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KARST ENVIRONMENTS OF GUAM, MARIANA ISLANDS

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ABSTRACT

Karst on Guam is found in two distinct physiographic provinces: the northern half of the island, which is an uplifted karst plateau formed on Plio-Pleistocene reef-lagoon deposits, and in the south, where most of the karst development is confined to Miocene limestone remnants on uplifted, weathered, volcanic terrain. Across these two provinces, the karst is remarkably diverse, exhibiting not only features typical of young carbonate island karst, but also classical karst landscapes generally associated with ancient limestone in continental settings.

INTRODUCTION

Guam is the southernmost island in the Mariana Archipelago and the largest island of Micronesia, in the western Pacific (Figure 1). Elongate in shape, it is 48 km long and 6-19 km wide. It is divided by a major fault (the Pago-Adelup Fault) into two distinct physiographic provinces (Figure 1). To the north is a low-relief plateau composed of a thick sequence of limestone. There are precipitous coastal cliffs standing 60-180 meters above sea level. To the south is a deeply dissected west-facing volcanic cuesta, with an uplifted limestone unit on the eastern flank, contemporaneous with the

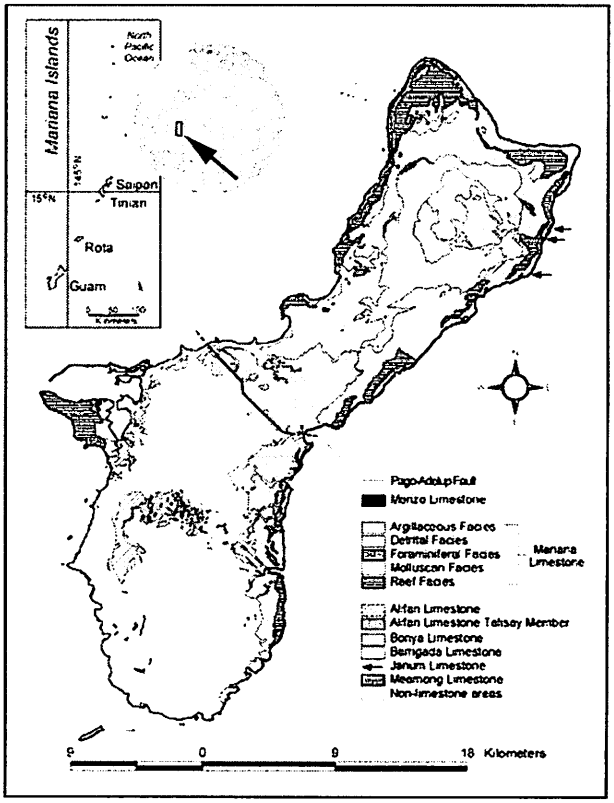

Figure 1. Simplified geologic map showing the Pago-Adelup Fault and limestone units of Guam, based on Tracey et al. (1964).

limestone of the north. It stands 60-70 meters above sea level. Less extensive remnants of older limestone units occupy an interior basin and cap the highlands, including the island's highest peak at 406 meters.

The oldest rocks are Eocene to Oligocene volcanic units, which form about half of the volcanic terrain of southern Guam and the basement beneath the limestone of the northern plateau. In the north, they are overlain by the detrital Miocene-Pliocene Barrigada Limestone, which is the principal aquifer on Guam. It contains the modern fresh-water lens and extends well above and below it. This formation appears at the surface in the interior of northern Guam but elsewhere grades laterally and upward into the Plio-Pleistocene Mariana Limestone, a reef and lagoonal deposit that dominates the northern plateau. Minor outcrops of Miocene argillaceous Janum Limestone and Holocene reef Merizo Limestone are exposed in coastal areas. In the south, the Eocene-Oligocene volcanic rocks are overlain by more silicic Late Miocene volcaniclastic deposits that contain occasional shallow-water limestone clasts. Atop these younger volcanic units are remnants of the Miocene Bonya Limestone in the interior, Miocene-Pliocene Alifan Limestone in the highlands, and the Mariana Limestone along the southeast coast (Tracey et al., 1964).

Due to the remarkable geologic complexity of Guam, limestone units exhibiting vastly different petrologies (from deepwater foraminiferal deposits to extremely heterogeneous coral and algal buildups) and diagenetic maturity (ranging from young fringing reefs to dense, thoroughly recrystallized rocks) are exposed in a variety of topographic, structural, and hydrologic settings. With numerous local environmental, geologic, and chemical factors superimposed on vastly different limestones, karstification produced an array of different karst types, distinct even on a very small scale (Taboroši et al., 2004a), each with its own range of typical features and hydrologic characteristics. The purpose of this paper is to outline the diverse karst environments found on Guam, some of which are described for the first time from a small oceanic island.

PREVIOUS WORK

The principal geologic reference for Guam is still the 1964 USGS report by Tracey et al. In support of their work, Schlanger (1964) documented the petrology of the limestones on the island. Hydrogeologic studies of the limestone aquifer of the northern plateau were summarized by Mink and Vacher (1997). The first comprehensive study of the karst features of the limestone terrain on Guam was undertaken by Taborpši (1999; 2000) and the other authors of this paper (Mylroie et al., 1999) between the summer of 1998 and fall of 2000. The central objective was to inventory and classify the island's karst features in the context of the Carbonate Island Karst Model (Mylroie and Jenson, 2000), a general theoretical model for the karst that characterizes the terrain formed in young limestones on small islands (Figure 2). Based on the results of the two-year field study of Guam, Mylroie et al. (2001) published a general overview of the karst of Guam in terms of the theoretical model. While they focused on the theory underlying the study, the full scope of the field investigation was reported in papers by Taboroši et al. (2004b; 2005), which contain maps depicting the locations and field relationships of all of the significant karst features examined. Based on this work Taboroši (2004) has published a comprehensive illustrated field guide to caves and karst of Guam. Taboroši et al. (2004c) discuss speleogenesis on Guam.

METHODOLOGY

The bulk of the data presented in this paper were collected during the previously mentioned project to inventory Guam's karst features (from summer of 1998 until fall of 2000). The data were acquired through systematic collection of unpublished records, interviews with local residents, aerial surveys and analyses of aerial photographs, boat and SCUBA surveys of coastal areas, and hundreds of hours of field work and mapping. All information was placed into a GIS database which was used extensively in evaluating the distribution and spatial relationships between different types of karst features. It greatly facilitated the morphogenetic classification of karst environments on Guam.

RESULTS

The two physiographic provinces of Guam exhibit fundamentally different types of karst (Figure 3). The karst in northern Guam is mostly *carbonate island karst*, while the karst in southern Guam is reminiscent of *classical karst*, as found in continental settings (Mylroie et al., 2001). Carbonate island karst is unique to young (Cenozoic) carbonate islands and is conceptually distinct from classical karst (Mylroie and Carew, 1995; Mylroie and Vacher, 1999). Its development is partly controlled by the lithologic heterogeneity and high primary porosity of the host limestones, which tend to be young and diagenetically immature units. Vacher and Mylroie (2002) have proposed the term *eogenetic karst* for this type of setting. These conditions cause fresh water infiltration and percolation to be predominantly diffuse, obviating the surface flow and subsurface conduit transport which are typical of classical karst. Carbonate island karst is further defined by the effects of differential dissolution associated with the mixing zones of vadose water, phreatic groundwater, and marine water; the migration of the mixing zones in response to glacio-eustatic and tectonic variations in relative sea level; and the position of the contact between the carbonate platform and the underlying non-carbonate basement with respect to sea level (Mylroie and Jenson, 2000).

The contact between the overlying carbonate, in which the karst terrain develops, and the underlying non-carbonate basement rocks that form the core of carbonate islands exerts important control on freshwater movement, conduit development, and freshwater interaction with marine water. Where the contact intersects the surface, surface water from the high-standing, non-carbonate terrain dissolves sinkholes in the adjacent carbonate rock as it descends along the contact. In the vadose zone, stream caves develop along the contact as descending water follows the less permeable basement to the water table. Where the contact passes through the freshwater phreatic zone into the freshwater-saltwater interface, it isolates the base of the freshwater lens from the influence of seawater.

Based on the position of the contact relative to the freshwater-marine interface and the island surface, carbonate islands can thus be classified into four ideal types (Figure 2): *simple carbonate islands* (Figure 2A), where carbonate rocks extend from the surface to beneath the freshwater lens; *carbonate cover islands* (Figure 2B), where non-carbonate basement rock rises above sea level to partition the fresh-water lens but is not exposed at the surface; *composite islands* (Figure 2C), where non-carbonate rocks partition the lens and are exposed above the limestone surface; and *complex islands* (Figure 2D), which may exhibit characteristics of all three models and contain sedimentary units of intermediate or mixed carbonate-noncarbonate lithology or complex structurally modified stratigraphic relationships (Wexel et al., 2001; Jenson et al., 2002).

While many islands can be described in terms of a single ideal type, northern Guam locally exhibits elements of each of the first three carbonate island karst environments (Figure 2). One percent of its land surface is occupied by the volcanic outcrops of Mt. Santa Rosa and Mataguac Hill (Figure 3), which protrude through the limestone plateau (composite island model, Fig. 2C). This area is characterized by allogenic catchments. Surface runoff is channeled into ephemeral streams in deeply incised blind valleys that terminate in sinkholes formed along the contact with the surrounding limestone. The water descends along stream caves that follow the contact between the volcanic basement units and the overlying limestone. Hydrologically, these basement conduits are simply roofed continuations of the ephemeral surface streams.

Beneath approximately 21% of the land surface (Figure 3), the basement extends above sea level, but is not exposed at the surface (Vann, unpublished) (carbonate cover island model, Fig. 2B). When the lowest (95m) long-term relative

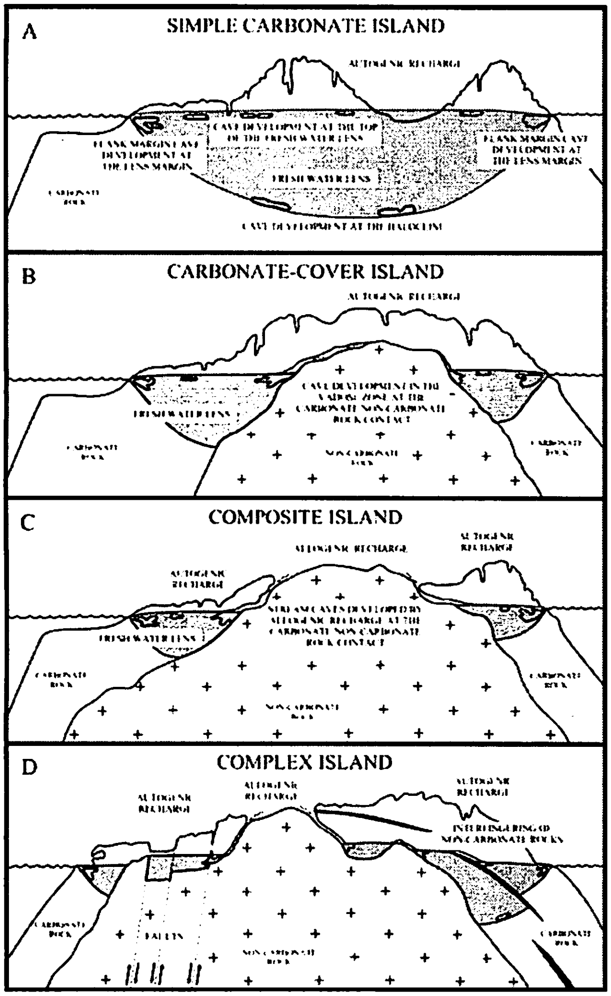

Figure 2. Ideal carbonate island types based on the relative position of the bedrock-basement contact with respect to sea level and terrain surface: A. simple carbonate island; B. carbonate cover island; C. composite carbonate island; D. complex carbonate island (A-C: Mylroie and Vacher, 1999)(D: Wexel et al,. 2001; Jenson et al,. 2002).

sea level stillstand (based on submerged marine terraces mapped by Emery in 1962) is considered, an additional 37% of the northern Guam's modern surface (Figure 3) may, during the past, also have fit the carbonate cover island model. This part of Guam's subsurface probably contains numerous basement conduits, the majority of which have become inactive due to relative sea level rise. It is conceivable that progradational collapse of such conduits may be responsible for some of the few collapse sinkholes observed on the northern Guam land surface.

Finally, the basement is sufficiently deep under 41% of the plateau surface (Figure 3) that it has probably not been exposed above sea level (simple carbonate island model, Figure 2C) subsequent to the overlying limestone bedrock being deposited (assuming that the current level of tectonic uplift is the highest the island has experienced). This category includes the entire coastline of northern Guam, and its most characteristic karst features are coastal springs (Jenson et al., 1997) and flank margin caves (Mylroie and Carew, 1990). The latter are hypogenic cavities produced by *mixing corrosion* (Bögli, 1964) in the outer margins of the freshwater lens. Because they form without connections to the land surface, these caves cannot be entered unless they have been breached by erosion.

The uppermost limestone unit in the southern part of the northern Guam plateau, and the unit flanking the east coast of southern Guam, both of which lie adjacent to higher-standing volcanic terrain, were mapped as the Argillaceous Member of the Mariana Limestone (Figure 1) by Tracey et al. (1964), so named because of its high clay content. The topography in both places can be classified as *fluviokarst* (Figure 3) (Taboroši and Jenson, 2002). Fluviokarst is characterized by mixed underground and surface drainage. While common in continental karst, it is not characteristic of carbonate island terrain. On Guam, it occurs only in karst areas adjacent to non-carbonate terrain and in the argillaceous limestone, where lower matrix porosity promotes limited water flow across the limestone surface. Thus, at the southern end of the northern Guam plateau, where argillaceous limestone lies next to the southern volcanic highlands, two perennial allogenic rivers and two autogenic rivers flow across the limestone surface without losing noticeable volume to underground flow. There is evidence, however, of former streams and rivers that have been diverted underground. This includes deeply incised *dry valleys*, and *valley sinkholes*, depressions in the valley floors that have taken the former surface streams underground. Locally, the floors and walls of dry valleys have become eroded, leaving only strings of sinkholes as the evidence of former streams. In the swampy area around Guam's capital, Hagåtña, dry valleys have been flooded and filled as relative sea level has risen.

The fluviokarst found in the southeast coast of Guam (Figure 3) fits White's (1988) model for *plateau margin karst,* characterized by carbonate rocks fringing a non-carbonate plateau. The karst topography of this area is dominated by six large allogenic rivers that head in the volcanic terrain in the interior and traverse the narrow coastal limestone apron on their way to the ocean. Although they lose some water, they do not disappear underground because of their high discharge volumes, the short distance across the limestone terrain, and the deep glacio-eustatic alluvial deposits filling their valleys. Only the Togcha River, which has the smallest drainage basin of the six, does not reach its mouth at the coast during the dry season, when its low flow is completely absorbed along the riverbed. It must be noted, however, that because fluviokarst areas on Guam are located very near or at sea level, they are also influenced by the ocean and saline groundwater, locally resulting in features characteristic of carbonate island karst.

Most reminiscent of classical karst is the topography of isolated limestone units in southern Guam. The limestones here, namely the Bonya Limestone of the interior basin and the Alifan Limestone on the flank and ridge of the southern mountains (Figure 2), are isolated from the ocean and therefore unaffected by marine groundwater and sea level changes. Moreover, these limestones are diagenetically mature, homogeneous, and have low porosity. Consequently, they exhibit karst features reminiscent of continental settings. Where limestone outliers stand topographically above the surrounding volcanic terrain, most notably on the Southern Mountain Ridge (Figure 3), *contact springs* form at the contact between them and the underlying volcanic rock. Some springs are seasonal and small, while others are permanent and large, forming the headwaters of significant streams. Where outliers are topographically lower than the surrounding volcanic terrain, they are completely traversed by allogenic rivers. Isolated remnants of Bonya Limestone and Alifan Limestone located northeast of the Fena reservoir in the topographic basin in central southern Guam (Figure 3) stand in the way of the allogenic streams. The streams crisscross the area, a part of which resembles classic mature tropical karst topography known as *cockpit karst* (see Sweeting, 1958) or *polygonal karst* (Ford and Williams, 1989). Inactive cave passages join the bottoms of some of the cockpit sinkholes. There are at least two examples of active subterranean flow where, upon reaching limestone outcrops, allogenic streams disappear into *insurgences* and emerge from *resurgence springs* on the opposite side.

Finally, an isolated outcrop of Alifan Limestone on the south side of the Pago-Adelup Fault exhibits karst features unusual on Guam.

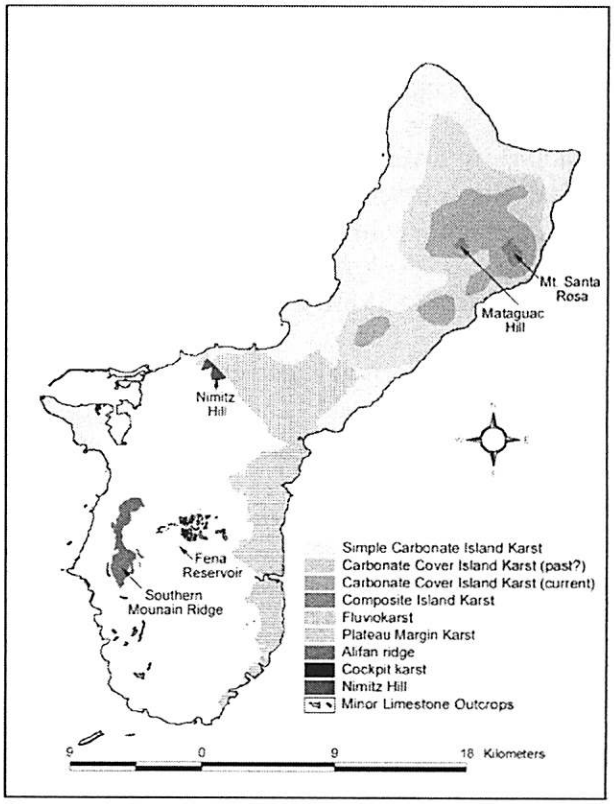

Figure 3. Karst environments of Guam. The north is almost entirely karst, with minor inliers of volcanic terrain at Mt. Santa Rosa and Mataguac Hill. The south is mostly volcanic terrain with karst on some outlying limestone units.

This heavily fractured area, on Nimitz Hill (Figure 3), is located near the ocean and adjacent to extensive volcanic terrain. It contains numerous fracture caves curiously combined with mixing zone dissolution chambers. The karst of this area is comparable to the features described from tectonically active carbonate islands (Stafford et al., 2003 and 2004; Stafford and Taboroši, 2004) and is the only part of Guam approaching the complex island type (Figure 2D) of the Carbonate Island Karst Model.

CONCLUSION

The great variety of Guam's karst features can be broadly divided into island karst, which characterizes the northern half of Guam, and classical karst, which dominates southern Guam. Each of these two contrasting categories contains many distinct karst types, considering the island's exceedingly small area, which makes the karstlands of Guam some of the most diverse in the world. This is the result of remarkably petrologically diverse limestones on Guam being exposed in numerous different topographic, structural, and hydrologic settings. The local environmental, geologic, and chemical factors superimposed on vastly different limestones allowed the karstification processes to produce a wide array of different karst environments on a small island.

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