and Carew, 1995). This combination of enhanced dissolution produces complex morphologies that form the largest and most common caves found on Tinian and Aguijan. Flank margin caves generally consist of one or more large globular chambers with many smaller interconnected passages (Figure 8c), which become more complex as the size of the cave increases (Figure 8d). They are commonly found along scarps and cliffs at consistent horizons reflecting previous sea-level stillstands (Figure 8e), because their position at the margin of the fresh-water lens makes them highly susceptible to breaching by scarp retreat and erosion (Mylroie et al., 1999). On Aguijan, horizons of flank margin caves have been identified at each of the three major terrace levels, suggesting that evidence for at least three previous sea-level stillstands is preserved on Aguijan. On Tinian, extensive faulting and differential uplift prevent the direct correlation of the many horizons of flank margin cave development across large regions, but an overland transect in the central portion of the island identified three distinct horizons of development, corresponding to three previous sea-level stillstands on Tinian, which is similar to data from Aguijan.

Fissure caves are the second most common type of subsurface karst feature on Tinian and Aguijan. They are linear features that appear to develop along brittle failures produced by structural deformation (Stafford et al., 2003). The planar surface created by brittle deformation provides a path for increased fluid movement through the subsurface. This results in preferential dissolution along faults, fractures and joints, which provide vadose fast flow routes and can thus distort the fresh-water lens morphology (Mylroie et al., 1995c; Aby, 1994). In the study area, three different types of fissure caves have been identified, each apparently associated with a different type of brittle deformation (Figure 6).

Fissure cave development associated with faults produces features that extend laterally along strike and descend at moderate to steep slopes along the dip (Figure 9a,c). Many show horizontal widening, either a result of dissolution of collapse material or from additional mixing dissolution when the fresh-water lens is intersected. Although no direct evidence of offsetting has been observed in fault-controlled

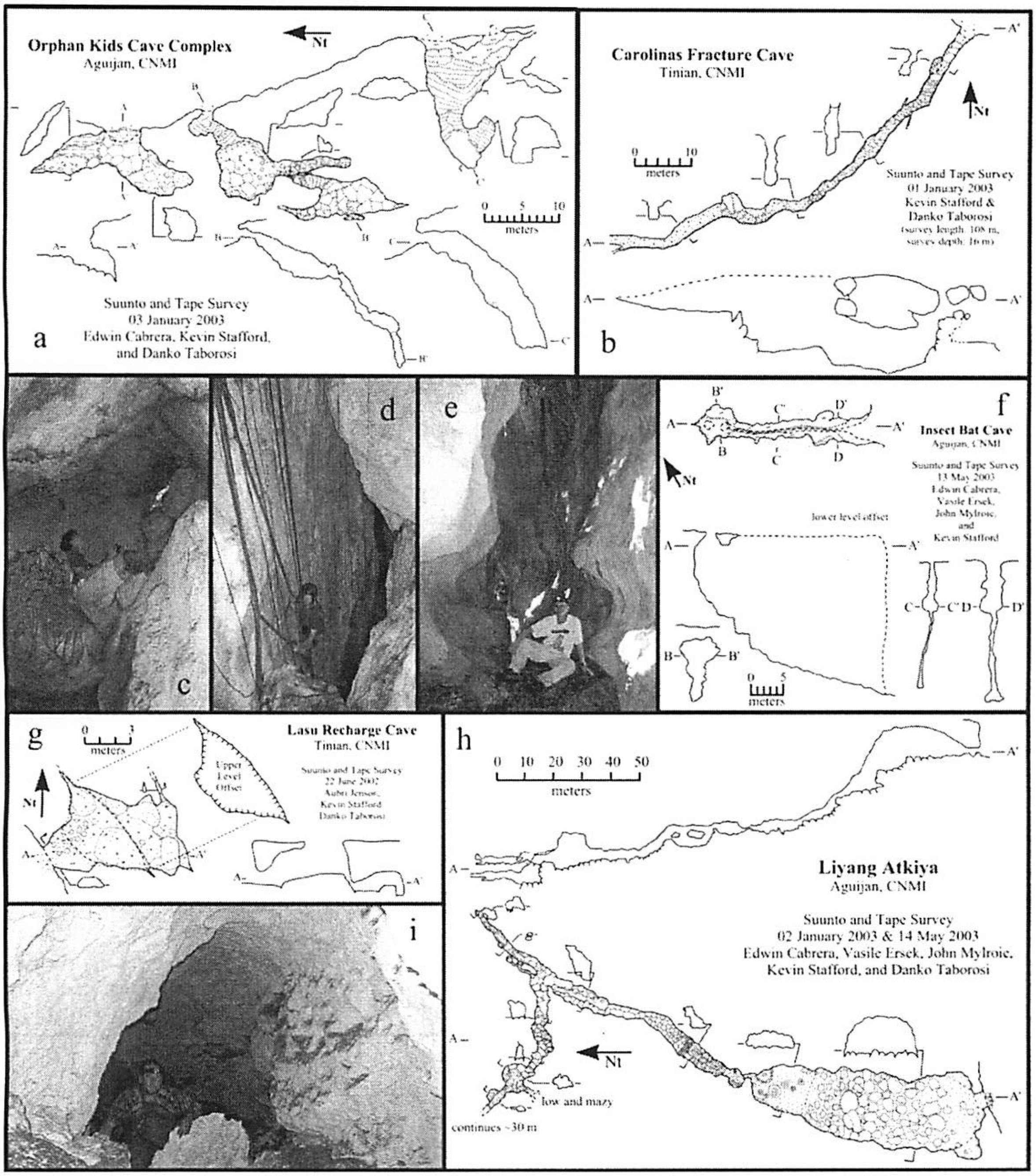

Figure 9. Subsurface karst development. Fissure caves develop along faults (a), margin failures (b), and tension-releaser fractures (f). Fault-controlled fissure caves develop along the strike (a) and descend at moderate to steep angles along dip (c). Margin failure, fissure caves form linear features parallel to scarps and coastlines (b) that descend near-vertically with relatively narrow widths (d). Tension release features form caves that are near-perpendicular to scarps (f) and frequently discharge freshwater or show horizontal widening from mixing zone dissolution (e) that indicates past fresh-water discharge. Mount Lasu Recharge Cave (g) is a contact cave located in the central portion of Tinian, where allogenic recharge enters the cave and descends through a small fracture into the subsurface. Liyang Atkiya (h) does not fit conventional models for island karst, with a broad entrance chamber, linear passages that bifurcate with depth, and scallops (i) that indicate previous conduit flow upgradient.

fissure caves, most likely because of extensive breakdown and calcite deposits, features do align closely with regional faults reported by Doan et al. (1960).

Fissure caves associated with fractures resulting from margin and scarp failures form laterally extensive features parallel to scarps and coastlines that descend near vertically to significant depths with relatively narrow widths (Figure 9b,d). These fissure caves can reach significant depths, can intersect the fresh-water lens, and contain extensive breakdown material, which comprises the majority of the floor and ceilings. Large portions of fissure caves formed by margin failure are unroofed due to ceiling collapse, but extensive speleothem deposits on passage walls indicate that in the past the unroofed sections were covered for a significant period of time.

Fissure cave development perpendicular or nearly perpendicular to scarps and coastlines appears to develop along tension release fractures that form perpendicularly to margin and scarp failures. This final type of fissure cave often extends inland for over 30 m with distinct joints observed in their ceilings and floors. When found at sea level, they frequently discharge freshwater and show horizontal widening from the mixing of fresh and saltwater. Features located above sea level exhibit similar morphologies, suggesting that they discharged freshwater in the past when sea level was higher and now represent paleo-discharge features (Figure 9e,f).

Contact caves (stream caves) form at the lithologic barrier of carbonate/non-carbonate contacts, where allogenic water originating on volcanic terrains is funneled into the subsurface (Figure 6). These features are generally associated with dissolutional closed depressions fed by perennial streams (Mylroie et al., 2001). Contact caves were not identified on Aguijan, because no non-carbonate rocks are exposed at the land surface. Only two contact caves were identified on Tinian, because of the limited volcanic exposures (less than 2% of the surface area). One of the two, Mount Lasu Recharge Cave (Figure 9g), shows evidence of rapid recharge with significant detritus accumulations within the closed depression, but little sediment coating the cave walls. Allogenic water enters the cave from the closed depression and after a short distance descends sub-vertically through a fracture less than 10 cm wide, demonstrating that although these features may be rare on Tinian they do provide significant direct, subsurface recharge for allogenic waters.

Liyang Atkiya, Aguijan, does not conveniently match any of the current cave types observed elsewhere in the study area and does not fit any current models for island karst development. The cave consists of a large entrance chamber floored with breakdown that descends and connects to a long, linear passage that bifurcates with depth (Figure 9h). Throughout the linear passage, scallops were observed on the ceiling and walls indicating previous conduit flow upgradient towards the entrance chamber (Figure 9i). Similar scallops have been documented in a lift tube in Kalabera Cave, Saipan, where water rose along a lithologic barrier between carbonate and non-carbonate rocks (Jenson et al., 2002). However, no non-carbonate rocks were seen in Liyang Atkiya that could provide this type of lithologic barrier. Much of Liyang Atkiya appears to be strongly controlled by geologic structure as indicted by the linear passages, while the main entrance chamber is reminiscent of mixing zone dissolution except for the absence of many side passages, which could be obstructed by the extensive breakdown. The current theory of speleogenesis suggests that non-carbonate rocks exist beneath the breakdown in the linear passage, which provided a lithologic barrier where water was forced upgradient over the contact along a plane of brittle failure. As the water rose and approached the paleo-coastline, now represented by the 50 m terrace level where the cave entrance is located, it mixed with saltwater at the margin of the previous fresh-water lens and formed the large entrance chamber. As relative sea-level lowered, buoyant support was lost and regions of the cave collapsed and the entrance was breached by scarp retreat, producing the cave as seen today.

Alternate theories suggest that the volcanic core of the island was still warm at the time of fresh-water lens formation, and the cave represents dissolution from thermal waters rising within the island, cooling (which leads to increased aggressivity), and discharging at the paleo-coastline.

Statistical Analyses of Cave Development

Island karst studies have suggested that mixing zone dissolution is the primary control on cave development in eogenetic rocks on carbonate islands (Mylroie et al., 2001; Mylroie and Carew, 1995). In continental settings and diagenetically mature rocks, variations in lithology and geologic structure are the primary controls on cave development. Kolmogrov-Smirnov statistical analyses of cave orientations with regional geologic structure have shown that regional brittle failure is not significantly different from cave passage development in continental settings (Nelson, 1988; Barlow and Ogden, 1982). A similar study was conducted on Tinian by Stafford (2003) to investigate possible relationships between cave development, geologic structure and fresh-water lens position, in order to evaluate controls on dissolution interpreted from cave morphology.

On Tinian, non-parametric statistical comparisons (Kolmogrov-Smirnov) for samples of mixing zone and fissure caves were evaluated with respect to the margin of the fresh-water lens, as represented by the modern and paleo-coastlines (*i.e.* terrace scarps), and geologic structure in the from of brittle failures. Length-weighted cave orientations were compared with length-weighted structural and geographic orientations, with comparison only being considered similar when they did not exhibit statistically significant differences ($p<0.01$) (Figure 10).

Statistical evaluations at the island scale and province scale did not show a high degree of dissimilarity for all cave development with structural and geographic orientations, most likely due to the complex depositional and tectonic regime of the Marianas. This makes it difficult to eliminate variables that are not significant to cave development at large scales. At the island and province scales, complex brittle deformation patterns and the curvature of the coastline and scarps provide a large range of structural and geographic orientations. Similarly, analyses of orientations for cave development for all surveyed features on the island or within a specific province produces a wide range of orientations. Therefore, when cave orientations are compared with structural and geographic orientations at the island and province scales no significant differences are seen amongst all groups of data, probably because the range of data orientations is too great to discern distinct differences. However, when statistical evaluations were performed for small-scale sites (1 km^2), similarities were found. At small-scale sites, analyses of fissure caves did not show statistically significant differences with brittle failure features and mixing zone caves did not show statistically significant differences with scarp and coastline orientations.

ISLAND SCALE	fissure caves	mixing zone caves
brittle failure orientations	similar	similar
scarp and cliff orientations	similar	similar
coastline orientations	similar	similar
PROVINCE SCALE	fissure caves	mixing zone caves
brittle failure orientations	similar	dissimilar
scarp and cliff orientations	dissimilar	similar
coastline orientations	similar	similar
SMALL-SCALE SITES	fissure caves	mixing zone caves
brittle failure orientations	similar	dissimilar
scarp and cliff orientations	dissimilar	similar
coastline orientations	dissimilar	similar

Figure 10. Statistical matrix showing results of Kolmogrov-Smirnov statistical comparisons of cave development with geologic and geographic orientations. Note distinct similarities ($p<0.01$) occur at small-scale sites (1 km^2) (adapted from Stafford, 2003).

These results suggest that the speleogenesis inferred by cave morphology is correct and that mixing zone cave dissolution is primarily controlled by the position of the fresh-water lens while fissure cave dissolution is primarily controlled by brittle deformation.

CONCLUSIONS

Eogenetic karst development on Tinian and Aguijan is complex and reflects a polygenetic origin for both surface and subsurface karst features. Karst development is largely controlled by the position of the fresh-water lens, but lithology and geologic structure provide significant controls on dissolution (Figure 6). Cave speleogenesis inferred from cave morphology is supported by statistical analyses of cave development with respect to geologic structure and island geography. Although most caves exhibit a single primary control on dissolution, specific features show evidence of multiple controls. Horizons of mixing zone cave development on Tinian and Aguijan suggest that at least three previous sea-level stillstands are preserved. More may exist due to differential rates of island uplift.

In relation to the Carbonate Island Karst Model, there are three distinct regions on Tinian, which are separated by high angle normal faults. Significant fresh-water discharge separating the central region of Tinian from the Northern Lowland and the Southeastern Ridge, suggests that the regions are effectively hydrologically separate. The Northern Lowland best fits the Simple Carbonate Island category; the central region (North-Central Highland, Central Plateau, and Median Valley) best fits the Composite Island category; and the Southeastern Ridge best fits the Carbonate-Cover Island category. The lack of observed non-carbonate rocks on Aguijan places it within the Simple Carbonate Island category, but, based on island geomorphology and the presence of Liyang Atkiya, it is likely that non-carbonate basement rocks on Aguijan distort the fresh-water lens, placing the island in the Carbonate-Cover Island category. Tinian and Aguijan demonstrate the functionality of the Carbonate Island Karst Model, but indicate that it must frequently be applied to regions within islands rather than islands in their entirety. Finally, the presence of Liyang Atkiya suggests that more research is needed to fully understand the complexities of eogenetic karst development on tectonically active carbonate islands.

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