PROCEEDINGS OF THE EIGHTH SYMPOSIUM ON THE GEOLOGY OF THE BAHAMAS AND OTHER CARBONATE REGIONS

Edited by
James L. Carew

Production Editors
Daniel R. Suchy
Nicole G. Suchy

Bahamian Field Station, Ltd.
San Salvador, Bahamas
1997

Front Cover: View to the SSE on White Cay in Grahams Harbour off the north coast of San Salvador, Bahamas. At this spectacularly scenic site one can see that marine erosion has removed the entire windward portion of these early Holocene eolianites (North Point Member, with an alochem age of ~5000 radiocarbon years B.P.) that were deposited when sea level was at least 2 meters below its present position.

Back Cover: Stephen Jay Gould, keynote speaker for this symposium, holds a *Cerion rodregoi* at the Chicago Herald Tribune's 1891 monument to the landfall of Christopher Colombus, which is located on the windward coast of Crab Cay on the eastern side of San Salvador Island, Bahamas. The monument consists of an obelisk constructed from local limestone which houses a carved rock sphere depicting the globe with the continents. The inscription carved in a marble slab, reads: "On this spot, Christopher Columbus first set foot upon the soil of the New World."

Printed in USA by Don Heuer

ISBN 0-935909-63-X

TRANSPORT TRAVEL TIME IN THE FRESH-WATER LENS OF NORTHERN GUAM

Wendell L. Barner
PG, CPG, Senior Scientist
ICF Kaiser Engineers, Inc.
Pittsburgh, PA 15219

ABSTRACT

Hydrogeologic investigations on the northern portion of the island of Guam, Mariana Islands, have provided challenging data regarding expectations of rapid flow within the fresh-water lens. Evidence from cave exploration and boreholes suggests karstification has occurred at the phreatic and vadose zone at a depth of approximately 150 m (500 ft) below ground surface, near sea level, and within the mixing zone between the fresh and marine ground water interface approximately 180 m (600 ft) below ground surface. Dye tracing results, isotope data, and non-flashy responses to rainfall on water levels in wells suggest ground water movement is representative of macro-porous media flow, not conduit flow that is commonly assumed in most karst aquifers. Ground-water flow is further complicated by lateral and vertical variation of reef facies, partial or complete diagenetic removal of primary porosity, complex structural geology, and karstification. Horizontal and vertical ground-water flow in the aquifer converges along the coastal area, and discharges as resurgences, or submarine springs. In contrast, flow within the vadose zone is rapid, and the direction of movement is highly unpredictable.

INTRODUCTION

During the past decade, site characterization investigations on the island of Guam have increased as a result of requirements for regulatory compliance. Military installations on Guam have been operating since 1944. In the intervening years, sanitary and industrial wastes from military installations, residences, and commercial activities have been disposed in various trenches, borrow pits, quarries, and dolines. Potential ground water degradation may result if hazardous leachate is released from these disposal areas. To address this concern, geologic and hydrogeologic investigations have resulted in the installation of numerous monitoring and municipal water supply wells for ground water study. As part of these investigations, evaluation of existing data, borehole drilling, borehole and surface geophysical surveys, water geochemistry, and tracer studies have been preformed to predict ground water flow directions and ground water flow velocities.

PHYSIOGRAPHIC SETTING

The island of Guam is the southern-most island in the Mariana Island chain, located approximately at 13°27' N and 144°47' E (Figure 1). Guam is approximately 2,500 km (1,550 mi.) south of Japan and approximately 5,300 km (3,300 mi.) southwest of Hawaii. The Mariana Islands are a complex island-seamount system that is divisible geographically, tectonically, and chronologically into two island arcs (Siegrist and Randall, 1992). There is an older frontal arc (middle Eocene; ~ 43 m.a.) which includes the larger islands of Guam, Rota, Tinian, and Saipan, plus two smaller uninhabited islands; and a younger arc (early Pleistocene; ~ 1.3 m.a.) of active seamounts and islands that lies to the west and north of the older arc.

Guam is approximately 48 km (30 mi.) long from north to south, and ranges in width from approximately 6.4 km (4 mi.) near the center of the island, to 13 km (8 mi.) in the north. Guam consists of a limestone-veneer on a nearly submerged volcanic ridge that lies between the Philippine Sea, to the west, and the Pacific Ocean basin, to the east (Cloud, 1951). The elevation of the northern plateau ranges from about 60 m (200 ft.) to 180 m (800 ft.) above sea level. The surface of the limestone plateau is interrupted by two

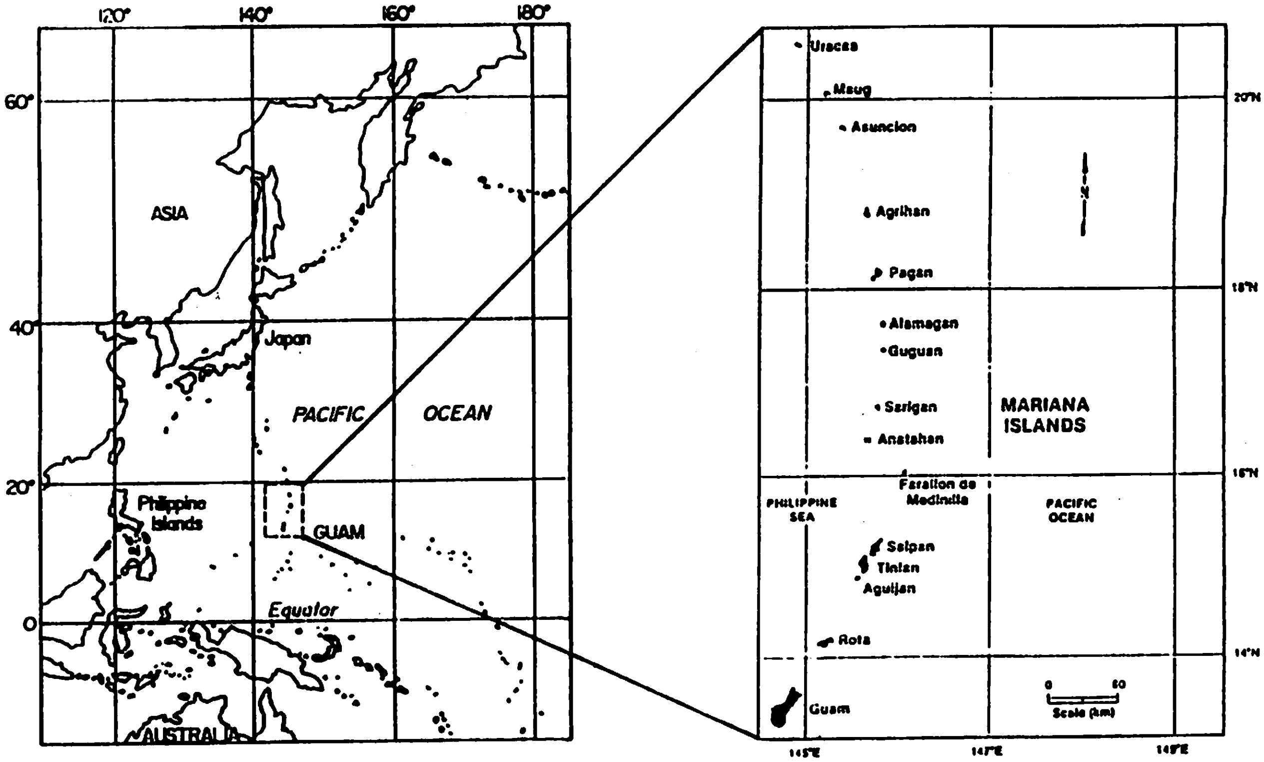

Figure 1. Location Map of Guam, Mariana Islands.

volcanic peaks, Mount Santa Rosa and Mataguac Hill, with elevations of 252 m (826 ft.) and 192 m (630 ft.) respectively, above sea level.

The island is subequally divided into the northern limestone plateau and the higher volcanic hills to the south. The northern limestone plateau is covered with thick vegetation consisting of limestone forest, mixed natural and exotic forest, and mixed natural and exotic shrubs (ICF Technology, 1994; Raulerson and Rinehart, 1991). The southern half of the island rises to a maximum elevation of 406 m (1,332 ft.) and the volcanic hills support mainly sword grass and small shrubs.

GEOLOGY OF NORTHERN GUAM

The geology underlying the northern plateau of Guam consists of two primary limestone reef deposits, the Mariana and Barrigada formations, overlying volcanic rocks (Figure 2). The Barrigada Limestone (late Miocene to early Pliocene; 11.2 to 3.4 m.y.) is usually white, chalky, fine grained, and composed of foraminiferal-algal wackestone distinguished by sparse, but locally abundant, accumulations of coral molds of *Porites* and *Astreapora*. Foraminefers largely consist of *Operculina*, *Cycloclypeus*, and *Gypsina*, which are useful for recognition of the formation (Tracey et al., 1959). The maximum thickness of the formation is unknown, but it is presumed to be greater than 162 m (540 ft.) based on similar lithology and fossil assemblages seen in boreholes. The Barrigada is interpreted as the deposits formed on a submarine carbonate bank with a depth of approximately 180 m (600 ft.). The peripheral slopes, and the abundance of coral and molluscan remains, indicate bank shoaling during late Miocene or early Pliocene time, which allowed reef formation on the underlying volcanic (Alutom) formation (Tracey et al., 1959; Siegrist and Randall, 1992).

Overlying the Barrigada Limestone is the younger Mariana Limestone (late Pliocene to Pleistocene; ~ 3.4 to 1.6 m.y.) which

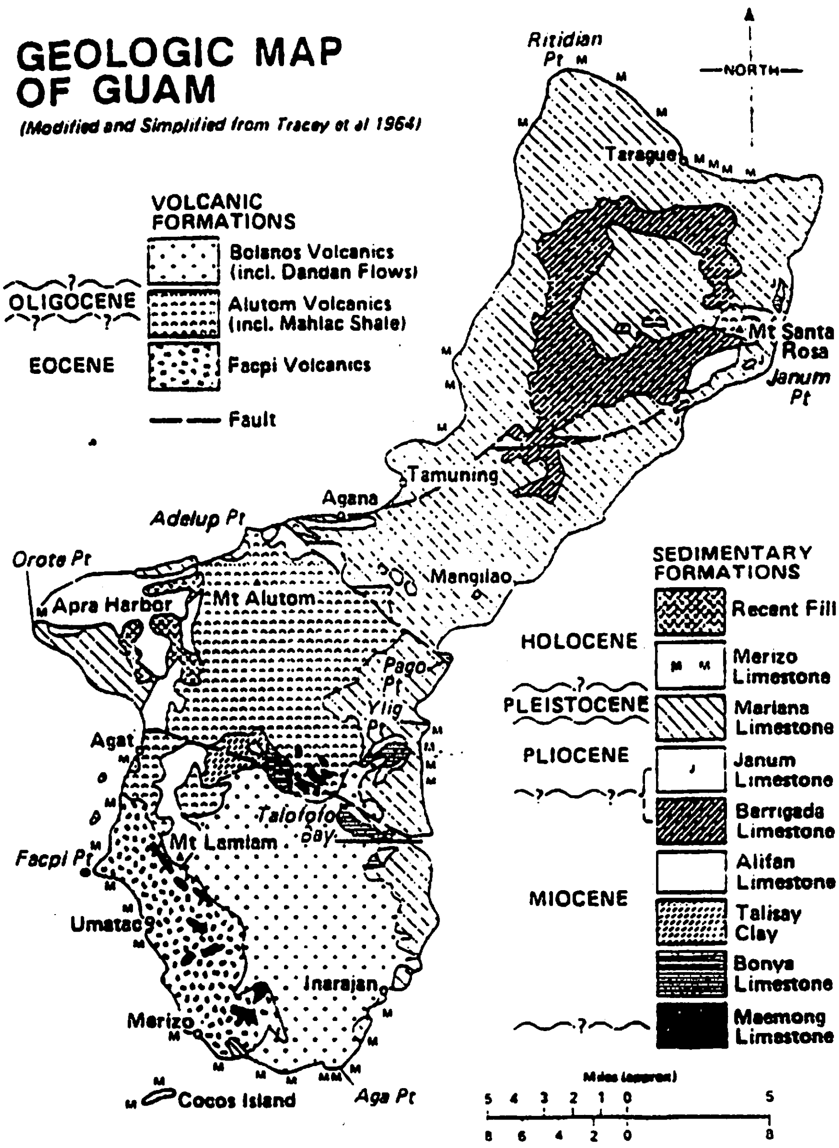

Figure 2. Generalized geologic map of Guam (simplified and modified from Tracey et al., 1964; Reagan and Meijer, 1984, and Siegrist and Randall, 1992).

comprises most of the surface rock of the northern plateau. It onlaps the Barrigada Limestone as a vertical and transgressional facies, and changes from deep to shallow water deposits. The Mariana Limestone consists of an unnamed member that comprises the main body of the limestone, and the Agana Argillaceous Member. The Agana Argillaceous Member has not been mapped in the area of investigation, and is not included in this discussion. The main body of the Mariana consists of four reef-associated facies, which include the reef facies, fore-reef facies, detrital facies, and molluscan facies. The reef facies are massive, white, generally compact, porous and cavernous, coralline and coralgal boundstones, coarse grainstones, packstones, and wackestones of reefal origin. This facies consists mostly of corals of the following genera: *Acropora*, *Favia*, *Goniastrea*, *Leptoria*, *Platygyra*, *Pocillopora*, *Porites*, *Stylophora*, *Symphyllia*, and *Turbinara*. Gastropods and bivalves also occur as molds and casts (Tracey et al., 1959; Siegrist and Randall, 1992). The detrital facies are white, friable to well-cemented, coarse to fine-grained, generally porous and cavernous, detrital coralliferous rudstone, micitic wackestone, and mudstones that are mostly of lagoonal origin. Fossil assemblages include benthic foraminerfers, corals, molluscs, oysters, turritellid gastropods, and *Halimeda*. The molluscan facies are fine-grained, white to tan, detrital limestone of lagoonal origin, that contain casts and molds of mollusks. The fore-reef facies consist of white, well-bedded, friable to indurated, foraminiferal packstones and wackestones deposited as a fore-reef sand (Tracey et al, 1964; Siegrist and Randall, 1992).

GEOMORPHOLOGY

The limestone formations have been eroded to form karst features such as dolines, caves, and cenotes. Dolines are especially abundant in northern Guam. These features have been formed through the chemical dissolution of limestone by weak carbonic acid derived from the atmosphere and soils (Palmer, 1991). Continued chemical dissolution through time allows dissolution to penetrate deep into the limestone bedrock. In addition to surface and near surface dissolution, additional, and probably the most significant, dissolution of the limestone occurs at the interface between two chemically different ground waters, where fresh ground water mixes with saline ground water. Dissolutional aggressiveness can be enhanced or renewed by mixing waters of contrasting chemistry (Esteban and Wilson, 1993; Palmer, 1991; Bögli, 1980). Figure 3 illustrates a typical karst terrane developed in a coastal setting.

GROUND WATER

The Barrigada and Mariana formations are the primary aquifers used to supply drinking water on Guam. The ground water found within the aquifer is commonly referred to as the Northern Guam Lens (NGL). The NGL has been designated as a sole-source aquifer by the EPA (Barrett Consulting Group, 1992). The NGL is recharged by rainfall which generally exceeds 200 cm (80 in.) annually on the northern portion of the island (Mink, 1976).

Because of the highly permeable limestones, there are no surface streams on Northern Guam. Rainfall, even during typhoons, infiltrates rapidly through the thin soils and into weathered bedrock. This water eventually recharges the freshwater lens, but it may be retarded in the more porous and permeable epikarst during its migration through the vadose zone. Migration pathways are reduced at depth as dissolutionally aggressive water becomes saturated with calcium and can no longer dissolve limestone. With additional supplies of meteoric water that is undersaturated with calcium, dissolution can continue. As infiltrating ground water reach the smaller pathways, ground water migration is then slowed, unless there are preferential flow paths such as enlarged fractures, faults, or lithologic boundaries where water is concentrated, and transmitted quickly to the freshwater lens.

Throughout northern Guam, fresh ground water floats on marine water in approximate buoyant equilibrium, which in combination of the effect of the dynamics of flow of the fresh water, results in a body of water with parabolic surfaces at both the fresh water-vadose and the fresh water-saline water interfaces. This equilibrium is referred to as the Ghyben-Herzberg Model (Ward et al., 1965). Based on this model, for every unit of fresh water above sea level, there will be 39 units of fresh water below sea level. Based on the measured water table levels, the calculated theoretical lens thickness can be in excess of 60 m (~ 200 ft.), assuming the existence of a sharp interface between the fresh and marine water. The actual size and shape of the lens will depend on recharge amount and rate, the size of the island, and the permeability of the rock (Vacher, 1988). According to Mylroie et al. (1995a), high permeability and low recharge rate produces a thin lens, whereas low permeability and high recharge rate will produce a thicker lens.

Selected geochemical parameters, and tritium concentrations, were evaluated by Mink and Lau (1977) to more fully understand the hydrologic cycle on island of Guam, and to identify prospects for additional water yield. Tritium (^3H) is a radioactive isotope of hydrogen which became enriched in the

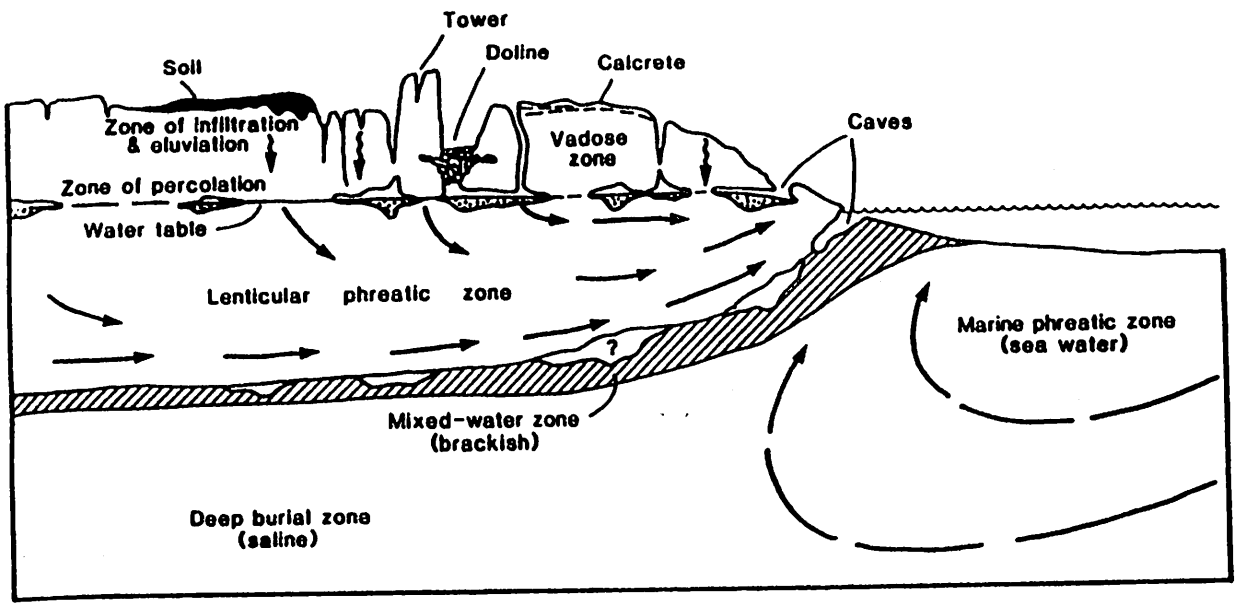

Figure 3. Diagram showing the general elements and hydrology of a karst terrane developed on recently deposited carbonates adjoining the sea. (from Choquette, P. W. and James, N. P., 1988).

atmosphere as a result of nuclear testing in the early 1950s. Atmospheric concentrations of tritium reached a maximum in 1963, and has steadily declined following the ban on atmospheric nuclear testing. Tritium concentrations in rainwater have been monitored, and it can be used to determine how recently water has been in contact with the atmosphere. These data were used in this study to ascertain the rapidity at which infiltrating rainfall recharges the aquifer. Tritium analysis of ground-water samples were compared to rain-water data monitored at Taguac by the International Atomic Energy Agency from December 1961 to December 1972. A ground-water age of "about five or less years old" (circa 1972) was determined by their study.

DISCUSSION

Geologic and hydrogeologic investigations included water-level measurements in existing monitoring wells, and additional borehole drilling around the landfill area. The ground water there exhibits a relatively flat hydraulic gradient that results from the high permeability of the limestones. The elevation of the water table ranges from sea level in the coastal areas to approximately 1.8 m (6 ft.) above sea level inland. Those water levels indicate a relatively flat ground-water gradient that slopes toward the northern coastal area. In Guam, the permeability of the limestone bedrock is high, and so is recharge. Approximately half of the annual rainfall is recharged to the aquifer. This has produced a fairly thick lens, towards the islands interior, that ranges from 27 m (90 ft.) to 36 m (120 ft.) thick, based on fluid conductivity logs and chloride measurements made of formation water during borehole drilling. However, the fresh water/ marine water boundary is usually diffuse because of hydrodynamic dispersion induced by movements of the interface from tidal changes, influences from changes in barometric pressure, seasonal differences in recharge rates, and withdrawals of fresh water by pumping (Mink, 1976; Vacher, 1988). This diffuse zone of brackish water between the saline and fresh ground water is referred to as the mixing zone, or the halocline. The thickness of the mixing zone is dependent on the dynamics of flow and potential for mixing with the fresh-water portion of the lens. The mixing zone varies in thickness, and has been measured at from 6-15 m (20-50 ft.). The depth to the water table across the northern plateau generally approximates sea level, and ground water exists as seeps, and or as submarine springs, along the coast.

Borehole drilling for this study consisted of placing boreholes in sinkhole areas and in assumed downgradient positions from the landfill complex. In addition, a natural potential survey along the northern beach area was performed so as to place boreholes on natural potential anomalies (Lange and Barner, 1994). Geophysical and video logging of the boreholes suggests that most of the caverns, vugs, and dissolution porosity occurs at the vadose/phreatic interface, and within the mixing zone. This was also confirmed from drilling logs (Figure 4). The size of the dissolutional porosity ranges from as little as a few centimeters to several meters. The cavernous zones and dissolutional porosity in the boreholes tend to be grouped at several discrete elevations or horizons which correspond to emerged caves, and which also provide evidence of former sea-level stillstand positions. This phenomenon also has been documented from the Yucatan Peninsula (Back et al., 1986), in Bahamian blue holes (Smart et al., 1988), as the flank margin caves of the Bahamas (Mylroie et al., 1995b).

The caves discovered along the northern coastal margin vary in height from 1-2 m (3-6 ft.) up to approximately 12-15 m (40-50 ft.). The caves generally have small entrances (approximately 1 m wide) with either a drop of several meters to the main cave floor, or they have sloping entryways before opening into the main cavern which can range, in horizontal distance, up to 60 m (200 ft.) widths up to 45 m (150 ft.). The caves usually terminate at a sharply sloping wall into a sump containing fresh water. In many cases, speleothems can be observed below the fresh-water in the cave pools, which provides evidence that the former water-table level, and former sea level, were lower during earlier geologic time.

Caves in Guam appear to have formed from the dissolution of limestone resulting from the mixing of two contrasting water types (fresh and marine ground water), which occurs within the mixing zone of the fresh and marine ground water and at the vadose/phreatic interface. The emergent caves are found at the margins of the limestone plateau, along topographic terraces, formed by past sea-level stillstands. Along the margins of the island, the fresh-water lens is thin, and it thickens inland. This thinning towards the lens margin, and the influence of tides and storm surges, creates a dissolutionally aggressive mixture that produces the dissolution porosity and caves. These observations are consistent with the flank margin model for dissolution cave development (Mylroie and Carew, 1990).

A dye trace was initiated to determine ground-water flow direction and estimated flow velocities within the fresh-water lens, and to simulate releases from landfill areas. The tracer study was monitored at over 70 locations that included existing wells and boreholes around the landfill area, boreholes drilled on natural potential anomalies along the beach area, and in caves along the base of the cliff face of Tarague Beach that contained fresh water sumps. One month of background data were collected prior to the dye placement in order to establish the background fluorescence of the aquifer. The background fluorescence conditions of the aquifer, and dye standards, were used to compare data during the evaluation of sample analyses.

Three dyes were used; rhodamine WT, Uranine, and Phorwhite BBH Pure. The dyes were placed in boreholes drilled around the existing landfill area, at depths of 15 and 60 m (50 and 200 ft.) below ground surface. A third injection was directly into the ground water at approximately 135 m (450 ft.) below land surface. Dye trace samplers consisted of activated granular carbon packets and undyed cotton swatches.

The dye trace program lasted 15 months and was terminated with positive results (Figure 5) indicating two types of flow; gravity flow, or drainage through the vadose zone, and saturated flow. Flow velocities were calculated assuming straight-line flow-path directions. Because of (1) the porous nature of the limestone, (2) the numerous caverns and other karst features, and (3) previous tritium studies showing relative young water, it was anticipated that ground water flow would be very rapid. However, saturated flow was not as rapid as was anticipated; and the combined vadose and saturated flow near the landfill area indicated more rapid movement in the vadose zone than

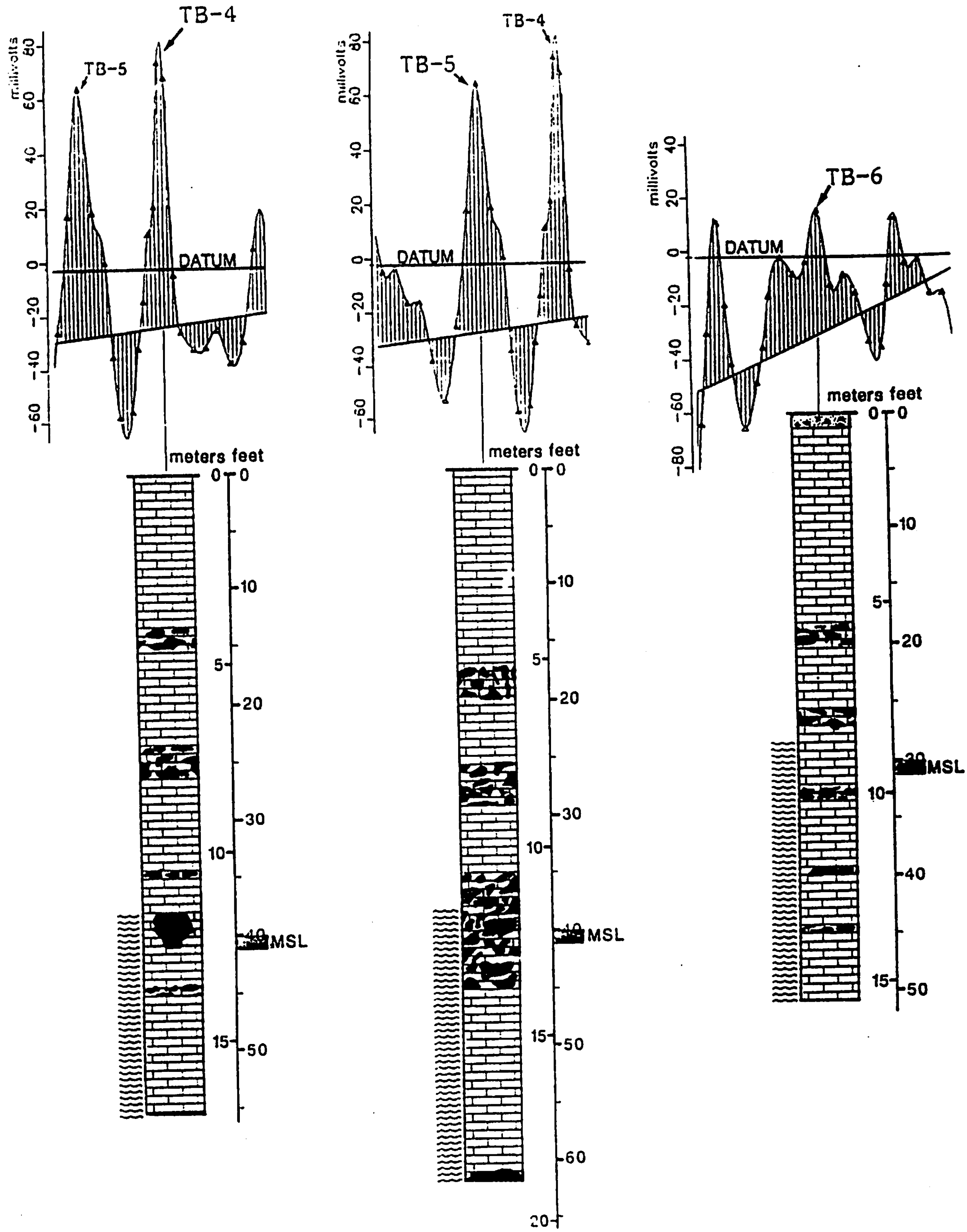

Figure 4. Anomalies and wells logs at sites TB-4, 5, and 6, along the beach highway, note voids are in black.

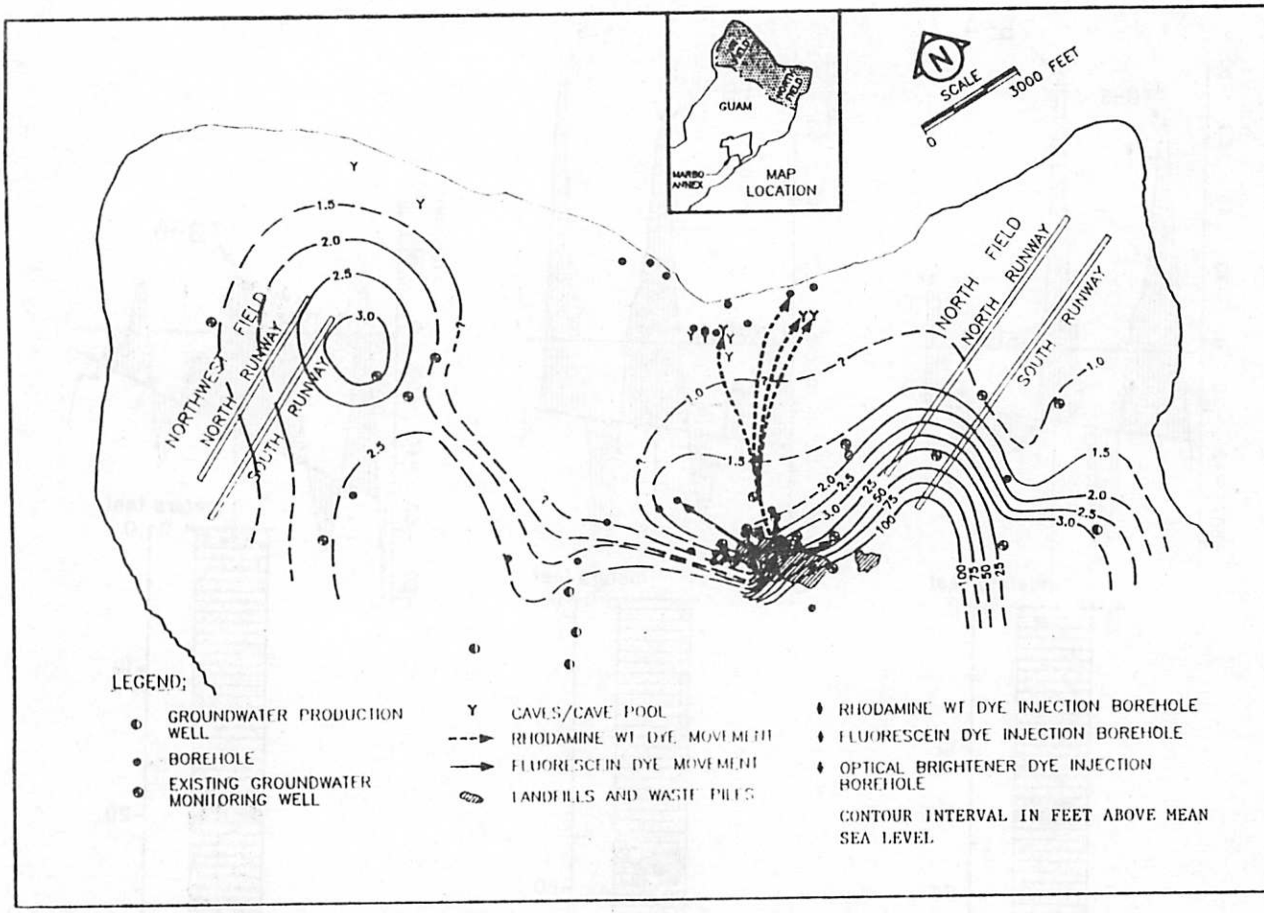

Figure 5. Dye tracing results.

after reaching the water table. Flow within the ground-water system is essentially advective flow along the hydraulic gradient, and is indicative of diffuse transport with the average flow velocity calculated to range from 6 m (20 ft.) per day to 11 m (36 ft.) per day. This is generally considered to be rapid flow in most porous media aquifers, but is slow flow compared to most karst aquifers reported in the literature (Quinlan and Ewers, 1985; Quinlan et al., 1992).

The vadose system appears to act as a rapid flow system with the water draining in multi-directions, and at different inclinations. This is understandable because of the depositional and stratigraphic complexities associated with the reefal limestone formation, and the fracturing and faulting of the bedrock associated with island arc tectonics. After passage through the vadose zone, water flow velocity is abruptly reduced when the water table is encountered. Travel time for the combined vadose and saturated flow ranged from 91 m (300 ft.) to over 240 m (800 ft.) per day. The combined flow regime includes approximate 75 m (250 ft.) of vertical travel through the vadose zone to the water table, before the saturated flow condition predominates.

In addition to the two flow components mentioned above, dye samplers placed deeper within the lens, that were positive for dyes, indicate that ground-water flow within the lens is both horizontal and vertical. Dye arrival times in the deeper samples were similar to those near the water table. However, the vertical flow gradient may be greater than the horizontal flow gradient, because of the extra travel distance required for the dye to migrate both downward and laterally within the lens to reach the deep sites.

Figure 6 illustrates a conceptual model

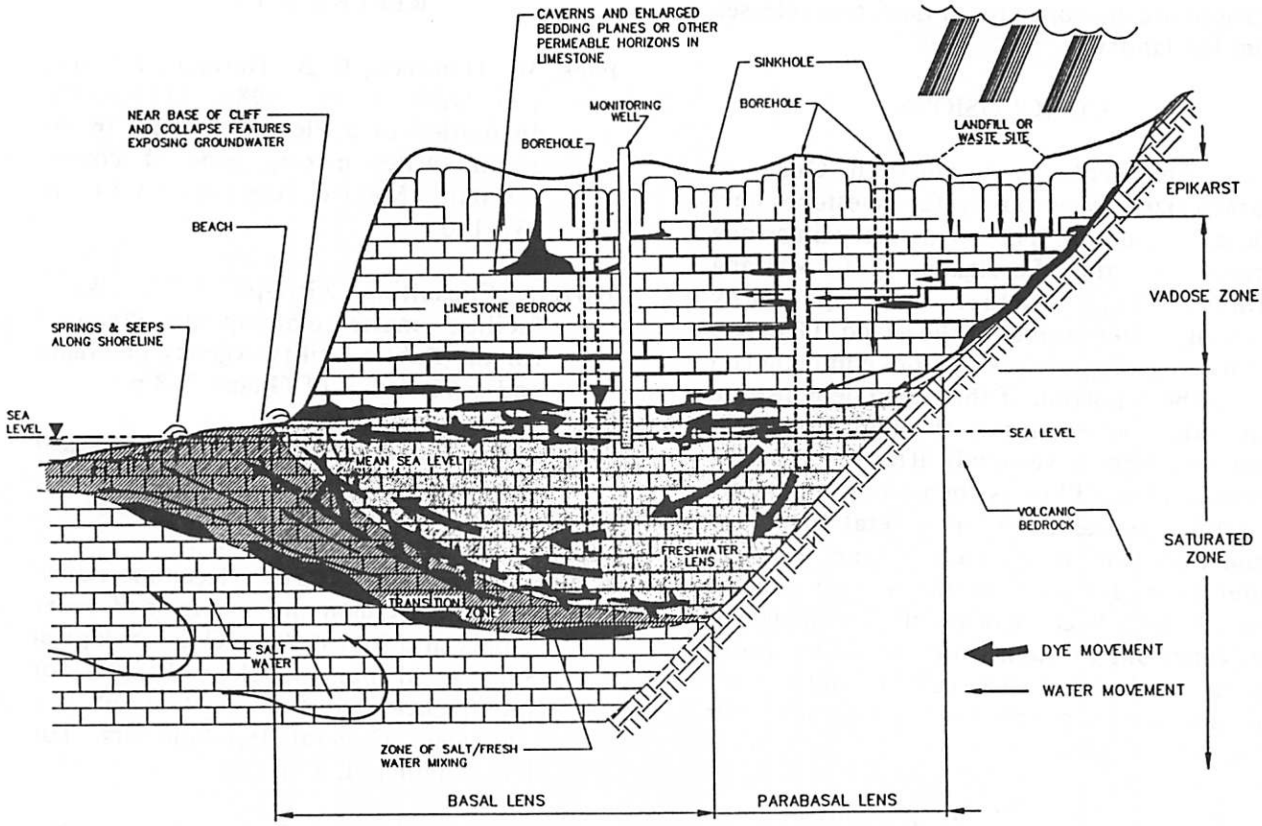

Figure 6. Conceptual Model for the hydrogeology of northern Guam.

for ground-water flow within the NGL. Rain falling on the surface percolates rapidly into the soils and limestone bedrock. The upper portion of the limestone is highly corroded and consists of a vast network of dissolution porosity capable of storing large volumes of water (epikarst). This zone continues to develop as new water is introduced to the system and dissolution of the limestone continues. The epikarst water is gradually released through other, smaller pathways to the underlying vadose zone and to the aquifer as diffuse recharge. Discrete concentrated runoff occurs only where there are enlarged joints, fractures, fault zones, and surface depressions that can direct surface runoff to the aquifer. As the ground water continues its travel to the aquifer, the flow direction can be altered, by encountering interconnecting fractures, dissolution cavities, or lithologic changes.

Upon reaching the aquifer, the influx of new meteoric water displaces water in the aquifer causing downward (vertical) flow as well as flow along the subtle hydraulic gradient. Because of the highly- permeable limestone, water levels do not respond rapidly by this influx of water. The rate and direction of flow can be altered within the aquifer by the occurrence of preferential pathways. Flow velocities within the phreatic zone mimic a macro-porous-media flow velocity (averaging 6-15 m per day). Flow within the vadose zone is similar, but can be very rapid if discrete high permeability zones are encountered.

These characteristics of the limestone aquifer of Guam are similar to those of other limestone systems such those of the Yucatan (Back et al, 1986), and the Bahamas (Mylroie et al., 1995a,b). These aquifer systems are characteristic of young limestone formations with relatively flat ground-water gradients, and high permeability. The information obtained from the dye trace study, while not comprehensive, is being used in conjunction with water level information, and past chemical analyses of the ground water, to site new monitoring well locations and to determine whether existing monitoring well locations are appropriate for detecting releases from the landfill.

CONCLUSIONS

The geology of northern Guam is characterized by porous reefal limestones on a volcanic seamount. The two primary limestone formations, the Barrigada and Mariana Limestones, contain the primary drinking-water source for the island. Geologic and hydrogeologic investigations conducted on the northern portion of the island demonstrate that water moves rapidly through the vadose zone, but then move slowly after reaching the phreatic zone. Flow is then along the subtle hydraulic gradient, and is several times less rapid than flow in the vadose zone. Ground water flow direction in the vadose zone is unpredictable because of the thick sequence of reef limestone through which the water drains under geologic or structural influences. Tritium data supports the dye trace results which indicate that ground water in the lens is less than five years old.

The information presented here, provides some interesting data regarding ground-water flow within carbonate island systems. Generally, it has been common and accepted knowledge that ground water flow within karst aquifers is influenced by conduit flow. On Guam, because of the great thickness of the vadose zone, some preferential flow pathways do exist. These are usually in the form of cavernous passageways that are the result of dissolution of limestone along the contact with the volcanic basement rock, or along joints and fractures that are enlarged by dissolution, or along faults zones. Most other flow within the vadose zone is diffuse, or similar to a macro-porous media-like flow regime until this water encounters the fresh-water lens. Upon reaching the lens, the water is slowed and flows horizontally along the subtle hydraulic gradient, and it also displaces water in the lens, thereby causing downward, or vertical, flow. This information is useful for future investigative work, whether for siting monitoring wells for regulatory compliance or for development of these fresh-water resources.

REFERENCES

Back, W., Hanshaw, B. B., Herman, J. S. and Van Driel J. N., 1986, Differential dissolution of a Pleistocene reef in the ground-water mixing zone of coastal Yucatan, Mexico: Geology, v.14, p. 137-140.

Barrett Consulting Group, 1992, Water facilities master plan update. Prepared for the Public Utility Agency of Guam and government of Guam, 308 p.

Bögli, A., 1980, Karst Hydrology and Physical Speleology: New York, Springer-Verlag, 270 p.

Cloud, P. E., Jr., 1951, Reconnaissance geology of Guam and problems of water supply and fuel storage: U.S. Geological Survey, Military Geology Branch for Intelligence Division, Office of the Engineer, General Headquarters, Far East Command, 50 p.

Choquette, P.W. and James, N.P., 1988, Introduction, *in* James, N.P. and Choquette, P.W., eds., Paleokarst: New York, Springer-Verlag, 416 p.

Esteban, M., and Wilson, J. L., 1993, Introduction to karst systems and paleokarst reservoirs, *in* Fritz, R., Wilson, J. L., and Yurewicz, D. A., eds., Paleokarst Related Hydrocarbon Reservoirs: SEPM Core Workshop No. 18, 275 p.

ICF Technology, Incorporated, 1994. Work plan addendum to operable unit 6 for operable unit 2, Andersen Air Force Base, Guam: Final report prepared for Andersen Air Force Base, 1st Revision, October 24, 1994, 210 p.

Lange, A. L. and Barner, W. L., 1995, Application of the natural electric field for detecting karst conduits on Guam: Fifth Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst, Gatlinburg, Tennessee, April, 1995, p.

425-442.

Mink, J. F., 1976, Groundwater resources of Guam: occurrences and development, Technical Report No.1: Water Resources Research Center, University of Guam, 275 p.

Mink, J. F. and Lau, S. L., 1977, Groundwater analysis by tritium technique: a preliminary evaluation: University of Guam Technical Report 2, 25 p.

Mylroie, J. E. and Carew, J. L., 1990, The flank margin model for dissolution cave development in carbonate platforms: Earth Surface Processes and Landforms, v.15, p. 413-424.

Mylroie, J. E., Carew, J. L. and Vacher, H. L., 1995a, Karst development in the Bahamas and Bermuda, *in* Curran, H. A. and White, B., eds. , Terrestrial and shallow marine geology of the Bahamas and Bermuda: Geological Society of America Special Paper 300, p. 251-267.

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

Quinlan, J. F. and Ewers, R. O., 1985, Ground water flow in limestone terranes: strategy rationale and procedure for reliable, efficient monitoring of ground water quality in karst terranes, *in* Proceedings of the Fifth National Symposium and Exposition on Aquifer Restoration and Ground Water Monitoring, p. 197-234.

Quinlan, J. F., Davies, G. J. and Worthington, S. R. H., 1992, Rationale for the design of cost-effective groundwater monitoring systems in limestone and dolomite terranes: cost effective as conceived is not cost effective as built if the system design and sampling frequency inadequately consider site hydrogeology, *in* Proceedings, Annual Waste Treatment and Water Quality Assurance Symposium, Washington, D.C., U.S. Environmental Protection Agency, Washington, D.C., p. 197-234.

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

Raulerson, L. and Rinehart, A., 1991, Trees and shrubs of the northern Mariana Islands: Coastal Resources Management Office of the Governor, Commonwealth of the Northern Mariana Islands, Saipan, Northern Mariana Islands, 120 p.

Reagan, M. and Meijer, A., 1984, Geology and geochemistry of early arc volcanic rocks from Guam: Geological Society of America Bulletin, v. 96, p. 701-713.

Siegrist, H. G., Jr., and Randall, R. H., 1992, Carbonate geology of Guam: summary and field trip guide; 7th International Coral Reef Symposium, Guam, U.S.A.: University of Guam, Water and Energy Research Institute of the Western Pacific, 39 p.

Smart, P. L., Dawans, J. M. and Whitaker, F. F., 1988, Carbonate dissolution in a modern mixing zone: Nature, v. 335, p. 811-813.

Tracey, J. I., Jr., Stensland, C. H., Doan, D. B., May, H. G., Schlanger, S. O. and Stark, J. T., 1959, Military geology of Guam, Mariana Islands: Part I description of terrain and environment; Part II engineering aspects of geology and soils. Engineer Intelligence Dossier Strategic Study: Marinas, Subfile 19 Analysis of the Natural Environment. Prepared under the direction of the Chief Engineers, U.S. Army by the Intelligence Division, Office of the Engineer, Headquarters United States Army Pacific with personnel of the

United States Geological Survey, 282 p.

Tracey, J. I., Jr., Schlanger, S. O., Stark, J. T., Doan, D. B. and May, H. G., 1964, General geology of Guam: U.S. Geological Survey Professional Paper 403, 104p.

Vacher, H. L., 1988, Dupuit-Ghyben-Herzberg analysis of strip-island lenses: Geological Society of America Bulletin, v. 100, p. 580-591.

Ward, P. E., Hoffard, S. H. and Davis, D. A., 1965, Geology and hydrology of Guam, Mariana Islands: U.S. Geological Survey Professional Paper 403-H, 29 p.