Micronesica 38(1):17–46, 2005

Karst Features 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 is an uplifted karst plateau formed on Pliocene-Pleistocene reef-lagoon deposits. In the south, the karst is confined mostly to Miocene remnants on uplifted weathered volcanic terrain; except on the southeastern coast, where it has developed in former fringing reef limestone contemporaneous with the limestone of the north. Across these environments, the karst of Guam is remarkably diverse—exhibiting not only island karst features, but also continental karst features generally associated with ancient, diagenetically mature limestones. Features are mapped and described in this paper in terms of five categories reflecting the sequence of water movement, namely (1) surface catchment features, (2) surface flow features, (3) closed depressions, (4) caves, and (5) discharge features.

Surface catchment features include karren and the epikarst, artificial ponding basins, storm water injection wells, etc. Surface flow features include streams originating on allogenic and autogenic catchments, insurgences, dry valleys, valley sinkholes, and contact and resurgence springs. Most closed depressions on the island are of primary depositional origin, but there are also numerous true sinkholes of solutional and collapse origin. Caves on Guam include pit caves at the surface, stream caves along bedrock-basement contacts, and water table, halocline, and flank margin caves, which are all hypogenic and associated with present and past positions of the fresh water lens. The vast majority of discharge features are located along the coast. They include beach springs and seeps, reef springs and seeps, flowing fractures and caves, and submarine springs, and their distribution and density reflect the relative areas and shape of the catchments feeding them. A few high-level springs can be found in the interior, mostly rising at carbonate-non carbonate contacts.

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Introduction

Guam is the southernmost of the Mariana Islands, an active magmatic arc delineated by a curvilinear chain of Neogene volcanic islands and seamounts. Located at 13°28'N, 144°45'E, it is the largest island (549 km^2) in Micronesia, elongate in shape, 48 km long and 6–19 km wide. Guam is divided across a major fault into two distinct physiographic provinces (Fig. 1). To the north is a low-relief limestone plateau with 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 its eastern flank, contemporaneous with the cliff-forming unit in the north and standing 60–70 meters above sea level. Less extensive remnants of older limestone units occupy an interior basin and cap the western highlands of the cuesta, including the island's highest peak at 406 meters.

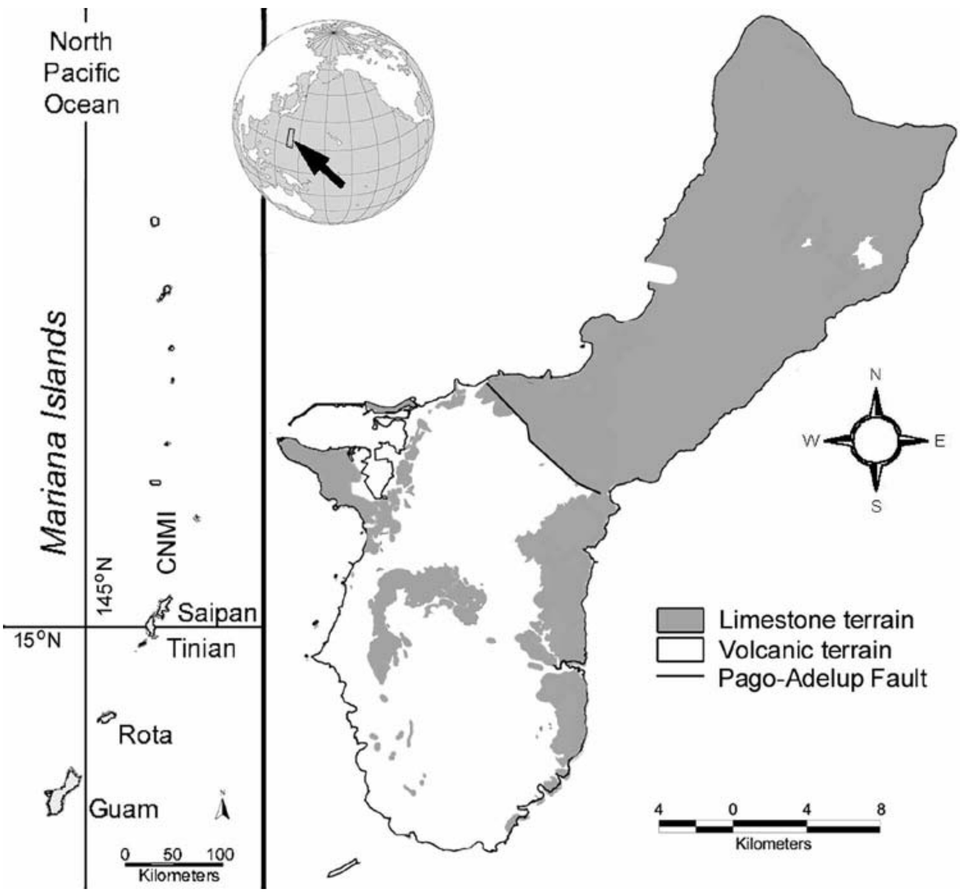

Fig. 1. Location of Guam and the extent of its limestone terrain over the two provinces separated by the Pago-Adelup Fault (map based on Tracey et al., 1964). The abbreviation CNMI stands for the Commonwealth of the Northern Mariana Islands, a self-governing U.S. territory.

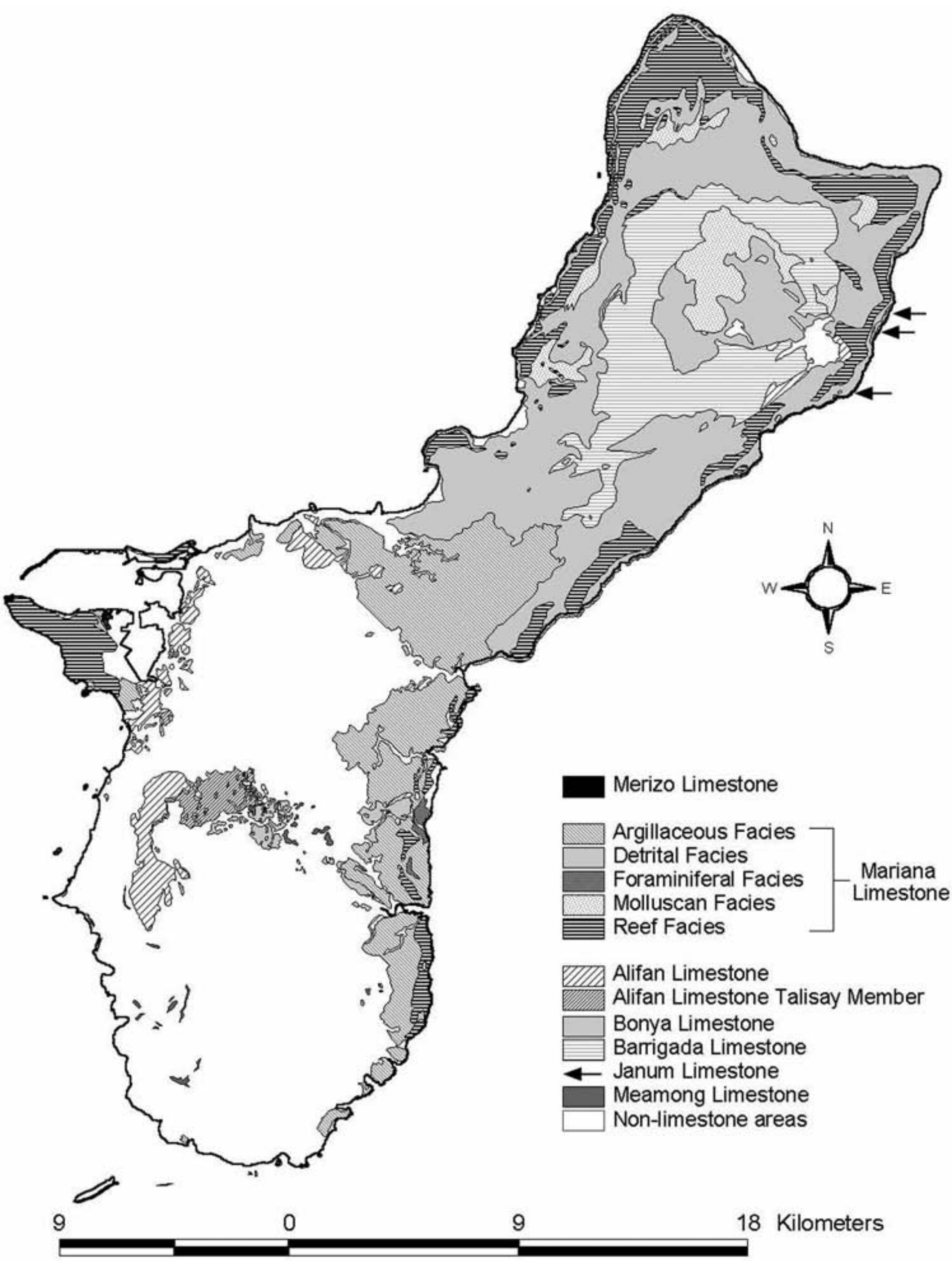

Fig. 2. Simplified geologic map showing the limestone units of Guam (modified from Tracey et al. 1964).

Uplift is estimated to have been more than 100 m (>0.05 mm/yr) during the late Neogene and Quaternary. Active tectonism is still occurring, and coastal geomorphology and radiocarbon data indicate approximately 1.8 m of uplift during the Holocene (Dickinson 2000).

The principal geologic reference for Guam is still the 1964 USGS report by Tracey et al. (Fig. 2), although the ages and stratigraphic relationships of the volcanic units were subsequently revised by Reagan & Meijer (1984). The oldest rocks are Late Middle Eocene pillow basalts and basalt flows cut by dikes. These are overlain by Late Eocene-Early Oligocene tuffaceous shale and sandstone interbedded with breccia and lava flows. This unit contains limestone clasts, lenses, and locally extensive overlying beds of calcareous shale. Tracey et al. (1964) assigned it to the basement beneath the limestone of the northern plateau. The two units together form about half of the volcanic terrain of southern Guam; the other half is formed on a more silicic Miocene volcaniclastic unit, which contains scattered outcrops of Late Oligocene-Early Miocene shallow-water limestone. Atop the volcanic units in southern Guam are remnants of the Miocene Bonya Limestone in the interior and the Miocene-Pliocene Alifan Limestone in the highlands. Remnants of Alifan Limestone also occupy the parts of the northwestern corner of the southern province and the flanks of Mt. Santa Rosa in the north. The Orote Peninsula, extending to the west of the southern province, from which it is separated by a north-northeast trending fault, constitutes a minor plateau with a surface composed of Mariana Limestone. It is flanked by cliffs rising up to 60 meters at its westernmost end. Tracey et al. (1964) mapped an outcrop of Alifan Limestone at the bottom of the section on the north side of the peninsula.

The largest-volume limestone unit of the northern plateau is the detrital Miocene-Pliocene Barrigada Limestone, which extends to the surface in the interior but elsewhere grades laterally and upward into the Pliocene-Pleistocene Mariana Limestone–a reef and lagoonal deposit that dominates the northern plateau. The Barrigada Limestone is the principal aquifer of the northern plateau, containing the modern fresh-water lens and extending well above and below the current lens position (Fig. 3). Minor outcrops of Miocene argillaceous Janum Limestone and Holocene reef Merizo Limestone are exposed in coastal areas.

Ward et al. (1965) published the first comprehensive report on the hydrology of Guam, which included information on water chemistry and well behavior, and a detailed map of the extant wells and springs. Mink & Vacher (1997) have summarized past hydrogeologic studies of the limestone aquifer of the northern plateau. In support of the work by Tracey et al., Schlanger (1964) documented the limestone petrology of Guam. Siegrist & Randall (1992) prepared a useful summary and field guide to the carbonate geology of Guam. The first comprehensive study of the karst features of the limestone terrain on Guam, however, was undertaken by Taboroši (2000) and the other authors of this paper between the summer of 1998 and fall of 2000. The central objective was to inventory and classify the island's karst features (Mylroie & Jenson 2000) in the context of the Carbonate

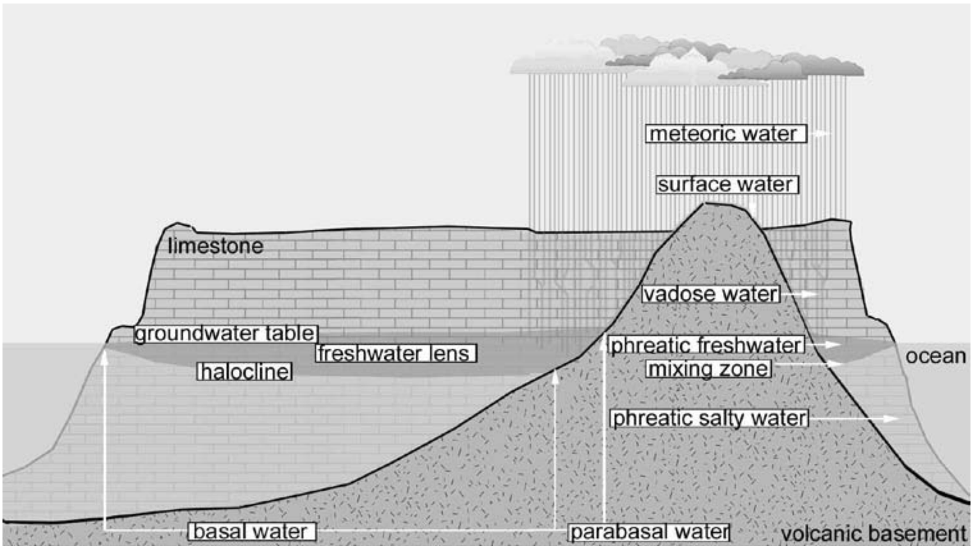

Fig. 3. Schematic cross-section of the Northern Guam Lens Aquifer. Not to scale. Parabasal water is part of the fresh water lens underlain by volcanic rocks; basal water is underlain by sea water.

Island Karst Model, a general theoretical model for the unique karst that characterizes the terrain formed in young limestones on small islands (Mylroie & Carew 1995). The CIKM is based on the seminal work of Mylroie & Carew on karst in small carbonate islands of the Caribbean and western Atlantic (cf. Mylroie & Carew 1995). Because of the relatively simple stratigraphy and tectonic stability of these islands, they were able to observe and interpret the results of karst processes unaffected by complex depositional history or structural modification. Guam is an appropriate subject for the first extension of this work to more complicated islands because while it has a complex relative sea-level history, its limestone depositional history and stratigraphy are relatively simple, and structural modification is modest and easily interpreted. In addition, the basic geology of the island has been thoroughly documented. Study of Guam's karst is thus a productive intermediate step to understanding more complicated islands, such as Guam's sister island of Saipan to the north, which exhibits both complex stratigraphy and complex structure (Cloud et al. 1956, Jenson et al. 2002, Wexel et al. 2001).

Based on the results of the two-year systematic field study of karst on Guam (Taboroši 2000), Mylroie et al. (2001) published a general overview of the karst of Guam in terms of the theoretical model. While Mylroie et al. focused on the theory underlying the study, and illustrated their discussion with selected examples of the features examined, the objective of this paper is to present an integral set of maps that depict the full scope of the study and show the locations and first-order field relationships of all of the significant karst features that were located and examined. The information included in the maps was acquired through systematic collection of unpublished data, interviews with local residents, aerial surveys and analyses of aerial photographs, boat and SCUBA surveys of coastal areas, and hundreds of hours of fieldwork and field mapping. Except where acknowledged, each feature marked on each map was visited and verified during the field investigation. Electronic copies of the maps are contained in a comprehensive GIS (Geographic Information System) database compiled during the study. This database is available on a CD and is deposited at the Water and Environmental Research Institute of the Western Pacific (WERI), University of Guam.

Types of Karst on Guam

The two physiographic provinces of Guam exhibit fundamentally different types of karst (Fig. 4). The karst in northern Guam is mostly *carbonate island karst,* while the karst in southern Guam is reminiscent of 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 continental karst. Its development is partly controlled by the lithologic heterogeneity and high primary porosity of the host limestones, which tend to be young, diagenetically immature units, for which Vacher & Mylroie (2002) have proposed the term *eogenetic karst.* These rock qualities cause fresh water infiltration and percolation to be predominantly diffuse, obviating surface flow and subsurface conduit transport, which are typical of continental 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 & Jenson 2000).

The contact between the overlying carbonate rock, in which the karst terrain develops, and the underlying non-carbonate basement rocks that form the core of carbonate islands exerts important control on fresh water movement, conduit development, and fresh water interaction with marine water. Where the contact intersects the land surface, surface water from the higher-standing non-carbonate terrain dissolves sinkholes in the adjacent carbonate rock where 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 fresh water phreatic zone down to the fresh water-saltwater interface, it isolates the base of the fresh water lens from the influence of seawater. Based on the position of the contact relative to the fresh water-sea water interface and the island surface, carbonate islands can thus be classified into four ideal types: *simple carbonate islands* (Fig. 4a.1), where carbonate rocks extend from the surface to beneath the fresh water lens; *carbonate cover islands* (Fig. 4a.2), where non-carbonate basement rocks rise above sea level to partition the fresh-water lens but are not exposed at the surface; *composite islands* (Fig. 4a.3), where non-carbonate rocks partition the lens and are exposed above the

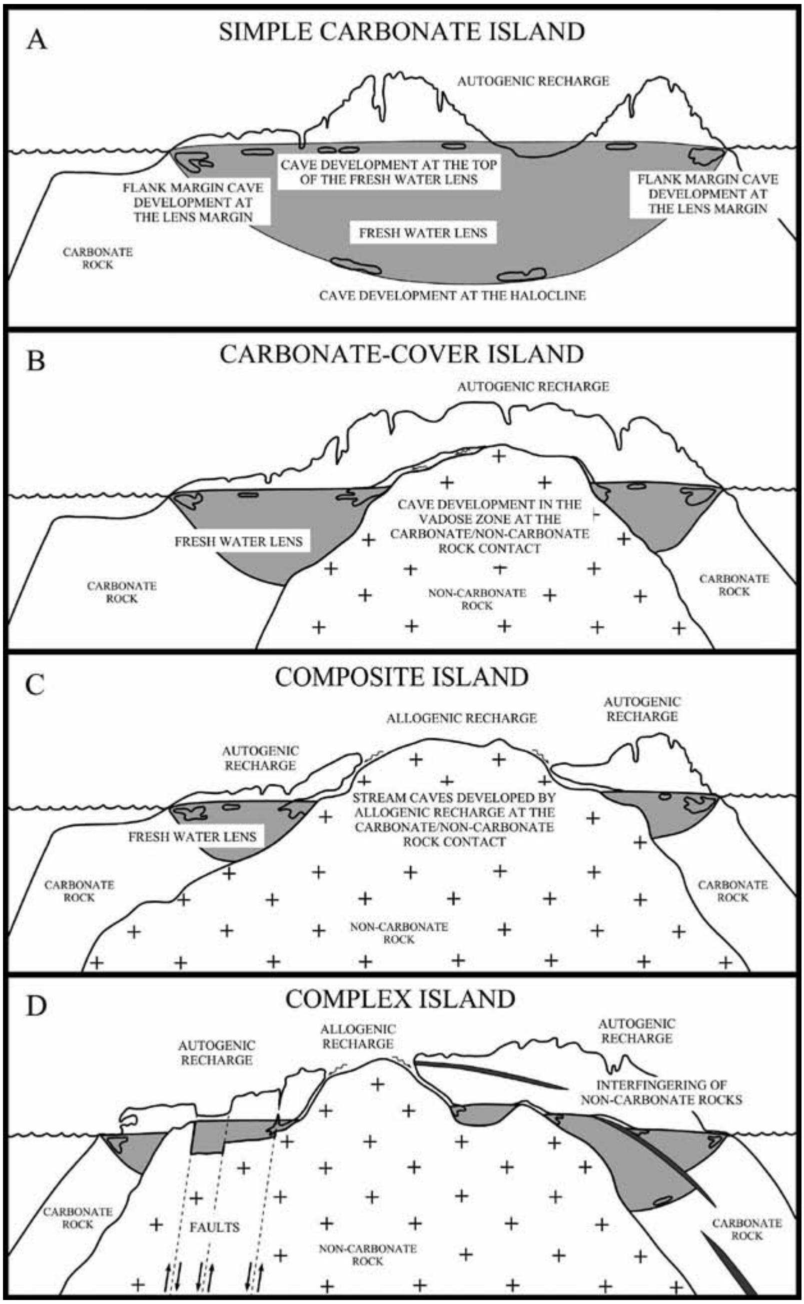

Fig. 4a. Ideal carbonate island types based on the relative position of the bedrock-basement contact with respect to sea level and terrain surface: 1. simple carbonate island; 2. carbonate cover island; 3. composite carbonate island; 4. complex carbonate island (1–3: Mylroie & Vacher, 1999) (4: Jenson et al., 2002; Wexel et al., 2001).

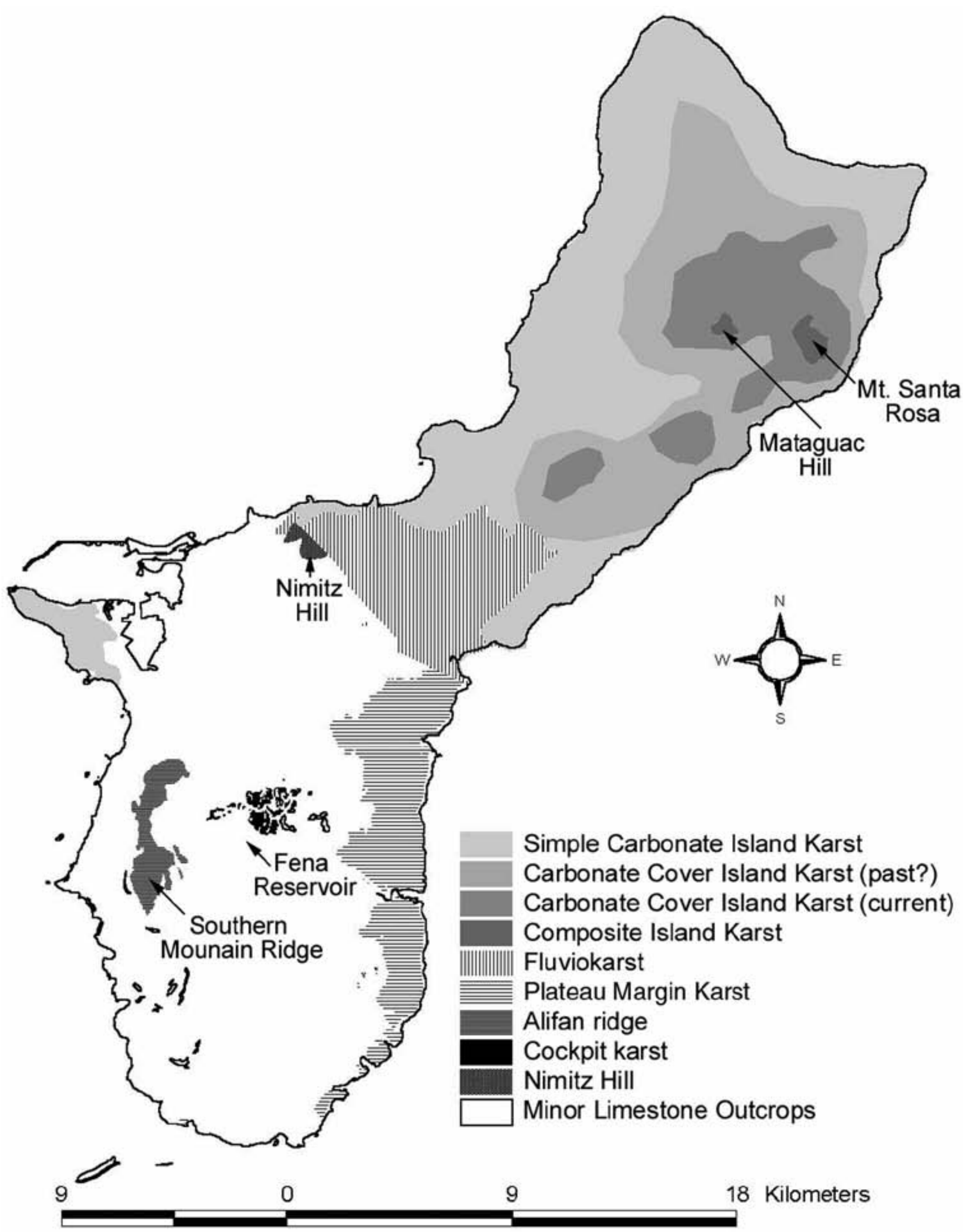

Fig. 4b. Karst environments of Guam. The north is almost entirely karst, with minor inliers of volcanic terrain at Mt. Santa Rosa and Mataguac Hill. The south is mostly volcanic terrain with karst on some outlying limestone units. The volcanic units also contain scattered minor outcrops of limestone. (Boundaries of island karst type areas in northern Guam are based on estimates of volcanic basement topography by Vann 2000.)

limestone surface; and *complex islands* (Fig. 4a.4), which may exhibit characteristics of all three models and contain sedimentary units of intermediate or mixed carbonate-noncarbonate lithology and/or complex structurally modified stratigraphic relationships (Jenson et al. 2002, Wexel et al. 2001).

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 (Fig. 4b). One percent of its land surface is occupied by the volcanic outcrops of Mt. Santa Rosa and Mataguac Hill, which protrude through the limestone plateau (composite island model, Fig. 4a.3). Beneath approximately 21% of the land surface, the basement extends above sea level, but is not exposed at the surface (Vann 2000) (carbonate cover island model, Fig. 4a.2). When the lowest long-term relative stillstand of 95 m below the modern sea level (based on submerged marine terraces mapped by Emery in 1962) is considered, an additional 37% of the northern Guam's modern surface may also have fit the carbonate cover island model during the past. Finally, the basement is sufficiently deep under 41% of the plateau surface that it has probably not stood above sea level (simple carbonate island model, Fig. 4a.1) since the overlying limestone bedrock was deposited, assuming that the current level of tectonic uplift is the highest the island has experienced.

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 by Tracey et al. (1964) because of their high clay content. The terrain in both places is characterized by a combination of mixed underground and surface drainage, and can therefore be classified as *fluviokarst* (Fig. 4b and Fig. 5) (Taboroši & Jenson 2002). While common in continental karst, fluviokarst is uncharacteristic of carbonate island karst terrain. On Guam, it occurs only on limestone adjacent to non-carbonate terrain and in argillaceous limestone, probably because the reduced matrix porosity in the latter promotes limited water flow across the limestone surface. The fluviokarst of the southeast coast of Guam, where large streams that originate on the volcanic terrain in the interior dissect the coastal limestone apron on their way to the ocean, can be further sub-classified as *plateau margin karst* (White 1988). Because fluviokarst areas on Guam are located very near or at sea level, however, they are also influenced by the ocean and saline groundwater, locally resulting in features characteristic of carbonate island karst.

In the Bonya Limestone of the interior basin and the Alifan Limestone on the flank and ridge of the southern mountains (Fig. 4b), the limestone units are isolated from the ocean and therefore unaffected by marine groundwater and sea level changes. Moreover, these limestones are diagenetically mature, homogeneous, and low in porosity. Consequently, they exhibit karst features typical of continental settings. The Bonya Limestone northeast of the Fena Reservoir, for example, exhibits classic mature tropical karst topography known as *cockpit karst* (see Sweeting 1958) or *polygonal karst* (Ford & Williams 1989).

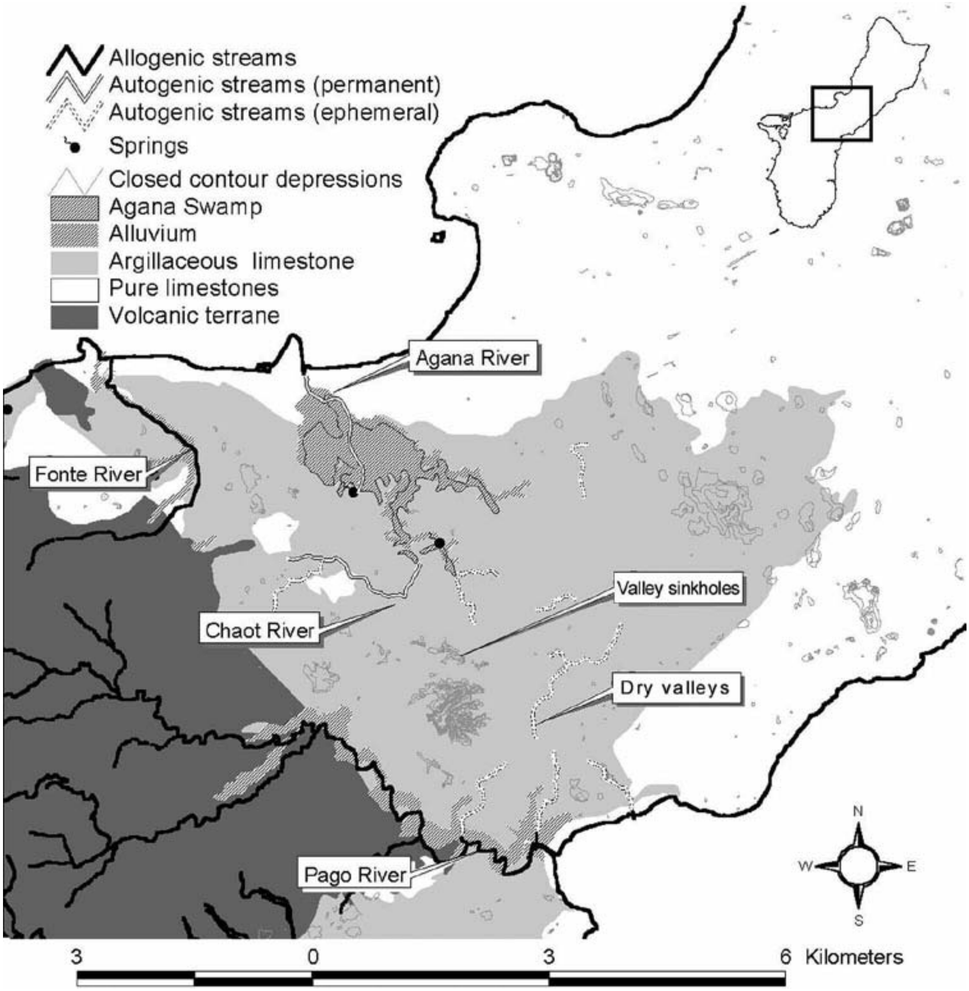

Fig. 5. Fluviokarst in the southern part of the northern Guam plateau.

Because of Guam's complex tectonic history, some karst areas on the island do not neatly fit into any single category. On Nimitz Hill (Fig. 4b), for example, the local karst features exhibit evidence of several processes, including fresh water/sea water mixing, allogenic water input from the adjacent non-carbonate terrain, and tectonic deformation and subsequent modification (e.g., dissolution widening of fractures) by vadose water.

Karst Features of Guam

The karst features of Guam can be discussed in five broad categories, according to their role in the capture, flow, and discharge of groundwater: (1) surface catchment features, (2) surface flow features, (3) closed depressions, (4) caves, and (5) discharge features. Such categorization reflects the sequence of processes that form the karst aquifer as well as the terrain. These categories are therefore useful not only to karst specialists and other earth scientists, but to environmental scientists, engineers, planners and others for whom appropriate land use or aquifer development decisions depend on an understanding of the karst and its interaction with the surface, ground, and marine waters.

Surface Catchment Features

Fig. 6 (inset) shows the general types of surface catchments on Guam. Nonkarst catchments, which characterize most of the south, support surface streams that may deliver allogenic water to karst terrain or directly to the sea. Autogenic catchments, which characterize most of the north, capture water on the dissolutional carbonate surface, through which infiltration can be either diffuse or concentrated, as in ponded sinkholes after heavy rainfall.

The surface catchment features of hydrologic significance on Guam include karren and various features associated with concentrated water input, notably insurgences, man-made ponding basins, and storm water injection wells. Taboroši et al. (2004) present a detailed description of the karren of Guam. The karren are integral parts of the *epikarst,* the top few meters of weathered bedrock containing dissolutionally enlarged fractures, pits, holes and other cavities, commonly filled with sediment. Individual features of the karren and epikarst are too small and numerous to map. Fig. 6 shows the locations of mappable features, including the numerous man-made ponding basins and storm water injection wells that have been installed in northern Guam. Because these are inevitably installed to obviate hazards or nuisances to human activity in areas in which natural ponding already occurs, they can be regarded as simple extensions of natural features. Ponding basins are in almost all cases simply overdeepened natural depressions, which may already feed ponded water to pre-existing *vadose fast flow* routes (see Jocson et al. 2002). Storm water injection wells constitute artificial fast flow routes, and in many cases are likely to simply augment or extend pre-existing natural fast flow routes through the vadose zone.

Surface Flow Features

Because of the high solubility of the host rocks in karst aquifers, surface flow is typically diverted underground. Surface flow is particularly rare on carbonate islands, where the young limestones retain much of the original high porosity. On Guam, it does occur in certain settings but is generally highly limited and quickly captured by insurgences (Fig. 6)

In northern Guam, almost all the rainfall immediately infiltrates or forms ephemeral pools in depressions. The only exceptions are found on the volcanic inliers of Mataguac Hill and Mt. Santa Rosa (Figs. 4 and 7) and in the argillaceous limestone flanking the volcanic terrain of southern Guam. Mataguac Hill and Mt. Santa Rosa are noncarbonate, allogenic catchments from which surface runoff is

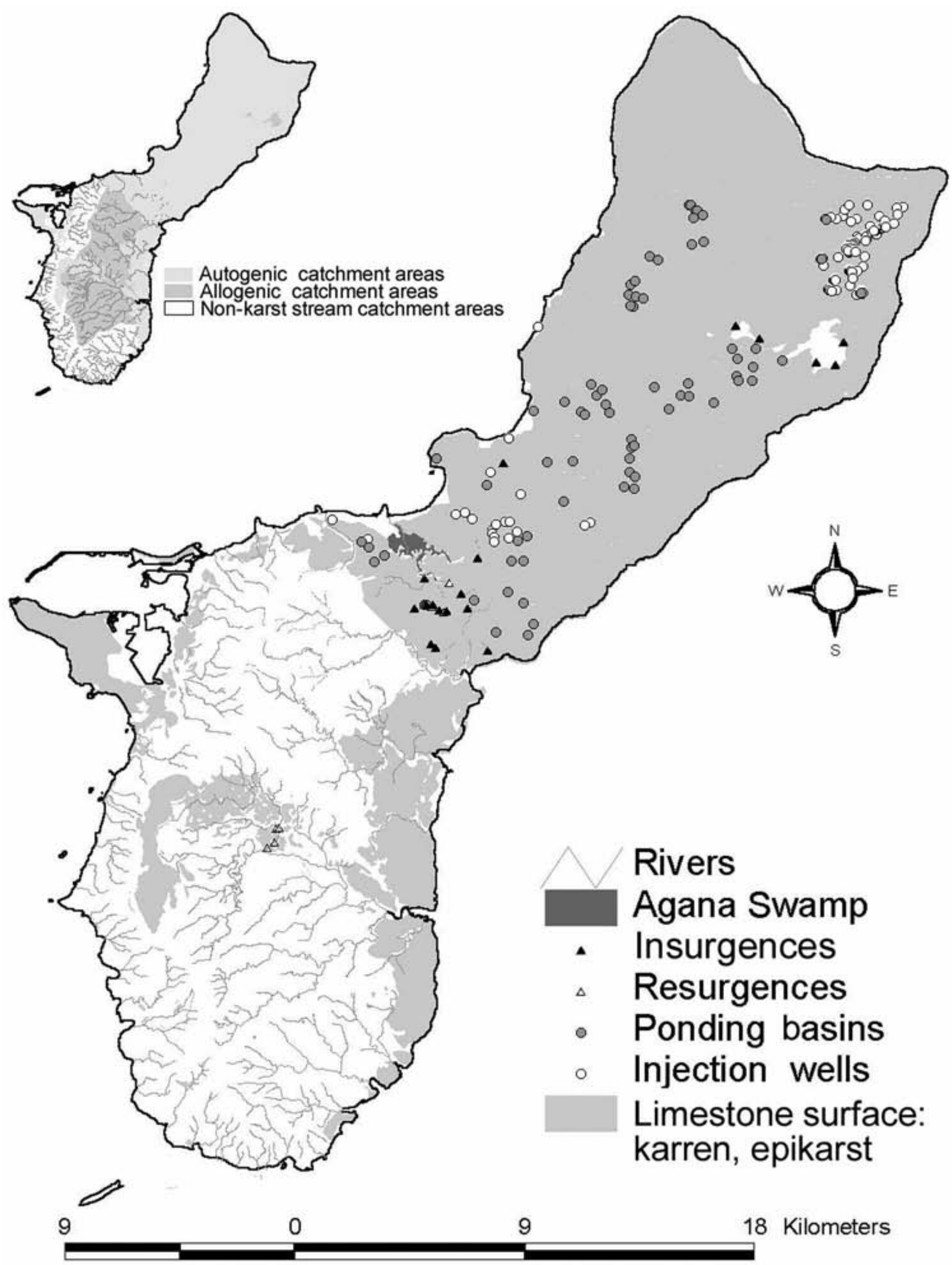

Fig. 6. Mappable surface catchment features of Guam, with inset showing the areas occupied by general catchment types. Locations of storm water injection wells are from Jenson et al. (1998).

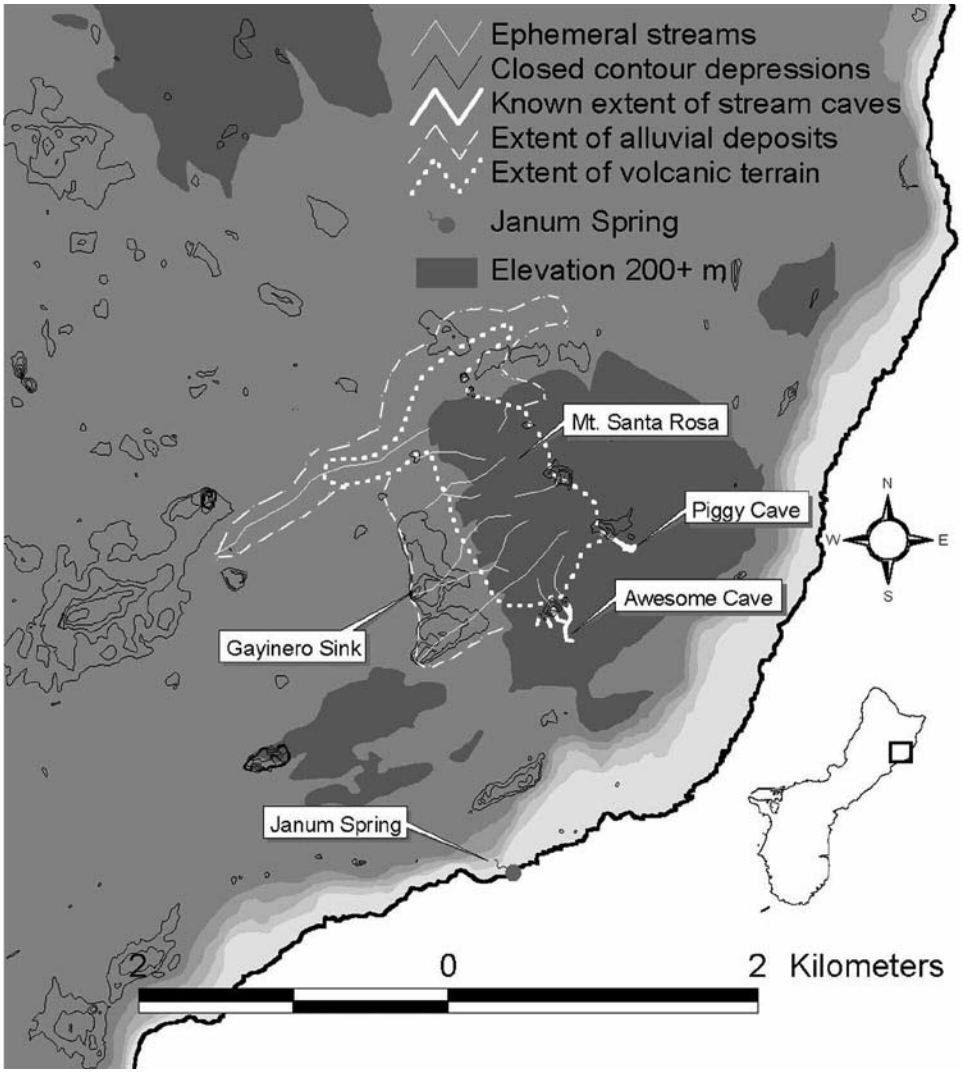

Fig. 7. Mt. Santa Rosa and associated karst features.

focused 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, some of which are traversable, that follow the contact between the volcanic basement units and the overlying limestone. Hydrologically, they are open conduits that are essentially continuations of the ephemeral surface streams. Some of the longest traversable caves on the island, such as Awesome Cave and Piggy Cave on the flanks of Mt. Santa Rosa, are stream caves. Janum Spring (Fig. 7), which is located at the coast south of Mt. Santa Rosa, is probably a discharge terminus of one such cave system. It

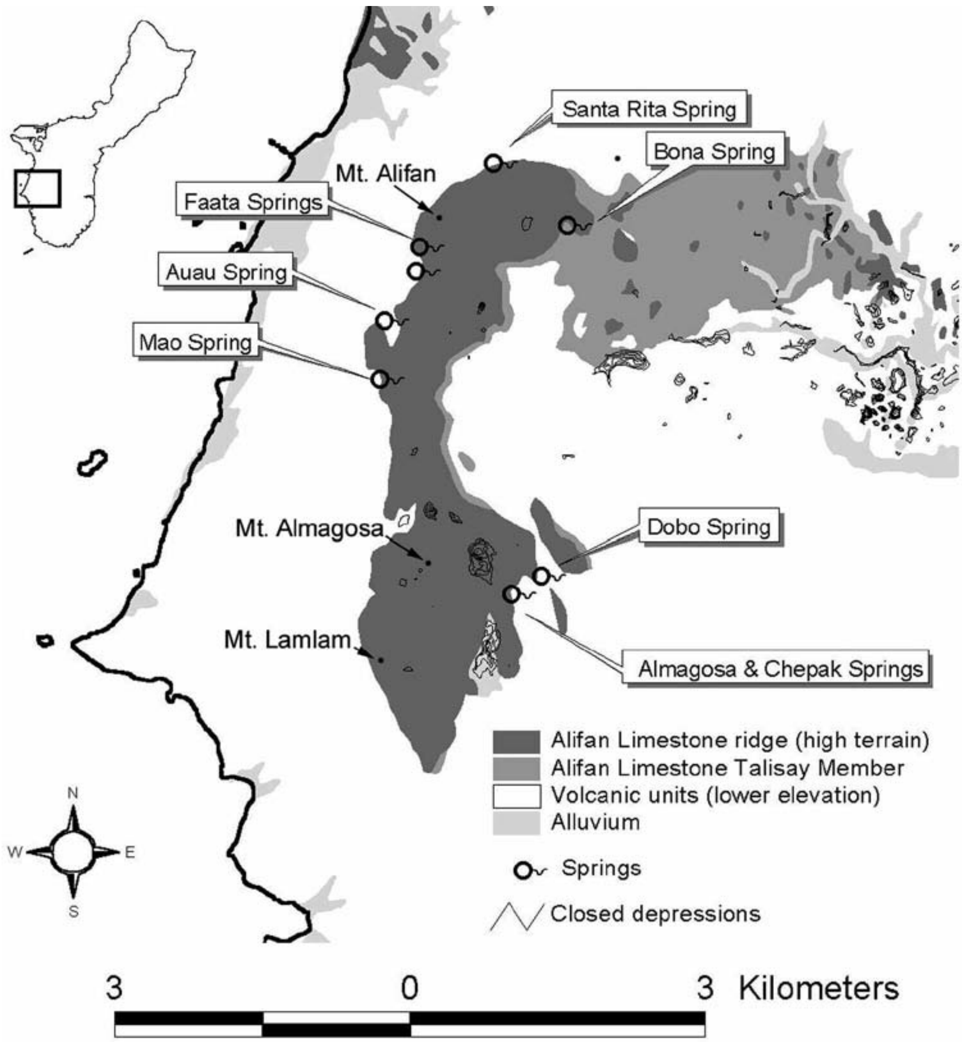

Fig. 8. Southern Mountain ridge and associated karst features.

discharges water of excellent quality, and has been observed to release reddish sediment-laden plumes following heavy rainfalls.

At the southern end of the northern Guam plateau (Fig. 5), the proximity of the southern volcanic highlands combined with the high clay content and resultant lower porosity of the local limestone allows some surface flow. Two perennial allogenic rivers, the Fonte and Pago Rivers, and two perennial autogenic rivers, the Chaot and Agana Rivers, flow across the limestone surface without noticeable volume being diverted underground. 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 area around Guam's capital, Hagåtña, dry valleys have been flooded and filled as relative sea level has risen, and now form the Agana Swamp.

In southern Guam, the remnant limestone inliers are relatively small. They are well integrated into the local surface drainage network and exhibit a variety of karst landforms associated with surface flow. Where limestone outliers stand topographically above the surrounding volcanic terrain, most notably on the ridge from Mt. Alifan to Mt. Lamlam (Fig. 8), *contact springs* form at the contact between them and the underlying volcanic rock. Some springs are seasonal and small, while others permanent and prolific. The largest springs, such as Almagosa Spring on the east side of the Alifan Limestone mountain ridge, form the heads of significant streams.

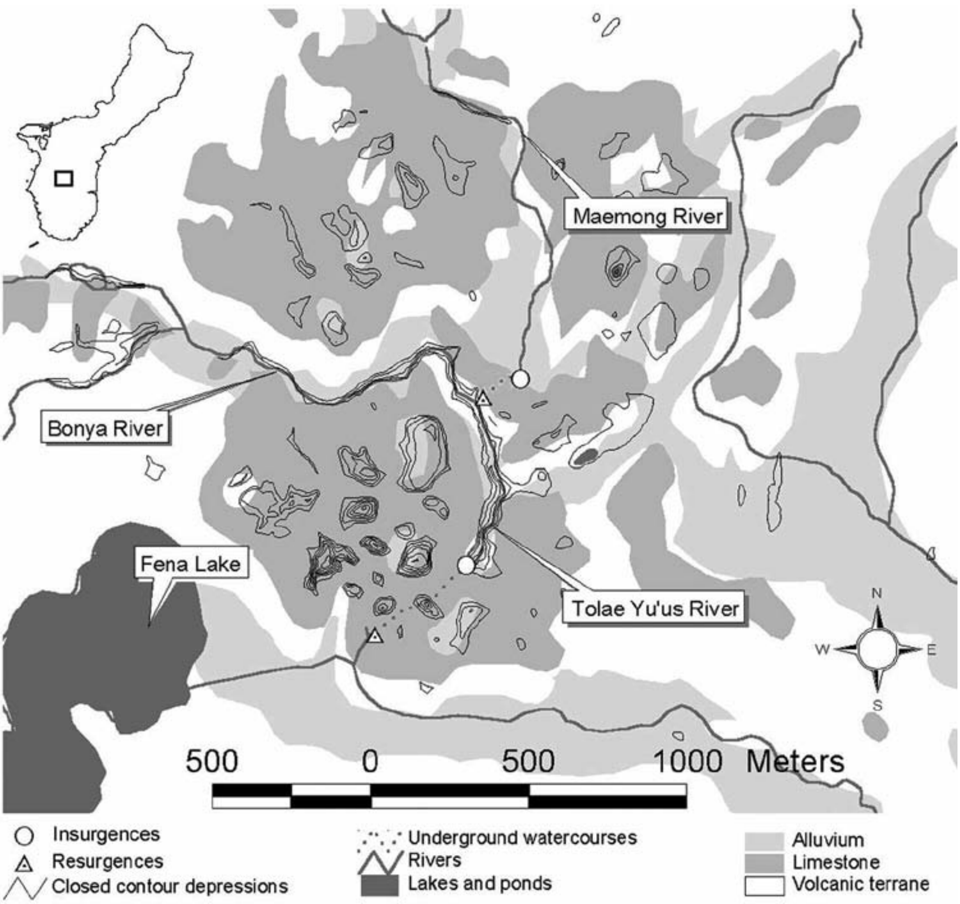

Fig. 9. Cockpit karst in the central basin of southern Guam.

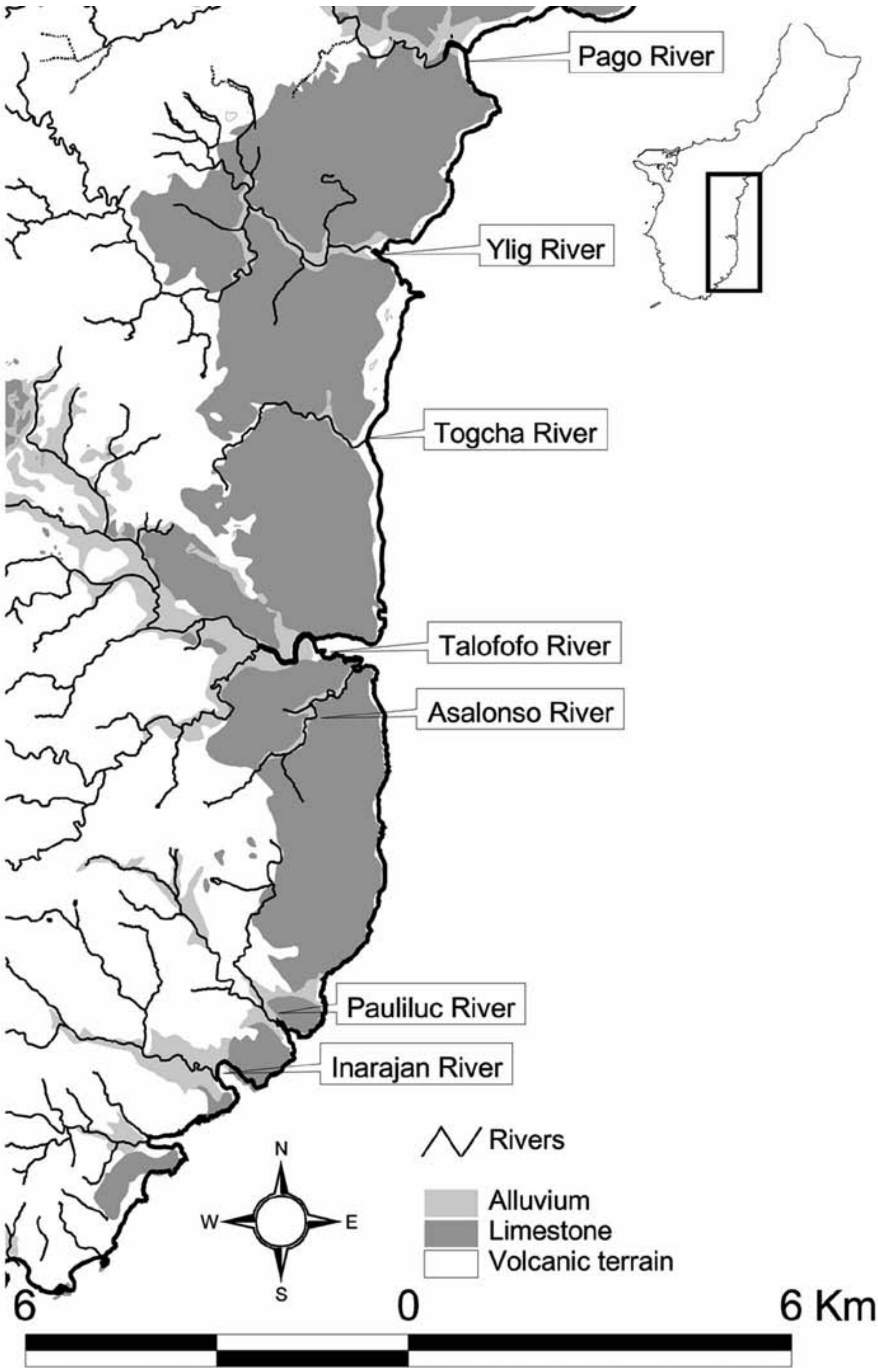

Fig. 10. Limestone coast of southern Guam.

Where outliers are topographically lower than the surrounding volcanic terrain, they are completely traversed by allogenic rivers. These rivers may flow along the contact beneath the limestone, as in the central basin of southern Guam (Fig. 9), or over the carbonate surface, as on the east coast of southern Guam (Fig. 10). Isolated remnants of Bonya Limestone and Alifan Limestone, located in the topographic basin in central southern Guam, stand in the way of two allogenic streams—the Maemong and Bonya Rivers (Fig. 9). Upon reaching a limestone hill, the Maemong River disappears into an *insurgence* and emerges from a *resurgence spring* on the opposite side of the limestone hill. It then joins the Bonya River to form the Tolae Yu'us River, informally known as the Lost River, which also encounters a limestone outlier and flows underneath it for at least 400 m before reappearing at the surface.

Six allogenic rivers traverse the narrow limestone apron on the flank of the southeast coast (Fig. 10). 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 alluvial deposits filling their valleys. Only the Togcha River, which has a relatively small drainage basin, does not reach its mouth at the coast during the dry season, when its low flow sinks along its bed before reaching the coast.

Closed Depressions

Internally drained closed depressions, or *sinkholes,* are characteristic features of karst topography. Closed depressions may be inherited from the primary depositional surface or may be secondary features formed by dissolution or collapse. Writers who use the term as simply descriptive, rather than interpretative, apply it to both types, regardless of origin. Both types of closed depressions are found on Guam. In northern Guam, they are scattered across the plateau surface (Fig. 11). An analysis of digital topographic maps derived from orthocorrected aerial photographs revealed more than 1200 closed depressions deeper than 3 m on the plateau. The vast majority is almost certainly of primary origin. In general, the focusing of surface water necessary to produce solution sinkholes is likely to be rare in the highly porous eogenetic limestones forming most of the local land surface. Moreover, most of the depressions show no diagnostic evidence of solutional origin; they exhibit no insurgences or blind valleys, and are generally broad and shallow, with only 15% deeper than 5 m.

Determining the origin of any particular depression can be complicated by anthropogenic alteration of the surface, including filling for construction and urban development, reshaping into ponding basins (Fig. 5), and quarrying (Fig. 11, inset), all of which have been common in northern Guam. It is currently thought that most of the closed depressions in northern Guam are of primary rather than secondary origin, reflecting the uneven depositional topography of the original Pliocene-Pleistocene lagoon, of which the denuded floor now forms most of the northern Guam land surface (Mylroie et al. 1999). No attempt has been made to estimate total post-emergence denudation or its effect on surface topography.

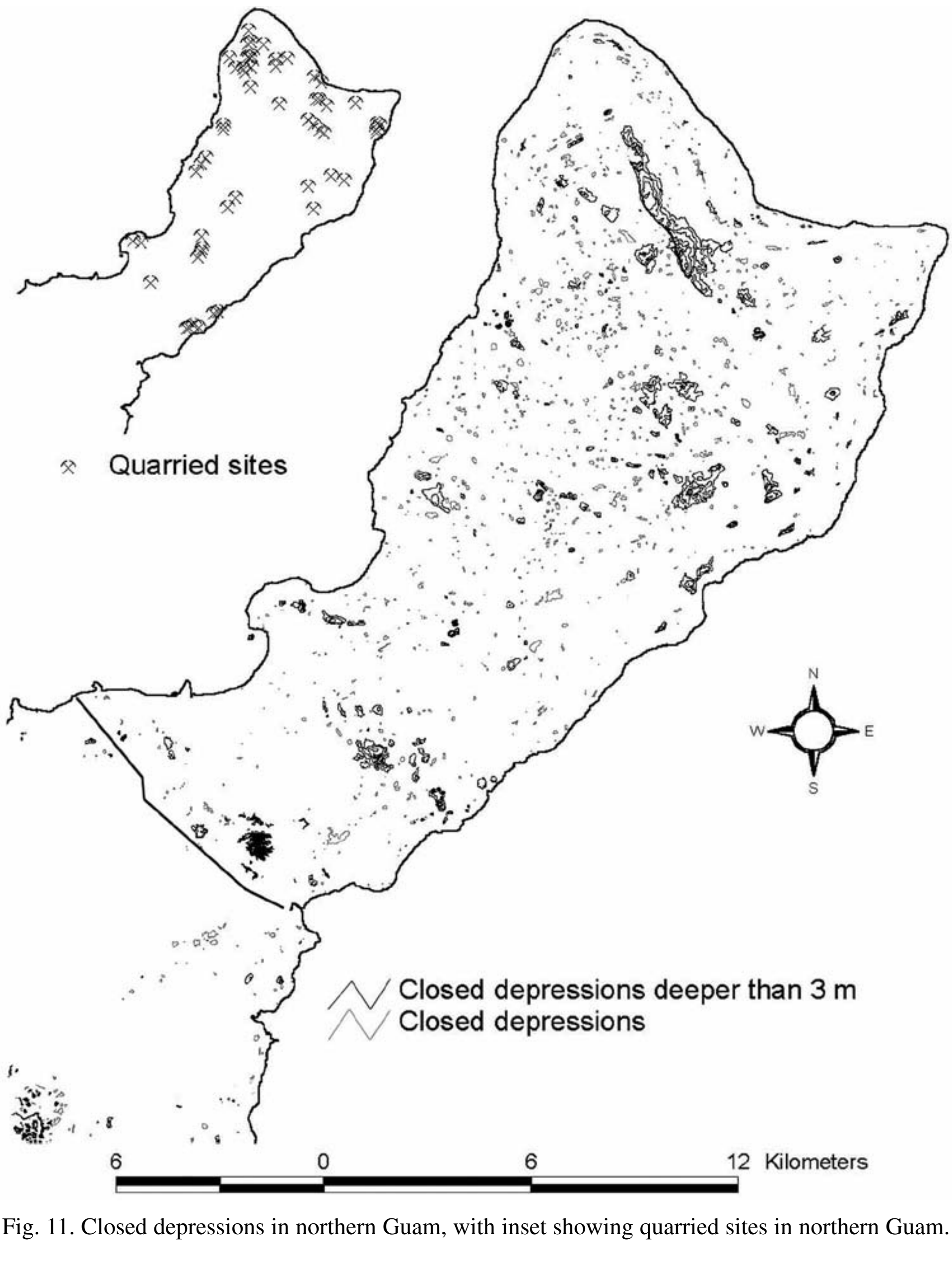

Fig. 11. Closed depressions in northern Guam, with inset showing quarried sites in northern Guam.

Some depressions in northern Guam are clearly true karst sinkholes. At least three categories are found, including *collapse sinkholes,* formed by collapse of subsurface voids; *point recharge sinkholes,* formed by ephemeral allogenic streams coming off the flanks of Mt. Santa Rosa and Mataguac Hill (Figs. 4 and

6); and *valley sinkholes,* found within the dry valleys in the argillaceous limestone at southern end of the plateau, where former streams became diverted to the subsurface.

Most of the depressions in southern Guam, where some 200 were identified, appear to be true sinkholes (Fig. 12). They are generally deeper than the depressions in northern Guam, and exhibit clear evidence of solutional origin, such as insurgence points, associated cave passages, and alluvial deposits. The largest and the deepest sinkholes are found on the Naval Magazine, in Bonya Limestone cockpit karst (Fig. 9). Other significant sinkholes in southern Guam are found in the Alifan Limestone capping the southern mountain ridge, and the Mariana Limestone flanking the southeastern coast.

CAVES

The caves of Guam, as with caves on all karst terrain, can be divided into two fundamental categories: *vadose caves* and *phreatic caves.* Vadose caves are created by water dissolving bedrock in the zone above the water table. Phreatic caves are formed below the water table. Taboroši et al. (2003) provide a comprehensive report on the caves of Guam. It is available on-line and contains maps and photographs of some prominent caves on Guam. Below, we summarize the types and distribution of the caves, the locations of which are shown in Figs. 13 and 14 for northern and southern Guam, respectively.

In northern Guam, extensive vadose caves are found only on the flanks of Mt. Santa Rosa and Mataguac Hill, where the volcanic slopes capture meteoric water, focus it into ephemeral streams, and deliver it to depressions on the contact with the surrounding limestone (Figs. 4 and 6). From these, it descends in *stream caves* that follow the contact to the water table. Although stream caves in general may fundamentally be vadose features, stream caves on Guam show ample evidence of phreatic dissolution as well. Observations in uplifted caves that show evidence of previous phreatic dissolution suggest enlarged chambers develop at the juncture with the water table (Mylroie et al. 2001). Stream caves may also undulate beneath the water table, and may undergo phreatic flow over their entire length during major storms, which are frequent in the Mariana Islands. Moreover, given the complex history of tectonic and glacio-eustatic changes in relative sea level, caves on Guam can be alternately overprinted by prolonged episodes of emergence and submergence.

Other vadose caves on Guam are simpler. These include dissolutionally widened fractures and vertical shafts called *pit caves* (Mylroie & Carew 1995). These are not associated with volcanic inliers and can occur anywhere that structural and lithologic conditions are conducive to focused vadose flow. A striking example is seen at the Two Lovers Park at Amantes Point, where a walkway has been built over the deep vertical shaft.

The vast majority of caves in northern Guam are phreatic caves (Fig. 13) produced by mixing corrosion (Bogli 1964). *Mixing corrosion* is enhanced dissolution that results when waters of different chemistry, each of which may

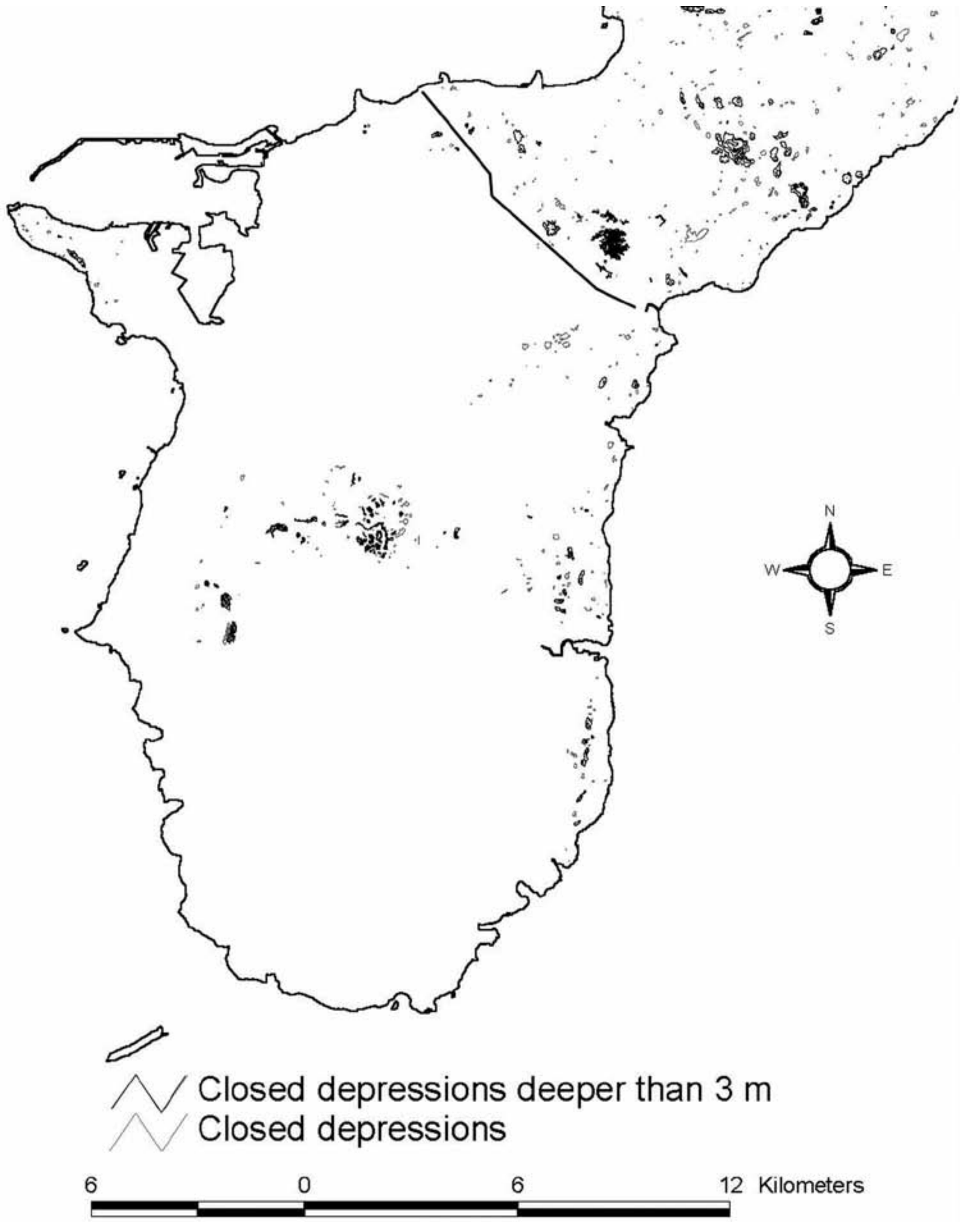

Fig. 12. Closed depressions in southern Guam.

even be saturated in calcium carbonate, mix to form an undersaturated solution. On Guam and similar islands (see Fig. 4a), such mixing occurs at (1) the top of the fresh water lens, where downward percolating vadose fresh water mixes with phreatic fresh water; (2) the bottom of the lens, where phreatic fresh water mixes

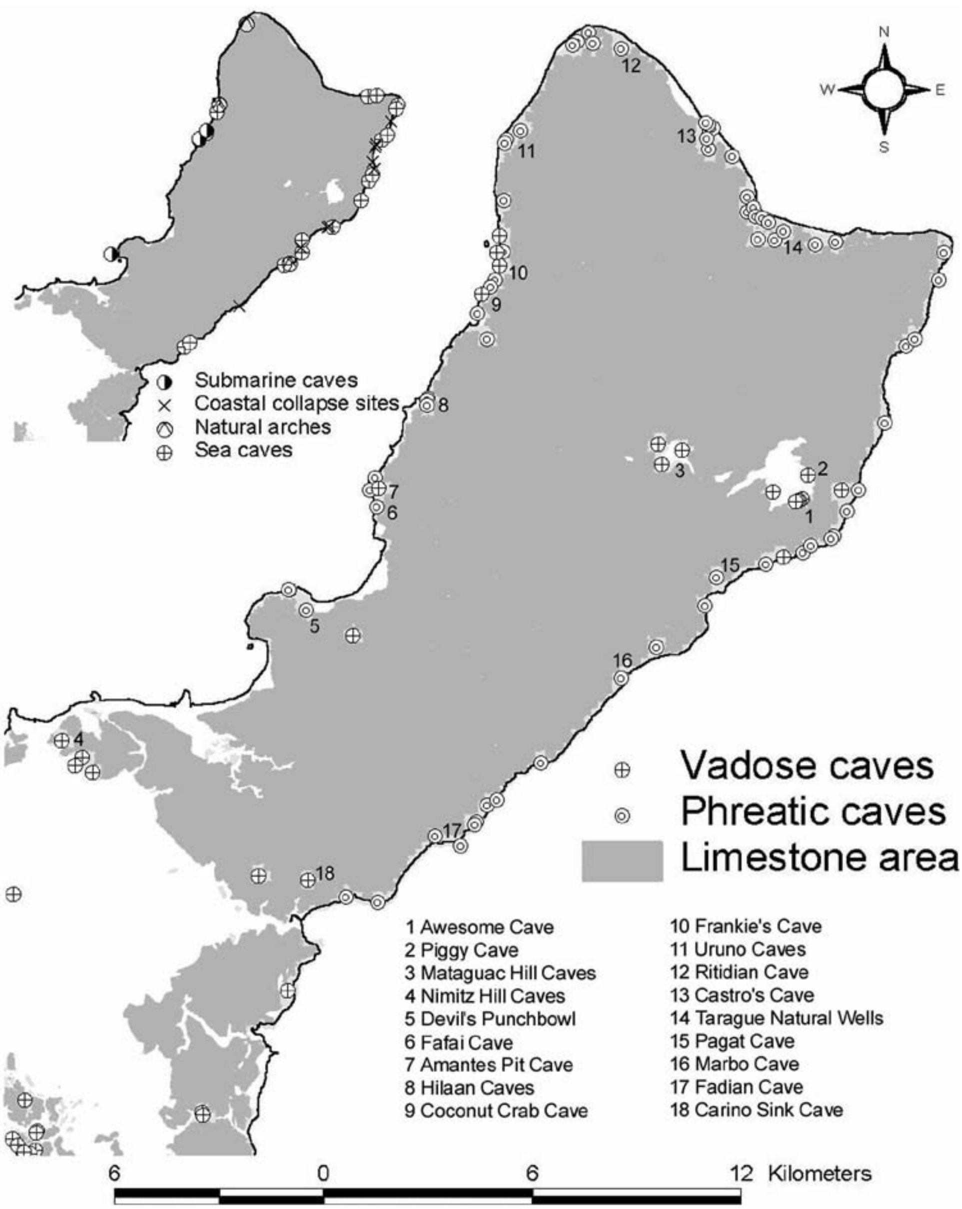

Fig. 13. Caves in northern Guam, with inset showing submarine caves, coastal cliff collapse sites, natural arches, and sea caves in northern Guam.

with phreatic seawater; and (3) the outer margin of the lens, where the top and the bottom mixing zones converge. The caves that form in these three zones, respectively, are called *water table caves* (Mylroie & Carew 1988) or, where ceiling collapse has opened them to the surface, *banana holes* (Harris et al. 1995);

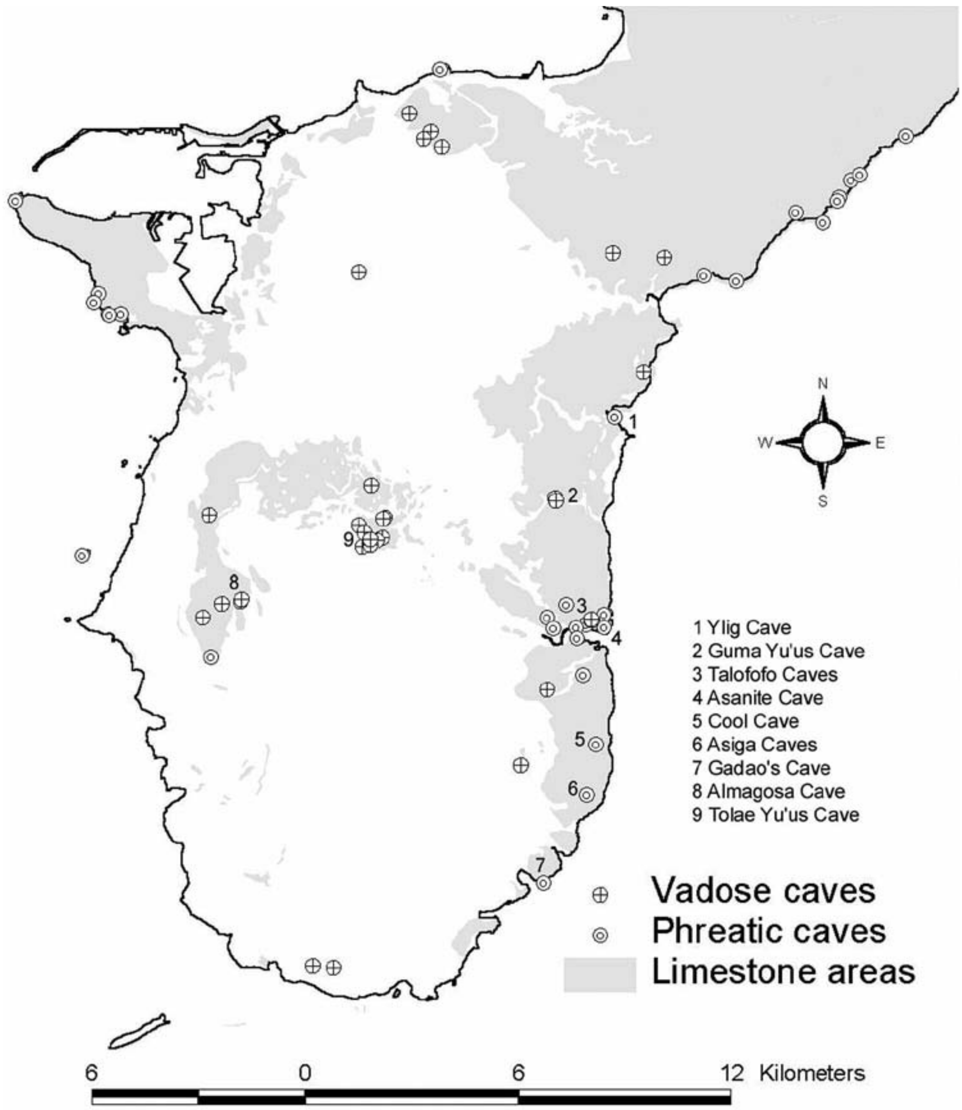

Fig. 14. Caves in southern Guam.

halocline caves (Palmer & Williams 1984); and *flank margin caves* (Mylroie & Carew 1990). Because they form without connections to the land surface, these caves cannot be entered by people unless they are breached by erosion.

Banana holes occur on Guam, but they are rare. Rapid uplift of the island may have brought most unbreached water table caves out of the phreatic zone before they were sufficiently extensive and thin-roofed to be vulnerable to collapse. Lenticular voids, which are common in the walls of deep quarries, where some of them appear to lie along uniform horizons, sometimes associated with changes in color and texture of the bedrock, could be either water table or halocline caves. Because flank margin caves form in the zone of continual and rapid erosion at the coast, breached caves are ubiquitous along coastal cliffs and terraces, not only at modern sea level, but also in cliff-face grooves that mark previous sea levels. Some coastal caves may be ordinary *sea caves* formed by wave erosion (Fig. 13, inset). Given the rate at which flank margin caves are exposed by coastal processes, however, even what appear to be ordinary sea caves can actually be overprinted flank margin caves, whose origin is obscured by recent wave erosion. Flank margin caves on Guam range in size from a few meters to tens of meters. Guam's best known caves, including Pagat Cave, Marbo Cave, and Fafai Cave, are flank margin caves.

In southern Guam, the situation is somewhat reversed from that of the northern half of the island. On the limestone coast of southeast Guam and the Orote Peninsula, flank margin caves are no less common than in the north, but in the Fena basin and the Southern Mountain ridge (Fig 4b) the caves exhibit no characteristics indicative of coastal or marine origin (Fig. 14). The limestone landforms in the Bonya Limestone and Alifan Limestone are small, surrounded by volcanic terrain, and are integrated into local drainage networks. Where the base of carbonate units lies topographically below the surrounding terrain, the caves are created by allogenic streams flowing beneath the limestone, such as Tolae Yu'us Cave, also called Lost River Cave. Where the base of carbonate landforms stands topographically higher than the surrounding terrain, cave passages are created as autogenic vadose flow in the limestone converges along the topographic gradient of the bedrock-basement contact and flow emerges from the resultant contact spring, as at Almagosa Cave.

Not all caves presently conduct water flow. Abandoned stream caves, whose flow was diverted elsewhere, are common in southern Guam. The best known examples are the Talofofo Caves, located in the coastal cliffs overlooking Ipan in southeastern Guam. They appear to have at one time conducted allogenic water from the island's interior toward the coast, but became dry as the island rose and flow shifted toward the local base level established by the nearby Talofofo River. Southern Guam also has a large number of vadose caves that have formed by vadose dissolutional enlargement of fractures. These are most common on Nimitz Hill (Fig. 4b).

Discharge Features

Along the coast of northern Guam, coastal discharge is seen in a variety of expressions (Fig. 15), including springs and seeps in beaches and fringing reefs, *flowing fractures and caves* in coastal cliff faces, and *submarine springs* (Jenson et al. 1997). Springs exhibit distinct vents from which fresh water emerges; seeps are less focused and lack distinct discharge points. Beach seeps can usually be observed only at low tide, when the effluent forms channels, parallel rills, and mini-deltas up to a meter across in the beach sand. Springs on the beach and adja-

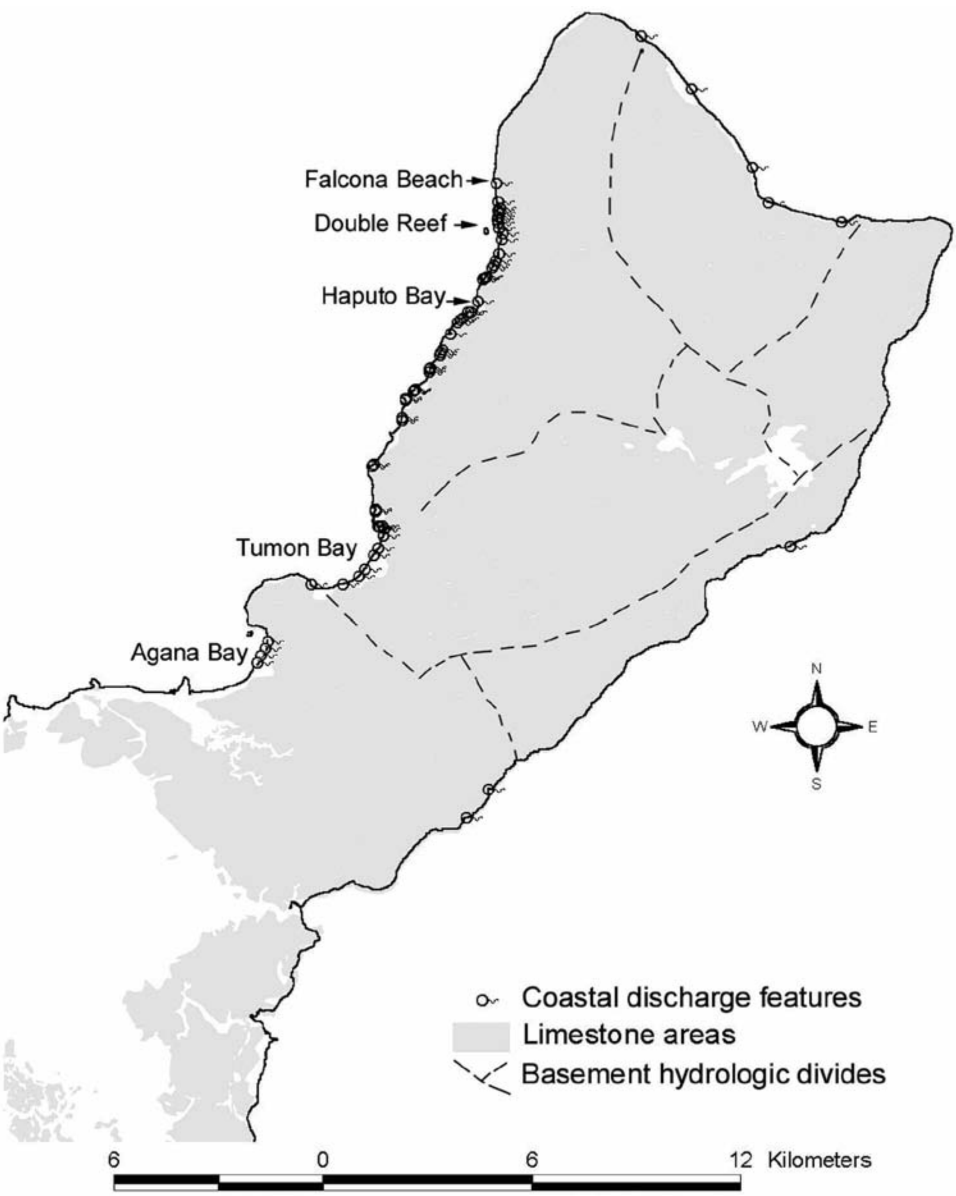

Fig. 15. Coastal discharge features in northern Guam. Also shown are the boundaries of the groundwater catchments that are defined by the ridges of the relatively impermeable basement rock.

cent fringing reefs are also best observed at low tide and calm surf, although the larger springs produce shallow water boils visible even at high tide, so long as the water is calm. Many of the springs and seeps emerging from fringing reefs are permanently submerged. Although their flux and exact discharge points are often difficult to ascertain, their presence is marked by plumes of cooler water and refraction from density currents that can readily be felt or seen while snorkeling in calm water. Beach and reef springs and seeps are most abundant in enscalloped embayments, notably Agana Bay, Tumon Bay, and Haputo Bay.

The largest springs in northern Guam are associated with fractures and caves, which are the characteristic discharge expression in coastal areas occupied by cliffs, especially between Double Reef Beach and Falcona Beach (Fig. 15). Flowing fractures and caves span a wide range of scale. Fractures range from joints only millimeters wide to dissolution-widened corridors up to several meters wide. Caves range from cm-sized openings to meter-sized caves traversable for tens of meters. The largest of the flowing fractures and caves discharge free-surface fresh water streams underlain by seawater, in volumes estimated to reach hundreds of liters of fresh water per second (Jocson 1998, Jocson et al. 1999). Submerged discharging fractures and caves have been identified at depths down to 12 m.

Most of the mapped discharge points are located along the northwestern coast from Tumon Bay to Double Reef, with just a few instances elsewhere. As can be seen in Fig. 15, the high density of the mapped coastal discharge points in Tumon Bay and along the northwest coast are likely related to the relative size and shape of the catchments feeding them. We would also concede, however, that the number of springs mapped on the east coast of the island may be somewhat underrepresented because the sheer coastal cliffs and relentless heavy-surf conditions of the Pacific Ocean make identifying eastern coastal fresh water discharge very challenging. An in-depth interpretation of the occurrence and distribution of springs on the coast is the subject of an upcoming paper by the authors.

In southern Guam, the groundwater collected in the overlying limestone units of the interior discharges from *high-level springs* (Fig. 16) that issue from the contact with the underlying volcanic rocks and thence flow to surface streams. We visited each of the springs shown in the south, with the exception of Dobo Spring, which we were unable to locate in the field. The spring is shown on the current USGS 7.5-minute quadrangle (USGS 1968a) for the area, but not on the hydrologic map that accompanied Ward et al's (1965) report.

A few high-level springs also occur in the north, most notably Agana Spring at the base of the scarp that bounds the southwest side of the Agana Swamp, and Maina Spring, which stands at the head of a west-northwest-trending incision that opens onto the Fonte River valley below. Ward et al (1965) reported that Maina Spring issues from the contact with the underlying volcanic rocks. Pedonlisong Spring, located in a topographic valley at the southeast end of the Agana Swamp may be an ancient dry valley resurgence.

Mataguac Spring, on the flank of Mataguac Hill, is not a karst spring, but rather issues from perched water in the volcanic rocks that stand above the surrounding limestone. The discharge, reported by Ward et al. (1965) to fluctuate from 1 to 10 gpm, disappears into a small stream cave that opens on the contact only a few meters from the spring. The locations for Santa Rosa and Chunge

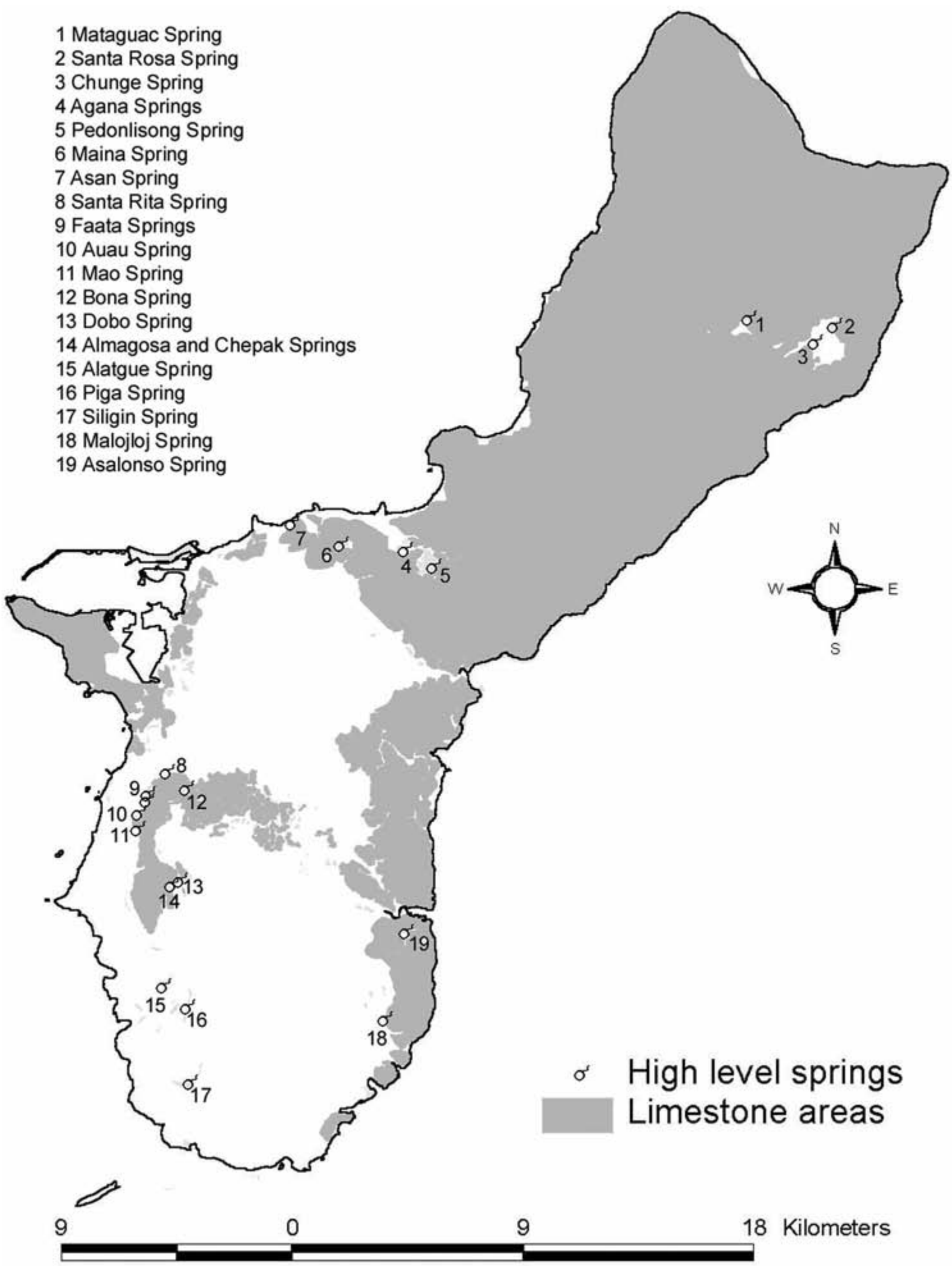

Fig. 16. High level springs on Guam. See text for explanation.

Springs shown in Fig. 16 are taken from the current USGS 7.5-minute quadrangle for the area (USGS 1968b), on which they are mapped as wells. Santa Rosa Spring was mapped as a spring on Tracey et al.'s (1964) geologic map and both were mapped as springs on Ward et al.'s (1965) hydrologic map. Ward et al. reported that both of these springs originate in volcanic rock and that the two springs have a total discharge of 2 to 20 gpm. We attempted to visit them but were unable to locate them in the field.

In the limestone apron on the southeast coast, the catchments are small, and the stream valleys that dissect them may divert some of the groundwater to discharge into the rivers rather than to the coast. Ward et al. (1965) inferred that the eastward-dipping volcanic basement surface was too steep for descending vadose water to accumulate, so that the water flowing down the slope is distributed broadly along the coast. Concentrated coastal discharge features along the southwest coast are commensurately few and small.

Summary and Conclusion

Understanding karst development and aquifer behavior in carbonate coasts and islands requires careful inventory and study of caves and other karst features so that a unifying model can be applied. This paper summarizes the field inventory of karst features on Guam that was undertaken to extend work begun on simpler islands to islands with more complex histories and resultant geology. The maps show the location of each of the significant features identified in the inventory, and illuminate the broad spatial relationships and first-order field relations between the karst, rock units, and terrain features of Guam. Taken together or individually, the maps described in this paper thus provide ready and coherent points of departure for specialized, in-depth studies of each type of karst feature or for more general studies of the geology or hydrology of selected geographic areas of the island. The maps and associated GIS coverages are maintained at WERI's Hydrology Laboratory at the University of Guam.

Acknowledgements

The research reported here is part of a project funded by the U.S. Geological Survey, Water Resources Division, through the Water Resources Research Institute, Regional Competitive Award Program, award number 1434-HQ-96-GR-02665. The initial work was also supported by the Guam Hydrologic Survey Program, instituted by the 24th Guam Legislature and supported by the subsequent legislatures. Invaluable support, both in and out of the field, was provided by David Vann, Curt Wexel, and John Jocson. The authors also deeply appreciate the assistance by Jim Carew, Doug Gamble, Ivan Gill, and Joe Troester and the graduate students and personnel at the Water and Environmental Research Institute of the Western Pacific.

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Received 22 March 2004, revised 9 Dec.