Guam Hydrologic Survey Program

Karst Geology and Hydrology of Guam:

A Preliminary Report

By
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ABSTRACT

The karst geology of Guam is being inventoried and studied in detail for the first time. Previous work on carbonate islands in the Atlantic and Caribbean suggests that a systematic model can be developed to describe the fundamental geologic features that control the movement of natural waters, both fresh and marine, through the rock. The depositional, glacio-eustatic, and tectonic histories of carbonate islands give rise to a unique combination of karst features, which in turn determine characteristic aquifer properties for limestone units in carbonate islands. This report documents initial work during the first year of a two-year project aimed at developing a general Carbonate Island Karst Model (CIKM) by incorporating observations from Guam into the current conceptual models of island karst environments, which have been largely derived from observations of Atlantic-Caribbean islands. Differences in climate and tectonic history between the Indo-Pacific and Atlantic Caribbean have produced features unique to each. Comparative study of islands from the two environments provides clues from each that will help resolve questions raised in the other and contribute to the development of a comprehensive general model. The broad categories of karst features on Guam that are being surveyed and classified according their hydrologic properties include the epikarst, closed depressions and caves. Along with meteorological variables, particularly the temporal and spatial distribution of rainfall, these features determine the rate of surface infiltration, and aquifer storage and transport rates and paths. Aquifer discharge points have been mapped on the northwest coast of Guam, from Tumon Bay to Double Reef, and continue to be studied. Observations of the spatial and temporal distribution of recharge provide important clues regarding aquifer properties and the hydrologic characteristics of the terrain. Work to date has focused on compiling a comprehensive inventory of karst features on Guam and comparing them with analogous features on carbonate islands elsewhere. Specific related questions and supporting work include resolving the origin of the cliff face notches making former sea level stillstands, characterizing spring hydrography through water temperature measurements, conducting petrographic and paleomagnetic analyses to gain insight into uplift rates and other key historical questions, and re-examining previous interpretations of lithology on the island. Research priorities are listed for these, as well as subsequent studies.

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Introduction

This report summarizes observations and tentative conclusions from the first year of a two-year study funded by the Water Resources Research Institute Program of the US Geological Survey. The investigation had its origin in an intensive two-week reconnaissance survey by authors Mylroie and Jenson in July 1998, funded by the Guam Hydrologic Survey Program. Observations from both the initial survey (Appendix I) as well as the first field season of ongoing long-term investigation (Appendix II) are incorporated in this report.

The fieldwork described herein is the first geologic investigation pointed specifically at understanding Guam's karst geology and hydrology. Such understanding is crucial to successful management of the island's fresh water resources because 80% of it's current potable water production and much of its remaining reserve is in the aquifer comprised of the carbonate units covering the northern half of the island. It is our intent to provide here a comprehensive and systematic overview of the carbonate hydrogeology and hydrology of Guam, based on current field observations and conceptual models developed to date (Jenson, 1999). After describing the fundamental geologic attributes of island carbonate aquifers and key karst features on Guam, we summarize meteorological, hydrographic, and field observations that provide crucial insight for interpreting aquifer behavior and framing well-constrained hypotheses for subsequent study. We then highlight significant observations and preliminary findings of the ongoing study and conclude by posing the outstanding research questions that we see emerging for Guam. These provide starting points for more detailed and specialized research into karst hydrogeology and aquifer dynamics on Guam.

The report is addressed to both specialists interested in following the scientific results emerging from the project as well as to water resource managers and others interested in the implications of our findings for public policy and water resource management. The difficulty of doing justice to both in a single report is not lost on the authors. We have attempted to present the theoretical and technical topics in terms that will be both meaningful to specialists and transparent to non-specialists who have had some exposure to basic hydrologic and geologic terms and concepts. We briefly comment throughout the report, where appropriate, on some of the more notable emerging implications of our findings for local water resource managers and policy-makers. We leave it to the reader, however, to select those portions of the discussion that are of most direct interest. We anticipate preparing a detailed assessment of the management implications of our research findings at the culmination of the project, alongside the specialized scientific papers.

Carbonate Island Karst

Field study of Guam's karst offers the first opportunity to apply insights gained from geologic and hydrologic studies of Atlantic and Caribbean carbonate islands (*e.g.* Frank et al., 1998; Mylroie and Carew, 1995; Mylroie et al., 1995, and references therein) to a Pacific carbonate island. A fundamental objective of the ongoing investigation is to not only advance our understanding of the karst on Guam, but to extend the current model of carbonate island karst geology and hydrology by integrating new insights from Guam with previous observations from elsewhere. Our ultimate objective is to eventually construct a general Carbonate Island Karst Model (CIKM) to provide a basis for reliable hydrogeologic interpretation and prediction and appropriate engineering practices for the development and management of carbonate island aquifers everywhere.

The limestones and dolomites of carbonate islands tend to share characteristics that result in unique karst hydrogeology and hydrology. These characteristics are:

- Young carbonates, of Tertiary and Quaternary age.
- Interaction of the fresh groundwater and marine groundwater, with profound geochemical implications.
- Glacio-eustatic variations in sea level, along with possible tectonic movement, resulting in a complex history of migration of the fresh-water lens through the carbonate mass.

Probably the single most important criterion for characterizing the hydrology of carbonate islands is the relationship of the carbonate rocks to the other rock types. Fig. 1 shows three configurations in a continuum of carbonate island rock relationships. This continuum begins with *simple carbonate islands* that are carbonate over their entire surface and to a great depth (Fig. 1a). The Bahamas Islands are an excellent example. An intermediate case is *carbonate cover islands*, in which the island is covered with a complete carbonate surface, but with the presence of non-carbonates at such shallow depths that they interact with the fresh-water lens (Fig. 1b). Bermuda is an excellent example. The final case is *composite carbonate islands* in which non-carbonate rock is exposed at the land surface with full or partial rings of carbonate rocks surrounding the non-carbonate inliers (Fig. 1c). Barbados is an excellent example.

In all three cases, part (or all) of the island aquifer is made up of carbonate rock in contact with marine water. If, in Figure 1c, sea level falls (either by tectonic uplift or glacio-eustacy, or both) and carbonate dissolution continues, the carbonate rocks become minor inliers on top of a non-carbonate platform. In such a setting, the carbonate rocks are de-coupled from marine groundwaters, and their behavior is most like a typical continental karst setting in tropical climate. The lessons learned from continental karst hydrology are then generally applicable, with deviations from the continental model being driven mainly by the youthful age of the carbonates.

What makes carbonate island karst unique is the interaction of marine and fresh groundwaters within a porous and youthful carbonate aquifer. Karst development in carbonate islands is unique in that it takes place in primary material, synchronous with diagenesis, glacio-eustatic sea-level fluctuation, and for some islands, tectonic uplift and subsidence as well (Vacher and Mylroie, Submitted). In general, porosity decreases but permeability increases as original porosity becomes more occluded and secondary pathways develop along complex networks of structural and stratigraphic features. The result is *eogenetic* karst, which exhibits a complex combination of diffuse flow and storage in porous zones, along with well-developed concentrated flow along fractures and conduits. The high porosity of these young carbonates, and their lack of burial diagenesis, allow them to behave at some scales as a classic porous media aquifer, while at the same time dissolutional processes have overprinted the porous media aquifer to produce preferred flow pathways up to and including cave conduits. The mixing of fresh and marine groundwater allows enhanced dissolution not readily accessible in continental situations, adding to the development of both diffuse matrix porosity and cavernous porosity in these islands. As glacio-eustasy has caused sea level to migrate over a 130 m range in the Quaternary, the mixing zone geochemistry of these island carbonate aquifers has similarly migrated. The result is a complex and commonly overprinted set of dissolutional pathways. Tectonically active islands exhibit additional complexity.

Karst Features of Guam

The karst features of Guam can be considered in three broad categories: epikarst, closed depressions, and caves.

Epikarst

The epikarst is the zone of dissolutional sculpturing (karren) and weathered bedrock that develops in the upper few meters of a carbonate rock surface. Karren is a general term used to describe the variety of dissolutional sculpturing on carbonate bedrock in the millimeter to meter scale. This sculpturing is almost entirely independent of the setting (i.e., the expression is the same on island as well as continental settings), except in coastal areas where salt spray produces an environment that produces biokarst (Viles, 1988) or phytokarst (Folk et al., 1973). Karren presents an extremely rough surface to movement of storm water, and in this environment supports little, if any, soil development. Such soils that do develop are commonly piped into the dissolutional cavities of the epikarst. The epikarst environment selects for specific vegetation, so its presence, absence, or modification (due to development) may be an important variable for evaluating variations in regional infiltration and runoff. Below the exposed rock of the karren, soil and weathered bedrock debris overlie solution fissures, holes and other shallow, small cavities in the bedrock, to make up the epikarst. The epikarst is probably capable of significant water storage and may contribute water to the deep vadose zone as diffuse flow, or through pits that bypass the deep vadose zone and supply water directly to the phreatic zone. The epikarst on Guam appears identical to that found on any number of carbonate islands in the Atlantic and Caribbean region (e.g., Bermuda, the Bahamas, Isla de Mona). Recent and ongoing work on Guam suggests that vadose storage, presumably associated with the epikarst, plays an important role in controlling the amount of rainfall ultimately captured in phreatic storage (Contractor and Jenson, in press; Jenson et al., 1997; Jocson, 1998; Jocson et al., 1999).

Water resource managers should be aware that development of wild, vegetated land, dominated by epikarst, to almost any other use probably decreases the infiltration capacity by orders of magnitude. Ponding basins installed on former epikarst surfaces may actually have less infiltration capacity than the natural surface, particularly if the basins are not kept free of sediment.

Closed Depressions

Closed depressions on carbonate islands can be the result of three processes: dissolution, natural construction, and human modification. It can be difficult to separate these three categories, especially as they may all have operated at various times to produce the closed depression observed in the field today. Dissolution on young islands generally produces closed depressions of small to modest size at best (Mylroie and Carew, 1997; Wilson et al., 1995). Areas with autogenic recharge are unlikely to develop large depressions, as dissolution tends to be widespread rather than focussed (Mylroie and Carew, 1997). Most large depressions found on carbonate islands tend to be constructional; that is, they are the result of depositional topography, or subsequent tectonic deformation (Mylroie and Carew, 1997). Dissolutional processes result in these constructional depressions being internally drained, but the entire volume of the depression cannot be ascribed to dissolution. Human activities such as quarrying and construction can produce closed depressions; under the proper circumstances, the existing dissolutional pathways from the epikarst to depth may be able to accommodate all the internal drainage so that these artificial depressions remain dry most of the time.

On Guam, the largest and deepest closed depressions are found on the scattered limestone outcrops of the southern half of the island, or in the area mapped by Tracey, et al. (1964) as the Agana Argillaceous Member of the Mariana Limestone. An important exception is Harmon Sink, which lies immediately south of Tumon Bay. The large closed depressions found on the Agana Member include blind valleys. Without the adjacent insoluble volcanic surfaces, and the colluvium derived from them, to perch meteoric water, and isolate it from active contact with the limestone prior to the stream sink point, the observed large closed depressions could not have formed. To the south, in the area of the Naval Magazine, very large closed depressions are found in the Bonya Limestone, in a pattern mimicking the cockpit karst of Jamaica. In this area, the Bonya Limestone outcrop is entirely surrounded by volcanic rocks, and several streams flow through the outcrop area. These streams provide local base level, and underdrain the limestone. As a result, large, deep closed depressions have developed so close to one another that they are separated by knife-edge ridges reflecting the position of the original land surface. At least one of the base-level streams flows through the subsurface in large conduit passages. To the west, in the Mt. Alamagosa area, some large closed depressions are found in the Alifan Limestone. While the mountain is high ground, the flanks of the mountain intercept surface flow from the adjacent volcanic terrain. This underflow creates conditions for large closed depression development, and the largest are found in areas immediately adjacent to the volcanic terrain, or overlying major conduit flow paths within the Alifan Limestone. Large closed depressions are also found in the Agana Argillaceous Member of the Mariana Limestone in the Talofofo region, where these limestones form a band separating volcanic catchment to the west from discharge points to the Pacific Ocean to the east. As in the region of the boundary fault to the north, the Agana Argillaceous Member's position relative to insoluble units promotes perching of surface water and the production of sinkpoints that create large closed depressions.

On the northern half of Guam, the purer facies and isolation of the Mariana Limestone results in few if any sinking streams and associated deep closed depressions. In the vicinity of Mt. Santa Rosa and nearby Mataguac Hill, however, these volcanic inliers create allogenic recharge that sinks upon reaching the limestone, creating blind valleys that have evolved into large closed depressions. Other large, closed, internally drained depressions exist in the north, but they tend to be broad and shallow, indicative of an origin by constructional processes such as depositional topography and secondary structural modification (primarily faults and brecciated zones). Harmon Sink, in the vicinity of Tumon Bay, appears to be a major exception. While the depression is entirely within the pure facies of the Mariana Limestone, this deep depression contains evidence of carrying water as sinking streams.

Today, building development has modified the depression, and runoff from paved surfaces—including the airport—is diverted into Harmon sink, where it eventually sinks in a series of capture points. These capture points are all inefficient, and as flow volume increases during storms, the water flows successively deeper into the depression to eventually sink at the lowest point. In general, the blocking of closed depressions—whether intentionally for land reclamation, or inadvertently because of the enhanced sedimentation from storm water diverted into them—has enormous implications for storm water drainage, since on karst terrain, these are the natural drain holes that deliver large quantities of storm water to the aquifer during the heaviest rainfalls. From a water quality standpoint, closed depressions generally have enhanced connections to the aquifer, since over geologic time they have delivered concentrations of storm water to the vadose zone. In general, water entering them, if unimpeded by blockage at the base of the depression, will infiltrate rapidly and travel by direct pathways to the saturated zone. As karst areas lack surface drainage, blockage of sinkpoints in depressions results in flooding during high rainfall events.

Caves

Cave development is extensive on Guam. The caves fall into three main categories: stream caves, pit caves, and flank margin caves. In the south, stream caves can be found in the Bonya Limestone at the Naval Magazine and in the Alifan Limestone at Mt Alamagosa. In the north, several can be found on the flank of Mt Santa Rosa. The existence of the latter owes to the adjacent volcanic rock, which provides allogenic catchment of meteoric water, forming surface streams that are both voluminous and dissolutionally aggressive when they reach the limestone. The result is a series of stream caves following the limestone-basement contact (Jenson et al., 1997), analogous to those found in tropical continental areas. In the south, the caves are on limestone inliers perched on volcanic rocks well above sea level, and as a result, have been little affected by glacio-eustatic or tectonic sea level change. At Mt Santa Rosa, however, the stream caves apparently deliver their water to the top of the fresh-water lens and to sea level at Janum Spring on the Pacific coast. As a result, their lower portions should show dissolutional chambers resulting from the mixing of fresh and marine groundwater. The upper levels of Awesome Cave in particular seem to show this effect from an earlier time when this part of Guam was emerging from the sea.

Stream caves typically form large springs, and on Mt Alamagosa, such a cave spring is used as a water production source. The risks of conduit flow for water quality (little filtration, little dilution, rapid transit time, crossing surface water divides) are evident here. The Agana Argillaceous Member of the Mariana Limestone has few identified stream caves, despite having many large sinking streams and blind valleys. In this locality, the relief is low as a result of the sea level rise out of the last glaciation, and the conduits may now be below base level and inaccessible, perhaps clogged with sediment in the low gradient conditions currently present.

Pit caves (Mylroie and Carew, 1995; Mylroie et al., 1995) are a collection of voids that develop to carry vadose water from the epikarst into the subsurface. The deeper ones are effective bypass routes for water, avoiding the slow diffuse flow regime of the vadose zone. These pit caves may intersect other voids at depth, either flank margin caves (Mylroie and Carew, 1995; Mylroie et al., 1995) or stream caves. They can be very abundant locally. In the epikarst, a broad gradation of sizes can exist, from shallow and narrow pipes that barely penetrate the depth of the epikarst, to enlarged fissures, to classic vadose shafts. On Guam they reach depths of up to 50 m (vadose shaft in the Two Lovers Point area). As caves, they are rarely significant features in their own right, but they do have an immense impact on water flow. As they provide a bypass route to the vadose zone, they accelerate the rate of water transfer, introducing flashy conditions in the phreatic water they overlie. They also can introduce contaminants rapidly with little modification directly to the water table.

Guam appears to have an abundance of flank margin caves, that is, caves that formed in the distal margin of the fresh-water lens at a time when sea level (and therefore the fresh-water lens) were at the elevation of the cave (Mylroie and Carew, 1995; Mylroie et al., 1995). These caves are interesting in that they are an excellent representation of the immense dissolutional power of the fresh water/salt water mixing zone. As these caves are fed by diffuse flow in the lens, they are not true conduits, but rather mixing chambers. Their presence indicates that conduit flow was not operating in their immediate vicinity (or it would have captured the diffuse flow that helped develop them). The morphology of these caves as low, wide chambers oriented parallel to the past shoreline is striking and consistent. Paget Cave is a classic flank margin cave showing overprinting by subsequent sea level events. It is currently half-filled with fresh water, yet the walls show evidence of vadose calcite deposition with later dissolution under phreatic conditions. Given glacio-eustasy, and the uplift of the island, such a complex history is expected. During aerial reconnaissance of the island, numerous cave openings were seen on Mariana Limestone outcrops along the periphery of the island, including the entire northern half of the island as well as in the Talofofo area. Most of these voids were clearly at preferred horizons, indicating past positions of the fresh-water lens. If uplift is rapid, then large voids do not have the time to form at a given horizon. The placement of these voids at specific horizons indicates either a glacio-eustatic still stand of sea level, a period of tectonic quiescence, or both.

A fundamental problem that needs resolution is the discrimination of bioerosion notches from similar-appearing voids that developed as flank margin caves but have since been opened to the air by cliff retreat. The standard diagnostic feature has been extensive stalactite-stalagmite development in these notches. Such calcite precipitates are believed to be hampered by the sunlight, wind, and variable humidity of the surface environment. The distinction is important, as bioerosion notches develop without much regard for the dynamics of the fresh-water lens within the island, but flank margin caves are direct representatives of the flow dynamics of the lens. On Guam what appear to be bioerosion notches exhibit extensive stalactite-stalagmite development, which is often soft and tuffaceous. A drilling program to sample both true cave and "surface" stalactite-stalagmite features may yield a diagnostic test of these deposits so that notch origin can be established in any given case.

From the discussion above it can be seen that not only must caves be recognized as components of the karst aquifer, but the different types of caves need to be understood if their implications for island hydrology are to be appreciated. Stream caves must be dealt with as if they were surface watercourses; however their cryptic nature and ability to cross under surface divides means that they can surprise the unwary. Pit caves demonstrate that meteoric input into the aquifer can occur at a variety of speeds, fast for pit caves and slow for diffuse flow. The speed with which contaminants reach the water table is important. For biological debris and sewage, diffuse flow may delay arrival of vadose water long enough for biological activity to render the material harmless, but pit caves will place the material directly in the phreatic aquifer. Flank margin caves indicate a diffuse flow aquifer at the time of their formation, without large-scale conduits. These caves can, however, form in conjunction with stream caves if those stream caves reach the fresh-water lens.

Aquifer Hydrology

Temporal and Spatial Rainfall Patterns

Guam's climate is tropical wet/dry. About 70% of annual rainfall arrives in the five months of July through November. The three driest months, February through April, see only about 10% of the annual total. Over the historical record (1945-1990), monthly rainfall totals below one inch have occurred in February through June. Monthly rainfall totals in excess of 20 inches have occurred in January, May, July, August, September, and October. The heaviest rainfall is associated with tropical cyclones, the likelihood of which is highest from September through November (averaging one in every two years from 1945-1990), and lowest in February and March (with each of these two months seeing only a single storm for the entire period of record). Tropical cyclones passing near or over Guam are responsible for a sizable portion of the total rainfall; from 1957-92, those passing within 180 nautical miles of Guam contributed 12% of the integrated rainfall (Lander, 1994). The seven tropical cyclones passing within 180 nautical miles of Guam during 1992 contributed approximately 40% of the annual total.

Roughly 250 cm (100 in.) of rain falls on Guam during the calendar year. Even though the island is quite small (535 km^2), and its mountains relatively low (401 m or less), the distribution of rainfall is affected by topography: mean annual rainfall totals among recording stations on the island differ by as much as 400 mm (15%). Some of this difference may be due to the effects of elevation (e.g., the driest recording station on Guam is at the International Airport, which under conditions of easterly winds is in the lee of the higher elevations of Mt. Barrigada and Mt. Santa Rosa. This rain-shadow effect of the higher hills is most pronounced in the dry season when east-northeasterly trade winds prevail; at such times the atmosphere is stable, and rain occurs mostly in the form of trade-wind showers or cloud formations with little vertical development (similar to the dominant precipitation regime of the Hawaiian islands, where the rainfall distribution *is* largely a function of elevation).

Except to the extent noted above, however, the spatial distribution of rain on Guam remains poorly characterized. The spatial distribution during the wet season, in particular is not well known, except to note that the large difference between the airport and other locations noted during the dry season is nearly absent. In the rainy season, the atmospheric conditions over the island become more conducive to the production of cumulonimbus clouds and other cloud systems of great vertical development (*i.e.*, deep convection). Isolated thunderstorms, mesoscale convective systems, monsoon squall lines, tropical-cyclone rainbands, and the eye wall clouds of tropical cyclones are examples of cloud systems of great vertical development affecting Guam during the rainy season. During the passage of tropical cyclones over Guam, the path of the eye wall cloud seems to be the only factor in the distribution of the rain: coastal regions are just as likely to report the highest total as other recording stations on hill tops or other elevated sites. Similarly, data from Guam's NEXRAD Doppler weather radar (operational since 1993), and observations of meteorologists on the island suggest that the amount of rain received from other deep-convection phenomena during the rainy season is not strongly related to elevation. On the other hand, for all deep-convection sources other than tropical cyclones, the topography *does* influence the distribution of rain, but by its constraining effects on local storm paths rather than elevation effects. It has been noted that most of the thunderstorm activity near Guam takes place downwind of the island, from just along the leeward coast (leeward being defined by the wind direction present at the time) and out into leeward waters. Given that the wind usually possesses an easterly component, most summer and fall thunderstorms pass seaward from the western coast, and reach a peak of radar-integrated rainfall within about 50 km to the west of the island. It is hypothesized that the highest wet season rainfall in the region of Guam may actually fall in a small area over the sea just to the west of Orote Point.

Current instrumentation of the island for precipitation measurement is described by Dumaliang et al., (1998). Forthcoming installation of rain gages on Mt. Santa Rosa in the north, and Mt. Jumalog Manglo in the south (planned for spring 1999 as part of the WERI-USGS Cooperative Data Collection Program begun in FY 1998) will significantly improve the spatial coverage of rainfall measurement on the island.

Recharge

Analysis of the historical record from the Tiyan (NAS) rain gage, 1956-1995, shows that about 20% of the rainfall comes on days when the daily total is only 0.25 in (0.4 cm) or less. Estimates of minimum monthly aquifer recharge based on differences between daily pan evaporation and rainfall (Jocson, 1998; Jocson et al., 1999) suggest the aquifer receives no significant recharge in months when rainfall is not at least 4 cm (1.7 in.) or more. The 20% of the total that arrives in daily amounts of a quarter inch (0.4 cm) or less is therefore probably unavailable for storage and withdrawal, as it fails to penetrate beyond the epikarst.

As noted in the previous section, a substantial portion of Guam's rainfall comes during heavy storms. Over 20% of the recorded rainfall arrives on days when the 24-hr total exceeds 5 cm (2.0 inches) (Jocson, 1998; Jocson et al., 1999). This suggests that at least another 20% of the total annual rainfall may fall too quickly to be captured and stored by the epikarst, vadose bedrock, or the fresh-water lens. The heaviest rainfall, therefore, may not necessarily provide a proportional amount of the recharge that can be captured in phreatic storage and intercepted by production wells.

The data examined to date thus suggest that most of the recharge to the freshwater lens is probably due to rainfall that arrives in moderate daily intensities, i.e., between 0.6 and 5 cm (0.25 and 2.0) inches. Although a significant proportion of the moderate-to-heavy rainfall that arrives during the dry season may be captured in storage, the portion of total rainfall that comes during the dry season (22%) is much smaller than the wet season portion. The dry season contribution to total annual recharge is therefore likely to be small. An important implication is that aquifer recharge is not degraded by an especially arid dry season. The amount of rain that arrives during the wet season and the rate at which it arrives is much more important. Water resource managers must understand that although drought conditions are most visible and arouse the greatest public interest during the dry season, it is actually wet season recharge that must be monitored and evaluated by hydrologists to be able to determine the impact of drought on water resources.

Infiltration Paths and Rates

Infiltration paths and rates have yet to be characterized in detail. Well hydrographs of daily average water levels prepared by Jocson et al. (1999) show that water table responses to heavy rainfall during the wet season are immediate and strong. The >10 inch (27 cm) rainfall from Typhoon Omar on August 29, 1992 produced about a 5 foot (1.5 m) rise in the water table at an observation well in Dededo (well M-11) within 24 hours following the onset of the storm in an observation well where the water table is about 200 ft (60 m) below the plateau surface. Notably, the well level recovered to nearly its original level in about two weeks following the storm. By comparison, a similarly heavy rainfall of 6 inches (15 cm) on 13 July, 1987, which was the first heavy rain to follow the preceding dry season, produced only a modest rise in the well level.

Together, these observations suggest the following:

- The epikarst and/or vadose bedrock zones are capable of significant storage when dry.
- Heavy rainfall received during the wet season, when the epikarst and/or vadose zones are near water-saturation, is delivered immediately to the lens—in only a matter of hours, maybe even minutes at the extreme, in spite of the vadose bedrock thickness of 60-180 m, through the use of pit caves and other vadose bypass routes.
- Most of the water that infiltrates from heavy rains received during the wet season probably runs off of the lens before much of it can be captured in storage. Specifically, wet antecedent conditions imply that vadose bypass routes must be utilized, as the epikarst is at full storage, so surface water must flow laterally to the pit caves. Vadose bypass routes load the lens with water at specific sites, not uniformly as diffuse flow would do; the local mounding produces larger-than-average heads that quickly drive the water through preferred routes to the sea. The preferred routes developed because they drain preferred vadose bypass routes. Once drained, the water table returns to "normal" and the diffuse flow regime dominates. In other words, lens storage is time-dependent, and like a sponge, if water is delivered to it a more rapid rate than it can absorb, the excess merely runs off.
- A significant portion of the precipitation captured in storage by the lens is probably associated with moderate-to-heavy rains that arrive early enough in the wet season that epikarst and/or vadose zones still possess substantial capacity to store the arriving precipitation, and as this storage is filled, diffuse flow allows previously stored water to be released slowly enough to be captured and stored in the underlying fresh-water lens.
- Most of the rest of aquifer recharge is probably due to light-to-moderate rainfall that arrives during the remainder of the wet season.

These assertions are further supported by comparing monthly average well levels with those calculated by a numerical model in which 100% of estimated monthly recharge is assumed to infiltrate to the lens within each monthly time-step of the simulation (Jocson, 1998; Jocson et al., 1999). Simulations over a fourteen-year period-of-record have consistently higher amplitude than their observed counterparts. The most straightforward explanation for this discrepancy is that a substantial amount of precipitation received during the wet season is retained by the epikarst and/or vadose bedrock and released slowly enough to buffer both the wet and dry season levels.

As previously mentioned, an important question, and one that in particular calls for a better understanding of the karst geology of the aquifer, is what proportion of infiltration is concentrated along direct, open pathways or vadose bypass routes (presumably draining the closed depressions) and what proportion travels as relatively diffuse flow (presumably from the epikarst). Observations described above indicate that certainly in the case of heavy wet season storms most of the rainfall must travel to the surface of the lens by way of relatively open pathways. Modeling of the infiltration through the vadose zone (Contractor and Jenson, in press) shows that best fits between simulated and actual water levels are produced when 32% of monthly recharge is assumed to arrive immediately. Beyond these generalizations, however, the relationships between precipitation rate, infiltration rate, vadose storage, and phreatic storage remain poorly known. Until these relationships are more precisely known, predictions of the aquifer response to pumping and storm water disposal will be limited by the lack of precision in estimates of infiltration rates and recharge.

Internal Transport

The nature of internal transport through either the vadose or phreatic zones has yet to be systematically studied, but ongoing work at environmental restoration sites by the military activities on the island has yielded important insights. Dye trace studies so far have shown evidence for directed flow in the vadose zone, and for both diffuse and directed flow in the phreatic zone. In September 1992, following Typhoon Omar, different dyes were simultaneously injected into the vadose zone and phreatic zone in a borehole installed next to a landfill remediation site, about 3.5 km inland on Andersen Air Force Base, at the northeast corner of the island. Dye injected in the vadose zone followed linear flow paths consistent with the dominant fracture orientation for northern Guam, with average transport rates of 90 to 240 m/d (300 to 800 ft/d). Notably, dye injected in the vadose zone was not intercepted at some intermediate monitoring sites along the lines between the injection point and monitoring sites at which dye was detected. Dye injected at the water table was subsequently detected at several down-gradient, transversely-distributed sites along the coast, consistent with a dispersed style of flow, suggestive of transport through porous media. Average transport rates were about 6 to 11 m/d (20 to 36 ft/d), nearly an order of magnitude smaller than those observed in the vadose zone.

In separate dye trace in July 1994, dyes were injected into boreholes penetrating a post-WWII dump site in a closed depression near the Navy's Finegayen housing area, about 2 km inland of Tanguisson Point (OEESCI, 1995). One dye was injected at the base of the landfill, a second at the water table. Monitoring wells were placed around the site at seven locations about 75-100 m from the injection points. None intercepted dye, even though dye was observed to disperse from the phreatic injection point. In October, dye originally injected in the vadose zone was detected in Lost Pond, a small cenote on the coast about 1 km north of Tanguisson Point (OEESCI, 1995, Appx. H). In a second trial at the same site in July 1999, dye was injected in a small banana-hole style sinkhole (Harris et al., 1995) adjacent to the site, into which stormwater from the now capped landfill is diverted. After priming the sink and chasing the dye with large amounts of water to simulate a heavy rainfall, dye was detected at the coast 4 hours after injection (P. Casey, personal communication).

Ongoing installation of production wells has shown that although all wells that penetrate the limestone to below sea level in the interior of the island yield some fresh water, hydraulic conductivity varies substantially. Ongoing pumping tests conducted in areas mapped as Barrigada Limestone (Earth Tech data, on file at WERI) show differences in hydraulic conductivity of about an order of magnitude, ranging from ones to hundreds of m/d. The relationship between conductivity and geologic conditions is not well known. Initial investigations at WERI of cuttings from these boreholes suggest that stratigraphy and variations in limestone composition in the Barrigada Limestone (the principal aquifer unit in the phreatic zone) may be more complex than previously known. More systematic study of borehole stratigraphy and lithology is required to identify the relationship between hydrologic properties of the bedrock and geologic variables.

The successful application of Darcian groundwater flow models to the Northern Guam Lens Aquifer (Contractor, 1981; Contractor, 1983; Contractor and Srivastava, 1990; Jocson, 1998; Jocson et al., 1999) reflects the fact that the aquifer contains sufficiently pervasive porosity to store and transmit a significant portion of the recharge through Darcian flow. Models using monthly or seasonal average recharge are able to reproduce the behavior of diffuse flow component of the aquifer, since the characteristic time of diffuse flow in the aquifer is on the order of months to years. Hydrograph analysis (Jocson, 1998; Jocson et al., 1999) shows, however, that rapid and heavy recharge from storms is discharged rapidly. This implies that relief pathways, presumably along fractures and conduits, must be active, as in continental karst systems. As discussed above at least 20% of the recharge to the aquifer comes in such heavy storms, so that it is not captured in diffuse storage, and is omitted by Darcian models.

Aquifer Discharge

The coastline of the limestone plateau around northern Guam exhibits three different morphologies, each associated with a distinct style of groundwater discharge (Jenson et al., 1997). Where sheer cliffs dominate the coast, there are no beaches. Here, groundwater discharges from the cliff faces, most commonly from dissolution-widened fractures, but also from caves that open to the sea. These have been mapped in detail from Tumon Bay to Double Reef on the northwest coast (Jocson, 1998; Jocson et al., 1999) (Fig. 2), but have not yet been systematically mapped elsewhere. In the area mapped by Jocson (1998) estimates of significant discharge from fractures range from about 200 m^3/d (0.05 mgd) to 7,500 m^3/d (2 mgd); estimated discharge from the caves ranges from about 2,300 m^3/d (0.6 mgd) to 20,000 m^3/d (5 mgd). Where the cliffs are recessed from the coastline, the shoreline typically contains linear beaches along the edge of the lowermost of the uplifted marine terraces that front the cliffline. On these beaches, some groundwater can be seen discharging from seeps exposed at low tide, and there are occasional springs with significant discharge, but combined discharge on such beaches appears to be small compared to the discharge from fractures and caves emerging where cliff faces form the coastline. The third important morphology associated with the limestone plateau is enscalloped embayments. These are flanked on either side by shear cliffs that come all the way out to the coastline. Inside, the cliffs recede, with the landward floor of the embayment sloping gently inland. The seaward opening of the embayment contains a beach, following an arc that is recessed inland, and protected by a reef platform extending seaward to the reef margin built along the line between the two flanks of the embayment. The most notable—and archetypical—of these is Tumon Bay. Haputo Bay, to the north, is much smaller, but exhibits the same morphology. In both of these, ubiquitous springs and seeps are exposed at low tide. Discharge appears to be especially concentrated near the flanks of the embayments, although this has yet to be rigorously examined. Field estimates of the discharge in Tumon Bay (Jocson, 1998; Jocson et al., 1999) total 8.3 x 10^4 m^3/day (22 mgd). Sasajvan, on the opposite side of the island, appears to be an uplifted, abandoned embayment of the same type. We are exploring the possibility that such embayments may be the result of karst dissolution resulting from mixing of discharging fresh waters with the sea, similar to the caletas reported by Back et al. (Back et al., 1984). The modern groundwater catchment behind Sasajvan, which is constrained by the Barrigada-Santa Rosa basement ridge that runs immediately behind Sasajvan, however, is much smaller the catchment behind Tumon Bay. It would therefore seem that groundwater discharge would be a significant determinant of Sasajvan's morphology, only if the basement ridged could have been overtopped by the lens at a higher relative sea level. The presence of Marbo Cave, where a pool of water connected to some sort of conduit system is exposed, suggests that the hydrogeological relationships are complex, and will require focused study to be better understood.

On southern Guam, the southeastern coast, mapped (Tracey et al., 1964) as the Argillaceous Member of the Mariana Limestone, lies on the flank of the dip-slope of the volcanic units that comprise the terrain to the west. Sheer cliffs dominate in some places. In others the cliff line is recessed, with linear beaches developed on the edge of uplifted marine terraces, as on the northern plateau. There are no enscalloped embayments. The most striking feature along the southeastern limestone coast, however, is the deeply incised embayment cut by the antecedent streams originating on the volcanic terrain inland. The streams have cut steep-walled valleys through the limestone, and coastal bathymetry verifies that the incisions continue down to the depth of the lowest glacio-eustatic still stands. The valleys are now filled to sea level by Quaternary alluvium that supports local agriculture and aquaculture. The nature of groundwater discharge from the limestone terrain on the southeastern coast has yet to be studied in detail. Without doubt, it is modified in important ways by interaction with the several stream valleys that intersect it. If serious attempts are eventually to be made to exploit groundwater resources from this limestone unit, a systematic study will need to be made to identify hydrologic boundaries and characterize the properties of the aquifer with each hydrologic unit.

Aquifer History

Review of the literature on the geology and hydrology of Guam reveals that little geochronology has been done on the island. Work to date has produced only a few Holocene dates for some of the relict fringing reef (Easton et al., 1978; Tracey et al., 1964). So far, only a single date earlier than Holocene has been obtained (Randall and Siegrist, 1996) for any of the limestone. The rates of uplift, and of karst development, have not been given systematic attention. Given that the position of the fresh-water lens and its mixing zone with marine water enhances porosity and cave development at depth in the island, such chronology is critical to developing an accurate picture of aquifer properties. Given that the island is raised, past fresh-water lens horizons should be present above modern base level. These laterally permeable areas may deflect vadose flow (such flow is audible in storm water injection wells on the north end of the island), with implications for both water supply and water quality management. In addition, since previous sea levels have occupied positions below the modern sea level, the dynamics of modern phreatic flow may have been modified in important ways. In particular, interaction with seawater along the coast could be influenced by way of higher-conductivity connections to the coastal zone that developed during still stands below present sea level.

In many carbonate islands, U/Th dating of fossil corals has been successful in determining the age of exposed fossil reefs. However, Guam has a very wet climate, and it is unlikely that corals more than 100,000 years in age are still aragonitic. Once meteoric water has produced inversion to calcite, closed system conditions are lost, precluding dating. However, cave speleothems (stalagmites are preferred) are originally precipitated as calcite, so no open system problems occur. The growth layers of stalagmites can be examined to determine rates of growth and potential interruptions, such as flooding by a sea-level highstand. The U/Th technique is reliable back to 350 ka (perhaps further with mass-spectrometer techniques), so a more powerful tool may be necessary. Paleomagnetics has proved useful in determining that some of the caves on Isla de Mona are more than 1.7 million years in age (Panuska et al., 1998), and paleomagnetics may also be utilized on Guam to determine cave, and therefore sea level, history. Carbon-14, because of its limited age range, is not an effective tool for this purpose. Both U/Th and paleomagnetic methods would be applied to flank margin caves and other chambers of perhaps similar origin (as in Awesome Cave), to determine minimum ages for cave development and hence fresh-water lens position at that horizon. A concurrent collection plan in the Bonya or Alifan Limestone caves of the south would provide control, as those caves should not have undergone the marine inundation experienced by the northern flank margin caves.

Water Geochemistry
The island has numerous seeps and springs around its periphery, and Guam has one of the best documented data sets on the distribution and flow of these springs (Ayers and Clayshulte, 1984; Emery, 1962; Jenson et al., 1997; Jocson, 1998; Jocson et al., 1999; Matson, 1993; Ward et al., 1965; Zolan, 1982). To date, however, little carbonate geochemistry has been done to determine the nature of the chemical processes experienced by water flowing through Guam's limestone units. A sampling regime from large and small springs may help evaluate the relative importance of conduit, fracture, and diffuse flow within the aquifer. Such an assessment would help predict the storage in the aquifer, as well as the transmission rate for contaminants, for site-specific conditions. Work on the water quality of selected springs is also important. For example, at the southern end of Tumon Bay, coastal springs have prolific growths of green algae. In other settings, such growth is associated with pollutants rich in nitrate and/or phosphate. Given that this area is immediately adjacent to Harmon Sink, analysis for plant nutrient content is imperative.

Principal Findings and Significance: 1999 Field Season
Specific significant findings from the first year's work include the following:

Guam Karst Inventory and Comparative Field Investigations
The karst inventory, including photo-documentation and survey of the island's caves and their hydrologic significance, is ongoing (Taborosi, 1999). Data being compiled into GIS maps and other media for spatial analysis will enable us to sort karst features into vadose, fresh-water phreatic and mixing zone features, and thereby delineate past fresh-water lens positions, which are fundamental to accurate interpretation and prediction of aquifer properties. During the summer 1999 field season, comparative studies were initiated by the authors and/or colleagues collaborating on the two-year project (Appendix III) on Saipan, Isla de Mona, Puerto Rico, and the main island of Puerto Rico. These studies will document the similarities and differences between karst features on Guam and those that have developed in different environments, which will enable more reliable interpretation of features and prediction of aquifer behavior on Guam.

The limestone units on Saipan, although deposited at about the same time, and having subsequently undergone a tectonic history similar to Guam's, reflect a range of depositional environments not found on Guam. Carbonate and volcanic units are interlayered, and structural features appear to influence aquifer properties to a greater degree than observed elsewhere thus far. Reconnaissance work on Saipan during summer 1999 indicates that a more intensive investigation will reveal important new insights into the relationships between aquifer properties and aquifer history.

Isla de Mona, Puerto Rico, has similar-aged limestone but simpler stratigraphy and a better-controlled uplift history. It therefore provides a basis for inferring how closely processes on Guam have come to reaching the expected end states, which in turn provides a basis for inferring the effect of Guam's uplift history on its karst features.

The island of Puerto Rico provides important clues regarding the evolution of karst in a large-island environment. Examination of evidence of repeated exposure and karstification, including dolomitization of certain limestone units, in Puerto Rico is expected to provide insights into the origins of anisotropic permeability patterns affect recharge and flow patterns in the shallow, water-table aquifer. We anticipate that the results of these comparative field investigations will reveal important insights regarding the evolution of karst in young limestone units and the inter-relationships between the resultant karst features, island size, climate, and other key variables that determine aquifer properties.

Notching in Uplifted Carbonate Rocks
Most of the horizontal notches cut into the cliff faces surrounded by the sea on carbonate islands have been interpreted as bioerosion notches. Lateral corrosion and cliff retreat may also produce notches, however. Interpreting the origin of the notches correctly is a key step in correctly characterizing the nature of groundwater flow and discharge in island karst and the concomitant development of island karst aquifer properties. We suspect many of the notches seen on Guam to be remnants of flank margin caves breached by cliff retreat. Detailed surveys of modern bioerosion notches and older notches of questionable origin began during the summer 1999 field season and will continue the summer 2000, along with petrographic analyses of the host rock and speleothems found in the notches. This work is the basis for a master's thesis project at Mississippi State University.

Spring Hydrography from Temperature Measurement
The thermal contrast between warm tidal waters and cooler discharging groundwater at coastal discharge outlets from fractures and conduits appears to match the visually observed halocline in these features, indicating temperature might be a proxy for degree of mixing and discharge. Promising early results suggest it might be possible to deduce pulses of storm-driven spring flow from temperature records. This will enable the first systematic hydrographic data to be collected on Guam's coastal springs. Sites identified as promising during the 1999 field season are currently instrumented, and the Guam-based members of the research team are collecting data.

Petrographic Analyses
Rock samples from Guam, Isla de Mona, and Puerto Rico have been evaluated and are being prepared for thin sectioning. When thin sections are complete they will be described and point-counted by the students who participated in the fieldwork. The thin-section data will be used to gain insight into the porosity and permeability history of the rocks, which will provide a basis for inferring expected hydrologic properties of the rock units from which they came. A sampling plan for next summer's fieldwork is being developed based on the findings from these samples.

Paleomagnetic Analyses
Reconnaissance sampling of oriented paleomagnetic cores was performed at a number of surface and subsurface sites on Guam. Early results show that some samples exhibit a strong signal, including a

reversal, but others will require application of cryogenic techniques. If successful, these data will provide important temporal control for deciphering the uplift and weathering history for the island. Radiogenic dating has limited application on Guam, because most of the limestone has been diagentically altered by exposure to meteoric water or fresh groundwater as the units moved up and down through the freshwater lens.

Reexamination of Previously Mapped Lithology
The Argillaceous Member of the Mariana Limestone on Guam, a major rock unit that flanks the volcanic terrain at the southern end of the aquifer, exhibits distinctly different karst morphology and hydrologic properties from the "clean" limestone to the north. These distinctive attributes have up to now been assumed to be derived from terrigenous sediment from the nearby volcanic terrain having been incorporated into the limestone during deposition. Field examination of selected exposures during the 1999 field season suggests, however, that the insoluble material in the rock might merely have been brought into the interstices of pre-existing rock by weathering and vadose transport. If substantiated during the next year's work, this will require a thorough revision of current explanations and assumptions regarding the hydrologic properties of the unit, with important implications for future water resource development and management. At the more fundamental level, it will also require a reevaluation of current geological understanding of processes and rates of lateral transport of weathered volcanic materials onto adjacent limestone outcrops by mass wasting and stream flow.

Porosity Enhancement by Condensation Corrosion in the Vadose Zone
Initial air temperature profile data from caves on Guam offer no evidence that the thermal regime of carbonate island caves would support the air flow and condensation necessary to support significant dissolution in the vadose zone. Condensation corrosion has been proposed as a process by which vadose caves could be enlarged over time. The absence of evidence for it on Guam and the other islands examined suggests that the evolution of vadose conduits must be explained in terms of hydrologic rather than atmospheric processes. This will help to bound the hydrologic characteristics that can be expected of conduits in the vadose environment.

Research priorities
To manage Guam's groundwater resources effectively as the needs to locate productive well sites and ascertain appropriate production limits become more urgent, hydrologists and water managers must have more accurate and detailed understanding of the aquifer processes and properties described above. Much insight can be gained by comparing features observed on Guam with those documented or are currently under study on similar islands elsewhere. Ultimately, observations from Guam will contribute to a more general and accurate Carbonate Island Karst Model that will provide an improved basis for groundwater management not only on Guam but all islands with carbonate aquifers. The following list of research questions is meant specifically for application to Guam in this report, but might serve as a point of departure for similar, parallel investigations on similar islands elsewhere as well:

Precipitation and Surface Infiltration

- What is the temporal distribution of rainfall on Guam at the scales relevant to aquifer recharge? These scales include daily, monthly, and seasonal scales of variation. How does rainfall intensity relate to infiltration rates?

- What is that spatial distribution of rainfall on Guam, particularly for the amounts and rates of rainfall most likely to contribute the largest portion of recharge to the aquifer? What rainfall phenomena are associated with it?

- How important is evapotranspiration? How do vegetation type, soil thickness, epikarst properties, rainfall rate, and seasonal conditions affect evapotranspiration? Are other variables important?

Vadose Storage and Transport

- What proportion of water infiltrates through the vadose zone by direct pathways (vadose bypass routes), at what rates, and under what conditions? At what rate is water stored in the matrix under various conditions, and how rapidly does water infiltrate by diffuse pathways through the matrix to the lens?

- Can closed depressions on Guam be classified according hydrological properties, in particular the rates at which they can capture water at the surface and deliver it to the lens? What are the likely genetic origins and subsequent histories of the closed depressions on Guam? What do their origins and histories imply about their hydrologic properties?

Aquifer Hydrogeological Characteristics

- Within the vadose and phreatic zones, are there likely to be significant zones of enhanced secondary porosity associated with former sea levels, as proposed in the eogenetic karst model (Vacher and Mylroie, Submitted)? If so, how extensive and how thick are they likely to be, given the generally high rate of uplift experienced by Guam? Which sites would likely be the most promising sites on which to conduct intensive local studies (e.g., dye traces) to identify pathways and quantify residence times and transport rates?

- Can different zones in both the vadose and phreatic zones be characterized in terms of the relative importance of porous, fracture, and conduit flow, as some observations by local studies to date suggest? Is Guam different in this respect from islands elsewhere? In other words, do differences in lithology, depositional, or karstigenetic history imply unique or characteristic combinations of porous, fracture, and conduit influence on groundwater storage and movement?

- Can the coastal springs and seeps that discharge fresh water along the coast be classified according to some hydrologic criteria that can be correlated with the nature of the drainage system feeding them? Specifically, are flowing fractures, concentrated spring flow, and distributed seeps fed by fundamentally different types of systems? Can hydrographic data such as temperature or chemical changes reveal storm pulses and quantify storage and transport rates in the aquifer?

Aquifer History

- How well can uplift history and ages of coastal caves be quantified on Guam? Can useful diagenetic dates be obtained, and if so, how do age and uplift rates modify features or hydrologic properties predicted by the eogenetic karst model (Vacher and Mylroie, Submitted)?

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Figures

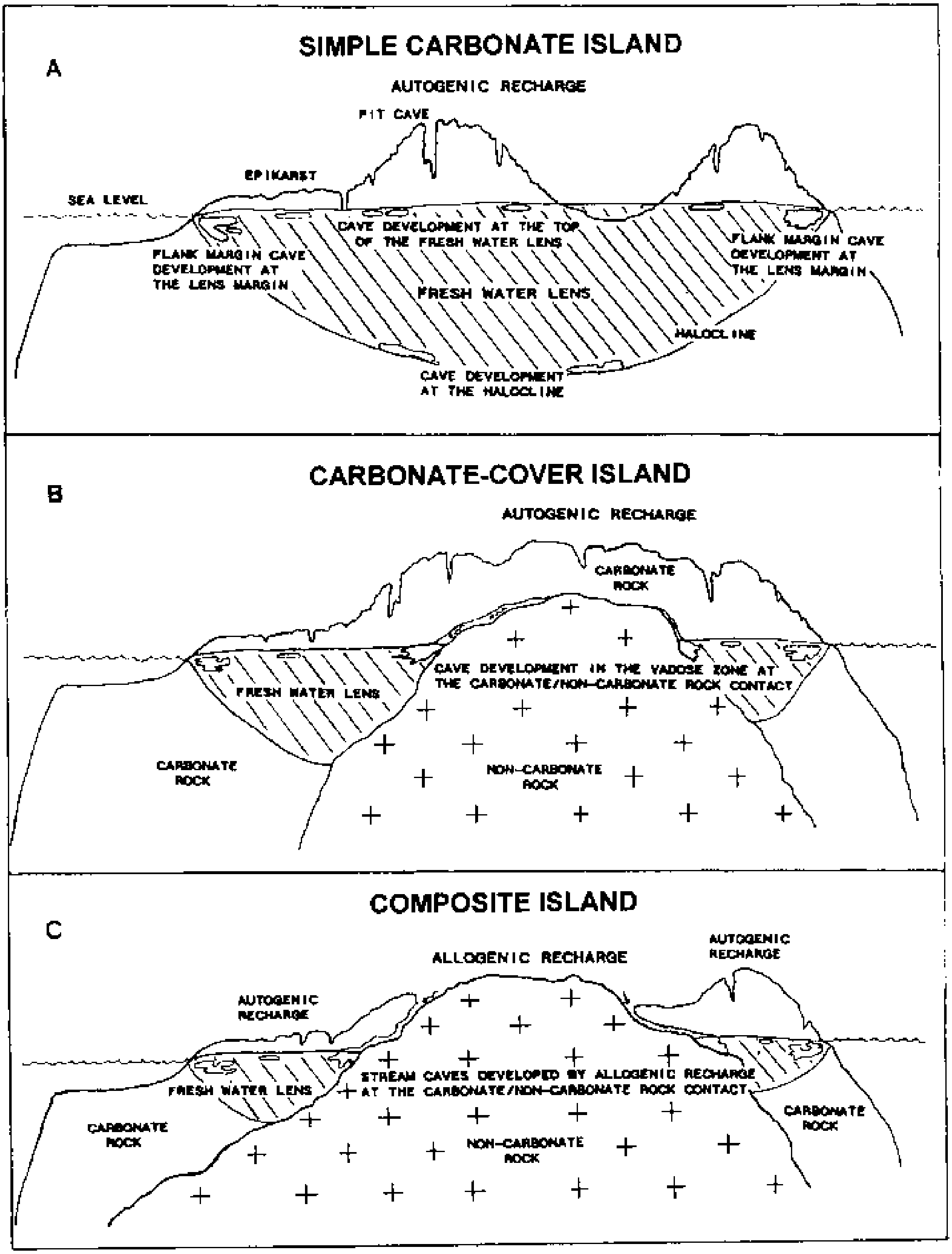

Figure 1. Features of the three major types of islands in the Carbonate Island Karst Model (CIKM) as it has evolved to date. Field relationships between the terrain surface, basement elevation and topography, and sea level produce characteristic configurations of the freshwater lens, recharge system, and caves that develop in the carbonate aquifer and along the aquifer-basement contact (after Figure 1, Mylroie and Carew, 1997).

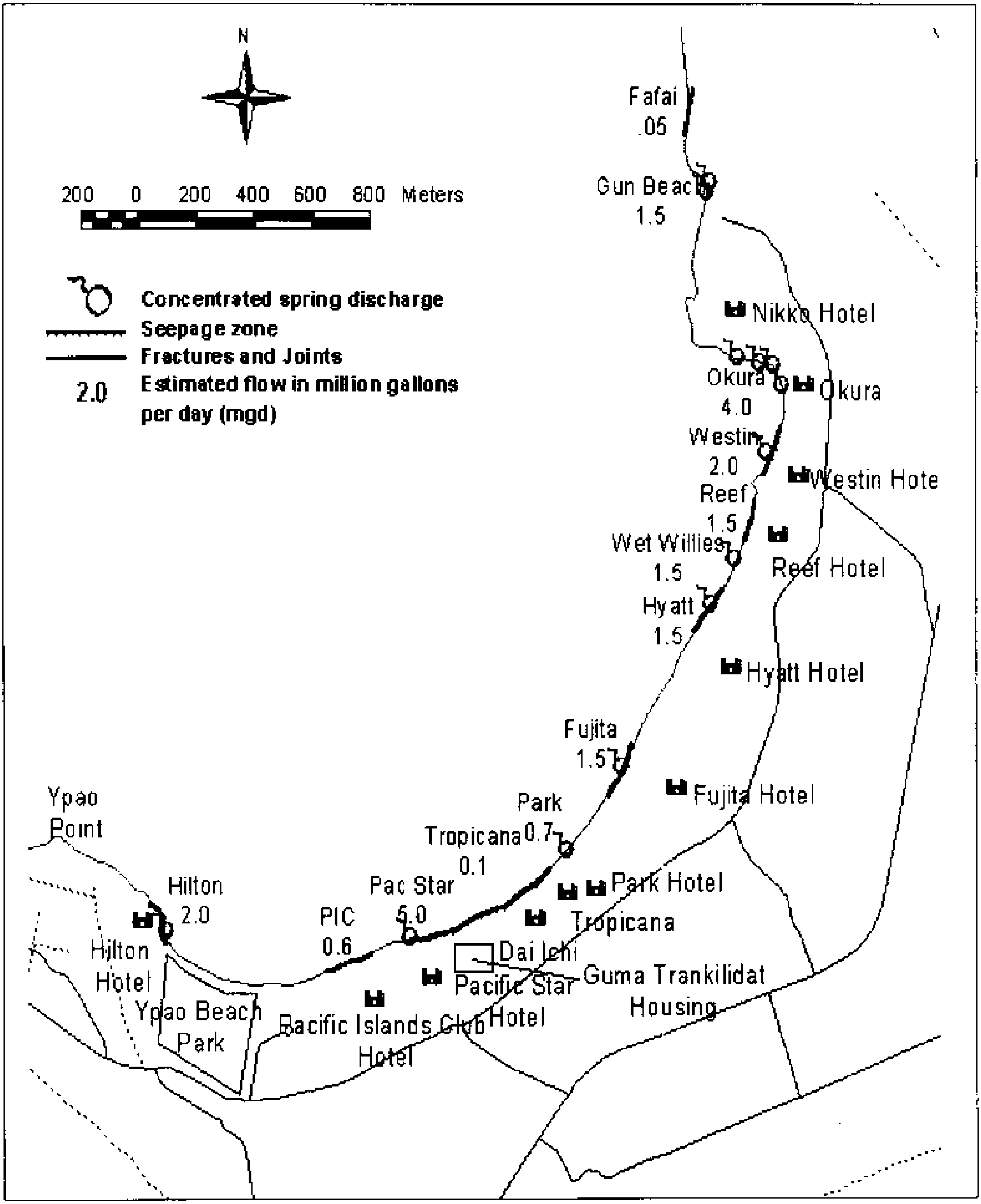

Figure 2a. Coastal groundwater discharge sites, sector 1, Tumon Bay.

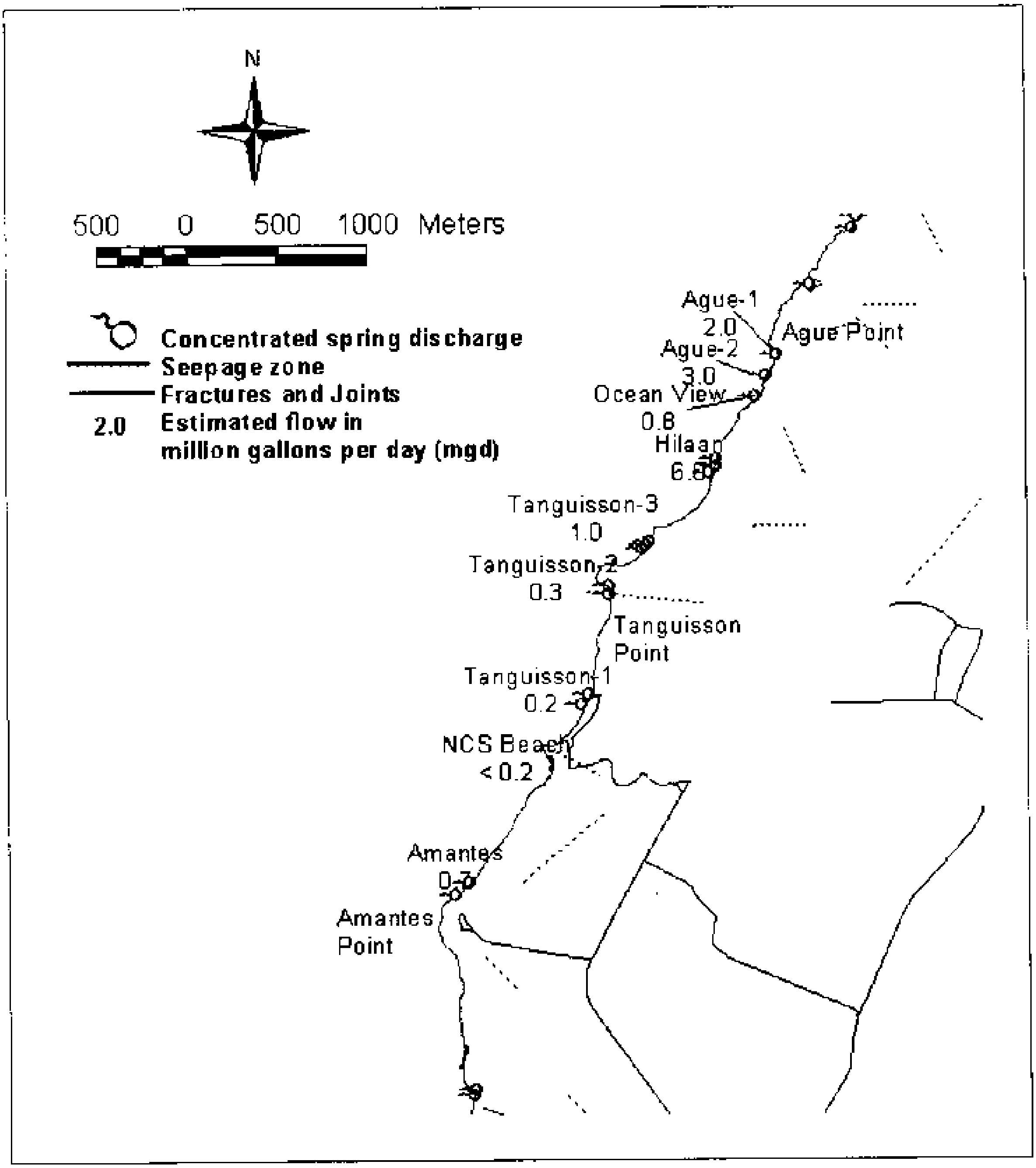

Figure 2b. Groundwater discharge sites, sector 2, Tanguisson area.

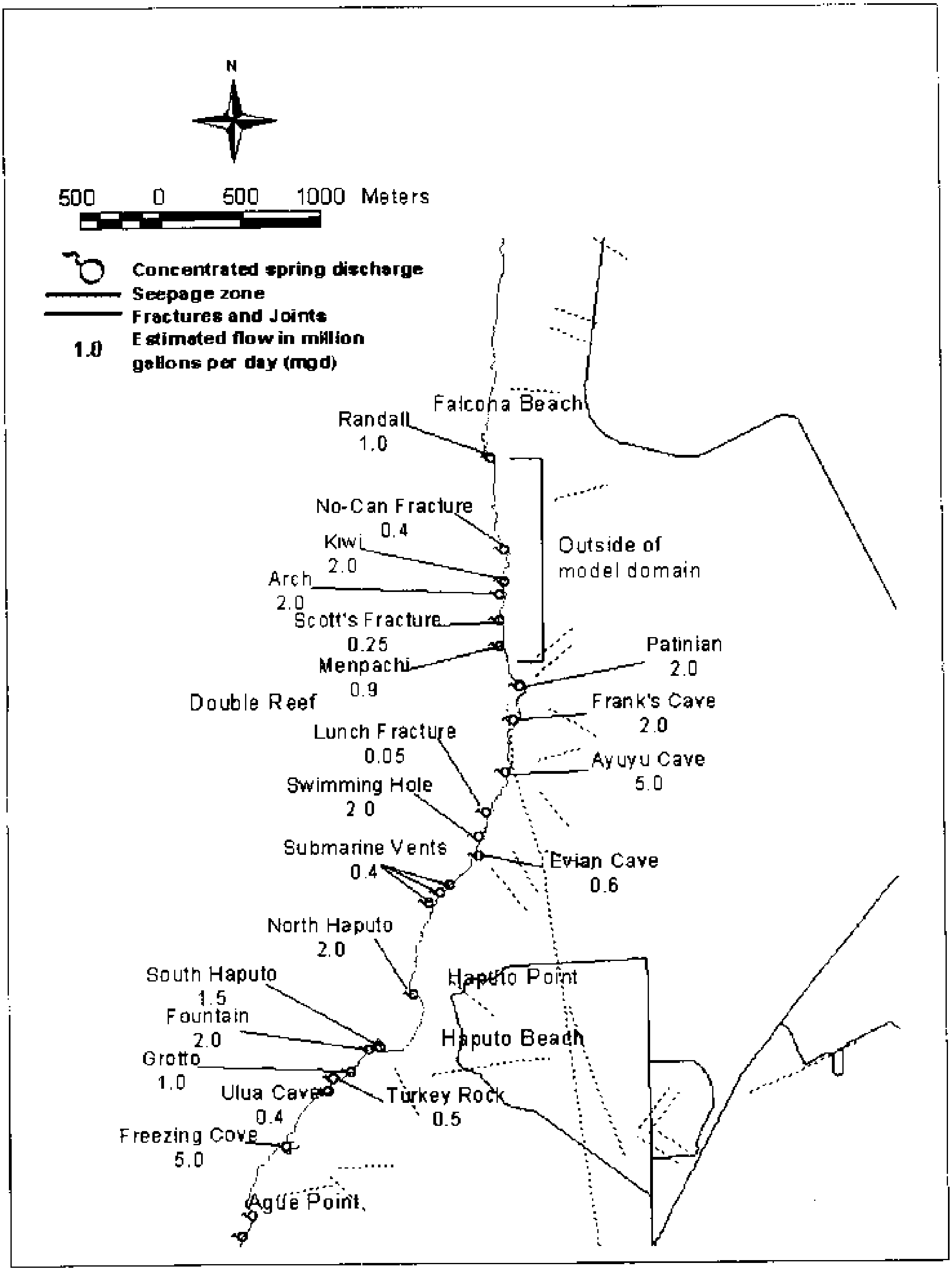

Figure 2c. Groundwater discharge sites, sector 3, Double Reef area.

Appendices

APPENDIX I

Karst Resources and Guam Hydrology: Trip Log, J. Mylroie, July 13-26, 1998.

Monday, July 13 - The day began with an introduction to the Water and Energy Research Institute of the Western Pacific (WERI), and the work being done there on the hydrology of Guam. Discussions with Dr. Jenson and his students provided an update on the current state of knowledge about Guam hydrology and the impact of karst processes. The majority of the day was spent touring the island by car, going north on the east side to Mt Santa Rosa, then west to the Philippine Sea side of the island and south to the Agana area. The tour continued east along the boundary fault between northern and southern Guam, then up into the volcanic highlands to Mt Alutom. From there, the tour continued east and then south along the Pacific coast, around the southern tip of the island, and north up the west coast to Agana again. The tour gave a quick and effective overview of the island, demonstrating the complexity of the geology and resultant hydrology. Numerous karst features were observed.

Tuesday, July 14 - The morning was spent in a fly-over of Guam from the air, taking both wide-angle and telephoto pictures. It was difficult to accurately appraise karst features from the air when the plane was over the island proper, but the flight past the coastal cliffs was extremely revealing, showing cave development at several consistent levels. The terraces related to uplift of the island were obvious, including elevated benches in the surf zone from Holocene tectonic activity. The afternoon was spent reviewing important literature on Guam, and tying geologic observations to the visual reconnaissance made by planes earlier in the day.

Wednesday, July 15 - The day was spent in a mini-conference on the hydrology of Guam and the importance of karst processes. People from Guam governmental agencies, the legislature, the Navy and Air Force, and the University of Guam were present. The purpose of the meeting was to share information across agency lines, and to familiarize these groups with the nature of karst development in carbonate islands. A number of talks were given. There was good discussion of the various aspects of the impact of karst on Guam's hydrology.

Thursday, July 16 - A field trip was taken to Pagat Cave on the east side of Guam, part way up the island from WERI. The cave is developed on a bench a few hundred meters from the sea, after a traverse down the steep wall of the island. The cave is apparently in the Mariana limestone, and is entered by way of a collapse. To the east is a single chamber with some small side passages. Some massive stalagmites are present which show evidence of dissolution under phreatic conditions. To the west, entrances lead down to water, where a low arch can be negotiated into a large chamber, flooded to the north but rising out as a sloping wall to the south. The lake portion of the cave reaches depths of over 2 m, and contains numerous stalagmites, some entirely below the water level. The wall near the entry arch shows clear evidence of dissolution of the cave wall through pre-existing flowstone. The cave walls and ceiling show large phreatic cusps and other features indicative of phreatic dissolution. The cave seems to fit the flank margin model for cave development at the discharging margin of a past fresh-water lens. The presence of stalagmites that have undergone phreatic dissolution is not surprising given past glacio-eustasy and tectonic activity on Guam.

Friday, July 17 - Field trip to Perez Brothers Quarry near Barrigada Hill. The active quarry is deep and impressive. The upper 2-4 m of the quarry wall show an excellent epikarst, with small dissolution pits infilled with red soil, soil breccia, and related features. The quarry walls show numerous normal faults of small amplitude, with slickensides. In places, the faults weep groundwater; in other places, the faults correlate with surface lows that bring runoff over the quarry wall. On the north wall of the quarry, quite deep down, is a low, wide dissolution chamber that appears to have formed at the top of a past fresh-water lens, but there is little collaborative information other than the cave's morphology. But for the cave's depth below the land surface, it would match a Bahamian banana hole in appearance. Moving to the inactive quarry where the rock crusher is operating, more lenticular voids are found, at two common horizons. This latter observation makes development of the voids near the top of a past fresh-water lens more likely. After lunch, we view a well site (M-11) that has one of the most flashy responses of any well on Guam. Such flashiness indicates a fairly direct connection to a major surface supply of runoff during storm events. Conduit flow is therefore implicated. Interestingly, adjacent to the well site is a retention basin which holds water for long periods of time, indicating that diffuse flow paths downward are blocked, probably by silt and trash. The "perching" of this water next to a well that may have access to conduit flow is a demonstration of the complexity of flow dynamics in carbonate island karst systems.

Saturday, July 18 - Field trip to the Mt Santa Rosa caves. From the top of Santa Rosa, gullies formed by stream flow on the volcanics can be seen. This allogenic recharge sinks upon encountering the Mariana limestone that rings the hill. Pig Cave is to the northwest of Santa Rosa. The cave begins as a series of large upper level chambers below which the cave stream meanders at the volcanic/limestone contact. The size of these large chambers can be explained in one of three ways, or as a combination of the three effects: 1) The chambers may represent a climate change, in which the larger size correlates with higher rainfall in the past relative to present. 2) The chambers are actually flank margin caves produced as uplift brought the fresh-water lens into this part of the limestone (and paused long enough for dissolution to occur), subsequently undercut by the vadose stream at the contact. 3) The chambers are the result of collapse as the vadose stream meandered on the contact, producing a low but wide void. As collapse occurred, the stream dissolved or otherwise transported the material away, producing the large voids. Based on quick visual examination of the chambers, the last option appears most likely. If true, then Pig Cave is an analogue for the model proposed for the development of large cave chambers on Bermuda. It is most unlikely that the large chambers were the result of higher rainfall in the past, as there is no reason such flow should have been above the contact; i.e. the large chambers should therefore have been at the level of the current stream. The field trip continued over to Interesting and Awesome Caves, southeast of Santa Rosa. Interesting Cave has upper chambers, but not as large as in Pig Cave. The stream quickly gets to the volcanics, and descends a very steep wall for 6 m. It would appear that the contact here is not depositional, but a fault contact. The steepness of the contact, and evidence of angular breccia in the limestone immediately above the contact, suggest a fault contact. Awesome Cave is a series of very large chambers descending as a series of steps, with the cave stream beneath the chambers at the contact. The chambers contain well-developed phreatic dissolution surfaces, and evidence of dissolution across both old flowstone and paleosol infill material (as has been reported on Isla de Mona). The roof of one chamber also contains bell holes, and a higher chamber appears to have undercut an old vadose canyon. The cave is quite complex. The chambers here appear to be flank margin chambers (as opposed to Pig Cave), and show at least two phreatic cycles. While the cave chambers could have a fresh-water lens origin, it is also possible that they began as collapse chambers, and were secondarily modified by phreatic dissolution when tectonics or glacio-eustasy placed the fresh-water lens at this elevation.

Sunday, July 19 - Field trip to the Hawaiian Rock Quarry. The quarry has numerous caves, primarily at specific horizons, and primarily of a lenticular shape consistent with formation in a fresh-water lens. The caves contain much stal, which would be useful for a U/Th dating campaign. The cave development is much more significant that at the Perez Brothers quarry, which may be the result of proximity to the coast and the discharging margin of the fresh water lens in the past at the Hawaiian Rock location, as opposed to lithological differences between the limestones of the two quarries. Another consideration is that to see flank margin caves, which develop preferentially at the margin of the fresh-water lens, the strike of the quarry face would have to be parallel to the strike of the discharging margin of the lens, or only a few caves would be intersected. If the strike of the lens changed with time, then that should appear in the quarry face as a change in number of caves intersected. At the lowest floor of the quarry, a very large chamber has been intersected. Developed in a coarse rubble faces that is poorly cemented, the walls record only large dissolution cusps, and those are hard to see. The cave is perpendicular to the current coast, which raises questions about its origin. If it is a flank margin cave, then it would appear that the lens had a strike different at that time than presently exists in the modern lens below the cave. If the recrystallized reef facies (which forms the resistant ramparts of the island cliff margin) had variable permeability, then this cave could represent a preferential flow path through those facies to the sea. In that case, its orientation (perpendicular to the island margin) is consistent with modern island and lens configuration. The quarry also has outstanding epikarst development, with significant soil breccia features.

Monday, July 20 - Field trip to Tanguisson Point and on to Lost Pond. This hike past the coastal cliffs reveals numerous breached flank margin caves, and the beach has a number of fresh-water seeps and springs. Coastal rocks show a series of notches (most likely bioerosion); the higher notch is low, the lower one high, most likely indicating different lengths of stability between uplift episodes. Lost Pond is a fresh-water pond up against the cliff, above which are several apparent flank margin cave openings. The pond does not exhibit any obvious flow, but is so large in cross section that such flow would be difficult to observe.

Tuesday, July 21 - Field trip to the limestone outcrops in the Navy munitions storage area on the south half of the island. Unlike previous field trips to the north, in this locality the limestone is the minor outcrop. The limestones are also among the oldest (Tertiary) on the island. First stop is the rise of the Lost River, which is partially impounded by a nearby dam. A small cave is entered above the rise, it looks like a paleo-lift tube associated with a past, higher base level. Climbing above the rise, a pit is located that leads to a single decorated chamber. The landscape is fascinating, being a series of depressions up to 30-40 m deep separated by knife-edge ridges, forming a classic cockpit karst in the Jamaican style. Numerous cave entrances are visible. Descending one sink, a large cave passage (4m x 5m) is entered, which leads to an adjacent sink after 100 m. Well decorated, with a muddy floor, the cave clearly floods. The field trip then goes to Alamogosa Spring and associated cave. The cave is large and well developed, with an active flow. It is a typical stream cave as could be found anywhere in the world. The cave is well decorated and contains a number of upper levels. The karst of this area may contain numerous paleoclimatic signals independent of sea level change, as these caves are not coupled to fresh-water lens position.

Wednesday, July 22 - We use the Marine Lab boat to launch at Agana and head north up the coast to Double Reef, where a number of fresh-water discharges in the cliffs are investigated. One of these discharge points can be entered on snorkel for over 40 m, the cleft showing classic phreatic sculpturing, and the halocline between the fresh and underlying marine water forming an obvious boundary. Mixing dissolution is certainly occurring here. Coconut Crab Cave, and a nearby cave entered through a ceiling collapse, both contain abundant fresh water. The amount discharging from Coconut Crab Cave is impressive. The aquifer feeding these springs must be a combination of diffuse flow, fracture flow, and conduit flow. On the boat ride back from this area, in the vicinity of Table Rock, the wind changes and comes onshore, bringing with it sewage from a ruptured sewer line that discharges off shore. A grim situation. From the observations of the day it can be argued that the embayments in the coastal cliffs, such as Tumon Bay as an active example, Sasajvan as an abandoned example, and Haputo Point as a developing example, are the result of dissolution produced by these fresh-water discharges. As dissolution begins to indent the coastline, it would draw flow laterally from adjacent points as a shorter pathway would exist. The captured flow would allow enlargement parallel to the coast more rapidly than it would inward, to produce the observed embayment.

Thursday, July 23 - The wind change of July 22nd allows use of the Marine Lab boat to examine the coastal areas of the Pacific (east) side of Guam. The coastal cliffs reveal a large number of caves, again at preferred horizons. The "beads-on-a-string" morphology is apparent in many areas, a key factor in differentiating breached flank margin caves from fossil bioerosion notches. Many fractures and collapses are evident. Some collapses are clearly associated with cave roof failure. Flank margin caves can also be differentiated from sea caves. The cave development in the Janum area is especially interesting, as the area has a large spring which is reported to discharge silt-laden water after heavy rains (presumably the resurgence point for the water in some of the Santa Rosa caves). A wind change in direction and magnitude makes the return boat ride interesting. In the evening, the team gathers at the "Top of the Mar" for a dinner and series of presentations on what we have learned so far about karst processes and hydrology on Guam.

Friday, July 24 - Field trip to Anderson Air Force Base, which provides a good view of the elevated Mariana limestone plateau. Examination of old shallow quarries and barrow pits is not very revealing, except to demonstrate how the past disposal of ordnance can produce depressions remarkably like sinkholes. Storm drain wells are shown that are used carry surface runoff into the aquifer to prevent surface flooding near runways and in the housing area. There are obvious concerns about the impact of this practice on water quality. The trip continues to the Tarague Beach area, where a number of cenotes exist. One has an abandoned pump house from when this water was used as a significant water supply to support the base operations. The sea cliffs to the west contain a series of small flank margin caves and notches. The notch issue is important. If the notches are bioerosion notches, produced at sea level when the cliffs were the actual sea/land contact, then they have minor hydrologic significance. If however, they represent breached flank margin caves, then they indicate a great deal of dissolution in the discharging margin of the fresh water lens at the time sea level was at that horizon. In either case, the notches are accurate sea level indicators, but only in the latter case can the size of the notches be used to estimate rate of dissolution in the subsurface. Many notches contain abundant stalactites and stalagmites. In the Bahamas, it has been argued that this stal can grow only in sealed conditions of a cave, therefore notches containing them are breached caves. However, punky, tufaceous calcite growths can form in the humid tropic outside atmosphere. An aggressive sampling regime with petrographic analysis would go along way to answering this question.

Saturday, July 25 - Field trip first to Harmon sink, the largest natural closed depression on Guam, which receives a lot of overland flow. The stream bed leading into the depression contains numerous sink points, small waterfalls, and epikarst pits. The sinking of pollutants into this depression is a major concern. Continuing on to Two Lovers Point, we observe a 50 m deep vadose shaft. The trip goes on to Tumon Bay, where the cliffs at Two Lovers are examined from below. At least 5 levels of cave development can be seen. Hiking back around Bijia Point reveals a number of classic flank margin caves, and numerous fresh-water discharge points. The hike continues south along the beach, where many large springs discharge from the beach to the water, building out small deltas of sediment. Fresh-water "boils" under the shallow ocean water are also common. Further south, these beach springs become progressively clogged with bright green alga, a clear indication of nitrate and/or phosphate pollution. This area is immediately seaward of Harmon sink. Quantitative geochemistry needs to be done with these springs, as the first step in the analysis of a calcium carbonate dissolution budget for Guam. Once done, such analyses, when coupled with volumetric data, will tell a lot about how the Guam carbonate aquifer functions.

Sunday, July 26 - John Jenson and John Mylroie meet to review the two weeks of field work, and plan for the field season in May and June of 1999 under the WRRI grant. Tasks are assigned and protocols established. Mylroie then prepares for an early departure on July 27th.

APPENDIX II

Guam Karst Inventory Guam Project Activities, May 10-30, 1999

<u>Monday, May 10</u>: Orientation day

- Local orientation tour: 9:00 AM-12:30 PM
- Kick-Off Presentations and Discussion, WERI conference room, 1:00- 3:00 PM.
  - 45-minute presentation w/15-minute discussion/break by Jenson on project history, objectives, geology of Guam, and preview of Tuesday's and Wednesday's field trips.
  - 45-minute presentation w/15/minute discussion by Mylroie on project objective, the island karst aquifer model, and relationship to work on Guam.

<u>Tuesday, May 11</u>: Southern Guam field trip (See field trip itinerary.)

<u>Wednesday, May 12</u>: Northern Guam field trip (See field trip itinerary.)

- 5:30 PM: Stopped at Togcha Cemetery to meet Galt Siegrist to examine reef.

<u>Thursday, May 13</u>: Day off.

<u>Friday, May 14</u>: Northwest coast reconnaissance and visit to Pagat Cave

- Boat team (Jocson, Carew, Gamble, Joan Mylroie, Reece, Dumars): 8:30 AM departure from Marine Lab boathouse. Returned about 4:00 PM.
- Cave team (Jenson, Taborosi, Aubri Jenson): 8:30 departure to Pagat. Returned to WERI 3:00 PM.

<u>Saturday, May 15</u>: Awesome Cave

- Met at 8:00 AM at Winchell's in Mangilao. Departed for Mt. Santa Rosa at 8:30 AM. Entered about 10:00 AM. Exited cave about 3:00 PM. Upper chamber work by John and Joan Mylroie, Carew, Jenson, Gamble, Dumars. Traverse from Awesome Cave entrance to Interesting Cave entrance by Reece, Wexel, Nace.

<u>Sunday, May 16</u>: Hawaiian Rock

- Worked in quarry from 8:30 AM to 12:30 PM.

<u>Monday, May 17</u>: Low tide (-0.5 ft.) at 3 PM, Coastal Traverse: Tanguisson to Tumon Bay

- Departed ML house at 9:00 AM with WERI truck and Jenson's pickup. Staged WERI truck at Matapang Beach Koban. Jenson dropped off field team (Jocson, Mylroie & Mylroie, Carew, Gamble, Reece, Dumars) at Tanguisson at 1030 and returned to WERI.
- Arrived Gun Beach, Tumon Bay by about noon, traversed bay at low tide until about 3 PM, when springs were exposed. Took truck back to WERI from Matapang Beach at end of day.

<u>Tuesday, May 18</u>: Low tide (-0.5 ft.) at 4 PM, Recover/Re-install Instruments on NW Coast.

- Boat crew (Jocson, Joan Mylroie, Carew, Gamble, Reece, Dumars) met Frankie at boat house at 08:00 AM for 08:30 AM departure. Returned about 4 PM.
- Jenson and Mylroie worked at WERI: reviewed reports on Saipan, discussed plans for present and future projects, discussed publication plan for coming year.

<u>Wednesday, May 19</u>: Low tide (-0.5 ft.) at 5 PM, Sampling at Perez Bros. Quarry & Pagat Cave mapping, sampling, and instrumentation

- Perez Bros. Sampling: Met at ML house at 08:00 AM for 08:30 AM departure. Arrived quarry about 9:00 AM, departed about 10:30 AM. Had lunch at Winchell's, then Jenson drove field team to Pagat Cave and went back to WERI.
- Jenson returned to Pagat with WERI truck at 4 PM to bring back field team.

Thursday, May 20: Day off.

Friday, May 21: Andersen Air Force Base

- Met at ML house at 08:00 AM for 08:30 AM departure. Arrived to meet Gregg Ikehara at main gate at about 9:30 AM. Visited cliff line with overview from north of runway. Gregg took us to see several pit caves along the cliff line, then to NW Field. Spent the afternoon at Tarague area: visited Tarague well #4. then cliff line west of the beach, sampling, taking photos.

Saturday, May 22: Janum Spring

- Met at ML house at 08:00 AM for 08:30 AM departure. Met Galt Siegrist at the Taitano home at 9:00 AM. Drove down to Catalina Point and visited the type locality of the Janum Limestone, hiked around the point to the south, took samples and photos. Hiked and drove out about 1 PM.

Sunday, May 23: Hawaiian Rock, Nimitz Hill Caves, and Talofofo Caves

- Met at ML House at 8 AM. Jenson, Mylroie, Carew, and Dumars departed at 8:30 AM departure to H.R. Worked at H.R. from 9-10:30 AM, and returned to ML House about 10:30 AM.
- Drove to Nimitz Hill, arriving about 11 AM. Located caves at end of trail that heads on the access road just south of the DODDEA High School.
- Visited Talofofo Caves in the PM. Spent about an hour in the "second" cave (i.e. the second one encountered on the trail in), exploring and photographing it. Made short stop at the back end and front of the first cave on the trail out. Hiked to the arch in the rampart overlooking the east coast.
- Departed Talofofo about 4 PM.

Monday, May 24: Naval Magazine: Surface Karst Features and Alifan Quarry

- Met at ML House at 7:45 AM, departed for Naval Magazine at 8:00 AM, arriving at 8:30 AM.
- Visited Alifan Quarry for about an hour, then drove to Lost River and hiked into the cockpit karst terrain in the Bonya Limestone to the east of Fena Reservoir.
- Drove along firebreak road to the high ground to the east for view of the Talofofo River valley and ramparts in the QTma along the Pacific Coast.
- Departed Naval Magazine main about 2 PM

Tuesday, May 25: Almogosa Cave (Reece & Taborosi, with Wexel and Micronesian Cavers); Karrenfeld at Mangilao Golf Course Park (Jenson, Mylroie & Mylroie, Carew); Return to Pagat Cave to recover data loggers: Gamble, Dumars.

- Reece met Taborosi and Wexel at the gate to the Naval Magazine at 9:00 AM. They exited the cave about 3 PM and returned to WERI about 4 PM.
- Other two teams met at ML House 8:00 AM for 8:30 depart. Karrenfeld crew dropped off Pagat Cave crew at about 9:30 AM, drove to Mangilao Golf Course and hiked down the beach access to the karrenfeld in the park area. Began hike out at about 1130, picked up Pagat Cave Crew at 1210. Lunch en route. Returned to WERI/Marine Lab at about 1:30 PM.

Wednesday, May 26: Gabgab Beach, Orote Peninsula

- Observed beach discharge from T_{al}, T_{al}/QT_{mr} contact, modern reef
- Met at Marine Lab House at 8:00 AM for 8:30 departure, arriving at Gabgab Beach at about 9:00 AM.

- AM: first dive 10-11 AM (Jenson, Carew, Gamble, Dumars)/snorkel (rest of group): examine composition and morphology of modern reef.
- Remainder of day off.

Thursday, May 27: Saipan visit: Jenson, Mylroie, Reece & Wexel

- Saipan team departed on 8:00 AM flight to Saipan. Met Rob Carruth at USGS Field Office. Studied maps, reports, sample collection. Visited selected sites with Mr. Carruth: Maui IV infiltration tunnel, Central Highlands, Sablan Quarry, USGS drilling site, Mt. Tagpochau. After lunch visited Kagman area, Matuis/Marpi area, Quarries (Mariana L.S., Tagpochau L.S.)

- Lab Work and data reduction at WERI: Carew, Gamble, Joan M., Dumars, Reece.

Friday, May 28: Saipan visit: Jenson, Mylroie, Reece & Wexel

- Saipan cave reconnaissance all day: Jenson, Mylroie, & Reece return on evening flight from Saipan.
- Day off for rest of field crew.

Saturday, May 29: Brief-out, 8:00 AM at WERI
Entire field team met at WERI to discuss observations and preliminary findings, identify plans for the remainder of the summer and coming year'

Sunday, May 30
Early AM departure from airport.

Field Trip Itineraries

Southern Guam: May 11, 1999
From UOG, follow Route 4 to Cross Island Drive (Route 17). Follow Cross Island Drive west to the intersection of Route 4A (interior road that goes south to Talofofo by way of the Talofofo Golf Course). Continue on Cross Island Drive for 2.9 miles from the intersection.

Stop 1. Knob formed by road cut on north side of Cross Island Drive, 2.9 miles from intersection of Route 4A. Vista of south Guam: central basin, dip slope of south Guam cuesta, limestone-capped peaks (Mt. Alifan to Mt. Lamlam). Mature karst terrain in Bonya Limestone in the Fena Basin. To north: Mt. Tenjo, Mt. Alutom, badland weathering.

Stop 2. Nimitz Hill, Spruance Drive. Alutom Formation basalt flows, breccias, volcaniclastic rock.

Stop 3. Mt. Alutom. Type locality of Alutom Formation. Outcrops of tuffaceous shale, volcanic boulder conglomerate, coarse breccia. Note the characteristic stratigraphic and structural complexity of the Alutom Formation. Tracey interpreted Mt. Alutom as the core of a northeast-trending anticline with a steeply dipping northwest limb. Eroded saprolites exhibit spheroidal weathering, relict fabric and structure. Magnetite crystals accumulate in low-gradient stream paths from eroded soil. Note stratification of vegetation on slopes to northwest, reflecting stratification of bedrock. To south, note incised drainage, distribution of vegetation.

Double back to Marine Drive and head south to the Pizza Hut at the start of Cross Island Drive. Turn onto Cross Island Drive and pull over immediately at road cut.

Stop 4. Road cut in Talisay Member of the Alifan Limestone. Only exposure of Talisay Limestone outside of the Naval Magazine. Basal member of the Alifan Limestone. Yellowish marly limestone, no more than 30 feet thick. Exposure of Alifan in the next road cut up the road is not the most representative but is the most convenient on this route.

Continue on to Agat. Park at transfer station just up the grade south of Agat. Walk back to road cut just below transfer station.

Stop 5. Pillow basalt in Facpi Formation. Note relict fabrics, weathering products, evidence of water pathways. En route to next stop, watch for fresh pillow basalt on inland side of the road.

Stop 6. Sella Bay Trailhead overlook. View of west face of mountains capped by the Alifan Limestone. Note the distinctive morphology of the limestone peaks compared to the peaks in the volcanic terrain.

Stop 7. Southern Mountains Overlook. Scarp face of the cuesta. Note characteristic steep drainage pattern, distribution of vegetation types.

Stop 8. Fort Soledad, Umatac Bay. Rest rooms and historic site. Excellent vista looking up the range of the southern peaks.

Stop 9. Ija Agricultural Experiment Station. Bolanos Pyroclastic Member and Dandan Flow Member of the Umatac Formation. If time permits and interior of experiment station is accessible, we may visit some of the badland sites.

Stop 10. Talofofo Bay. Observe interaction of stream, bay, and ocean, sediment deposition and mineralogy. Observe entrenchment of the river through the limestone fringe of the southern coast.

Stop 11. Notre Dame High School. Argillaceous Member of the Mariana Limestone. Vista into the interior of the Talofofo River Basin.

Return to Cross Island Drive by way of Route 4A.

Stop 12 (if time permits) Baza Garden. Hike down into tributary of Togcha River to observe Bonja Limestone.

Stop 13. Pago Bay overlook. Vista of karst terrain incised into QT_{ma} limestone at the south end of the northern plateau. View of Pago-Adelup Fault Scarp.

Northern Guam: May 12, 1999

Stop 1: Exposure of QT_{ma}. Road cut along Chalan Inda, off Route 4 along Pago Bay. Take Route 10 west to Route 4, turn south and take Route 4 to Pago Bay. Near the bottom of the grade, just before the bridge, turn right (west) onto Chalan Inda (marked) and go uphill to the road cut on the south side of road near the crest of the hill. (10 minute stop. Total: 10.)

Stop 2: Exposure of T_{al}, paleosol, QT_{ma}. Road cut in Sinajana, south of Chaot River Bridge. From Stop 1, backtrack along Route 4, crossing Route 10 continuing through Chalan Pago and Ordot to Sinajana. Stop at road cut on right (northeast) side of road, just before the grade drops down to the river. (15 minute stop. Total: 25 min.)

Stop 3: Vista of Agana Swamp. Continue through Sinajana to Agana. On way down road into Agana, pull over to the right and park at Sunrise Tower Condominium. (10 minute stop. Total: 35 min.)

Stop 3: Exposure of paleosol/non-conformity in fresh excavation off Maimai road. Cut in excavation on the west side of Maimai road, just before Apusento Garden Condominium. From Stop 2 backtrack along Route 4 to Maimai Road, and turn left (northeast). Stop immediately by the excavation on the left side of the road. (10 minute stop. Total: 45 min.)

Stop 4: GWA Well and vista from Maimai Road. From Stop 3, continue along Maimai Road to the GWA well on the right side of the rode just after the DepCor facility. (10 minute stop. Total 55 min.)

Stop 5: Vista from Ladera Tower. From Stop 4, continue along Maimai Road until it ends at the intersection with Route 10 by Price Elementary School. Cross through the intersection onto Route 15 (back road to Andersen) and continue to the sign to Ladera Tower. Turn right on the access road at the sign. Park in the parking lot. We will go into the building and ask permission to go to the roof. (20 minute stop. Total 1 hr. 15 min.)

Stop 6: Marbo Cave. From Hawaiian Rock, head north up Route 15 to the access road to Sasajvan. Drive to end of pavement. Walk down to Marbo Cave. (20 minute stop. Total 1 hr. 35 min.)

Stop 7: QT_{mr} in road cut on Marbo access. Return up the access. Stop along cut face where the road levels off just before rising again in the last grade to the top. (10 minute stop. Total 1 hr. 45 min.)

Stop 8: Mount Santa Rosa. From Stop 8, return to Route 15 and continue north to Mount Santa Rosa. Take the right turn at the Y in the road where the road straightens out at heads to the Andersen back gate, just after rounding the base of Mount Santa Rosa. Drive to the top of the hill at park by the radar installation. (30 minute stop. Total 2 hr. 15 min.)

Stop 9: Yigo trough. Backtrack to the turn-off to Yigo and head west. Note that we are dropping down into the trough. Stop briefly by ponding basin near Yigo Elementary School. (10 minute stop. Total 2 hr. 25 min.)

Stop 10: Finegayen Seabee Landfill Dye Trace Site. (Tentative.) Go to Potts Junction and follow the road to the Navy Housing Area in Finegayen. (20 min. stop. Total 2 hr. 45 min.)

Stop 11: Harmon Sink. Continue from the main gate down Marine Drive to Upper Tumon. Just before the sewage lift station, which appears just before the Hornet Sporting Goods Store at the base of Airport Road, turn onto the paved road that drops down into Harmon Sink. We will park at the bottom and fight our way through the sword grass into the base of the sink. (30 minute stop. Total 3 hr. 15 min.)

Stop 12: Perez Bros. Quarry. Go up Airport Road to top of hill and turn left onto the first or second dirt road after the Exxon Station. (60 minute stop. Total 4 hr. 15 min.)

APPENDIX III

Principal Investigators and Collaborating Scientists on Island Karst Hydrology of Guam and its Incorporation into a General Carbonate Island Karst Model (CIKM)

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