

Travel time prediction within the hydrologic cycle of a carbonate-rimmed island

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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 freshwater lens. Evidence from cave exploration and boreholes drilled suggest karstification has occurred between the phreatic and vadose zone at a depth of approximately 150 m (500 feet) below ground surface, and within the zone between the fresh and salt water interface, near sea level. Tracing results, isotope data, and non-flashy responses on water levels in wells suggests groundwater movement is representative of a macroporous media-like flow and not a conduit flow system that is usually expected in most karst aquifers. Groundwater flows in the aquifer both horizontally and vertically, converging along the coastal area, and discharges as resurgence or as submarine springs. Flow within the vadose zone, however, is rapid and the direction of movement is highly unpredictable.

Predicción del tiempo de recorrido dentro del ciclo hidrológico de una isla con orilla carbonatada

Resumen Las investigaciones hidrogeológicas en la porción norte de la isla de Guam, islas Mariana, proporcionaron datos alentadores con respecto a las probabilidades de régimen torrencioso en depósitos de agua dulce. Las evidencias de la exploración de cuevas y de perforaciones realizadas sugieren que la karstificación ocurrió entre la zona freática y vadosa a una profundidad de aproximadamente 150 m bajo nivel de terreno, y dentro de la zona de interfaz de agua dulce y salada cerca del nivel del mar. Los resultados de diagnóstico, datos isotópicos y respuestas no torrenciosas en los niveles de agua de pozos sugieren que el movimiento de agua subterránea es representativo de un sistema fluidal similar al de un medio microporoso, y no de un sistema fluidal de conducto que es el que normalmente se espera en la mayoría de los acuíferos de karst. El agua subterránea fluye en el acuífero de manera horizontal y vertical, convergiendo a lo largo de la zona costera, y desemboca como resurgencia o fuente submarina. Sin embargo el flujo dentro de la zona vadosa es rápido y la dirección de movimiento es altamente imprevisible.

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 World War II after liberating the island from the Japanese in 1944. In the intervening years, sanitary and industrial wastes from these facilities have been disposed in various trenches, borrow pits, quarries and sinkholes. Potential groundwater degradation may result if hazardous substances, in the form of

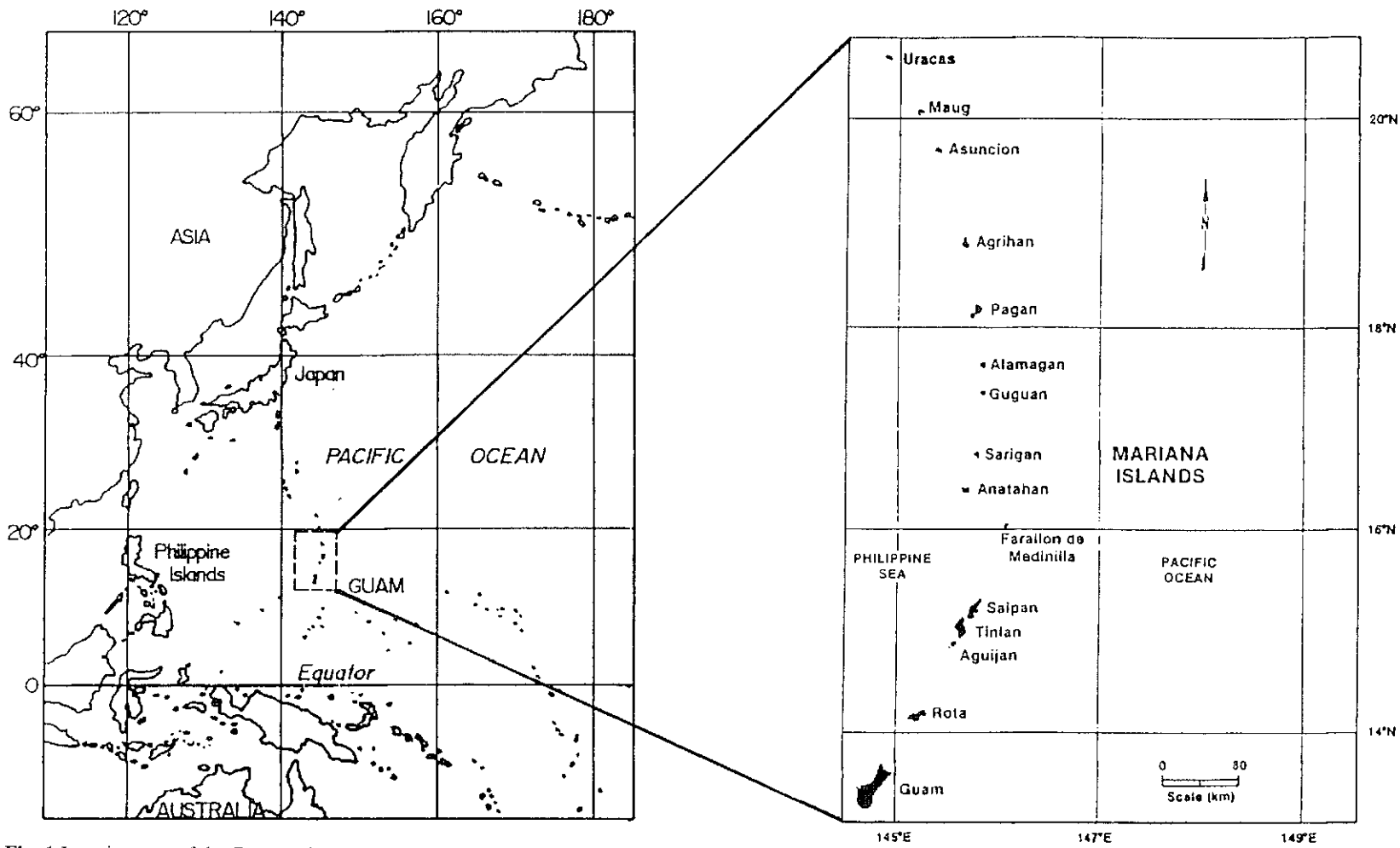


Fig. 1 Location map of the Guam and Mariana Islands.

leachate, are released from these disposal areas. Implementation of geologic and hydrogeologic investigations resulted in the installation and sampling of groundwater monitoring wells to address this concern. As part of these investigations, an evaluation of existing data, borehole drilling, borehole and surface geophysical surveys, and a tracer study were performed to predict groundwater flow directions and velocities.

PHYSIOGRAPHIC SETTING

The island of Guam is the southernmost island in the Mariana Island chain, located approximately 13°27' N latitude and 144°47' E longitude (Fig. 1). Guam is approximately 2500 km (1550 miles) south of Japan and approximately 5300 km (3300 miles) southwest of the Hawaii Islands. The Mariana Islands are a complex island-seamount system, divisible geographically, tectonically and chronologically into island arcs (Siegrist & Randall, 1992); an older frontal arc (middle Eocene, 43 million years before present [m.y.b.p.]) which includes the larger islands of Guam, Rota, Tinian, and Saipan, plus two smaller uninhabited islands. A younger arc (early Pleistocene; 1.3 m.y.b.p.) of active seamounts and islands lies to the west and north of the older arc. All islands in the Mariana Arc are located on the Philippine Plate known as the "andesite line", which separates the Pacific Basin from the Philippine Plate and identifies those Micronesian islands that form the eastern edge of the Philippine Plate (Karolle, no date given).

Guam is approximately 48 km (30 miles) in length running north-south, ranging in width east-west from approximately 6.4 km (4 miles) near the centre of the island to 13 km (8 miles) in the northern part of the island. Depositional environments of Guam represents a limestone-veneered peak on a nearly submerged volcanic ridge between the Philippine Sea to the west and the Pacific Ocean basin to the east (Cloud, 1951). The elevations on the northern plateau region range from about 60 m (200 feet) to 180 m (800 feet) above sea level. The surface of the limestone plateau is interrupted by two volcanic peaks, Mount Santa Rosa and Mataguac Hill, with elevations of 252 m (826 feet) and 192 m (630 feet), respectively, above sea level.

GEOLOGY OF NORTHERN GUAM

The geology underlying the northern plateau of Guam consists of two primary limestone reef deposits overlying volcanic rocks (Fig. 2). The limestone consists of the Mariana and Barrigada Limestone formations. The Barrigada (late Miocene to early Pliocene; 11.2–3.4 m.y.b.p.) is usually white, chalky, fine grained texture composed of a foraminiferal-algal wackestone distinguished by sparse, but locally abundant accumulations of coral moulds (Tracey *et al.*, 1959). The maximum thickness of the formation is unknown, but has been presumed to be greater than 180 m (540 feet) based on similar lithology and fossil assemblage from borehole drilling. The Barrigada is interpreted as being a submarine carbonate bank formed at a depth of approximately 200 m (600 feet) below sea level. The peripheral slopes, and the abundance of coral and molluscan remains, indicate bank shoaling during late

GEOLOGIC MAP OF GUAM

(Modified and Simplified from Tracey et al 1954)

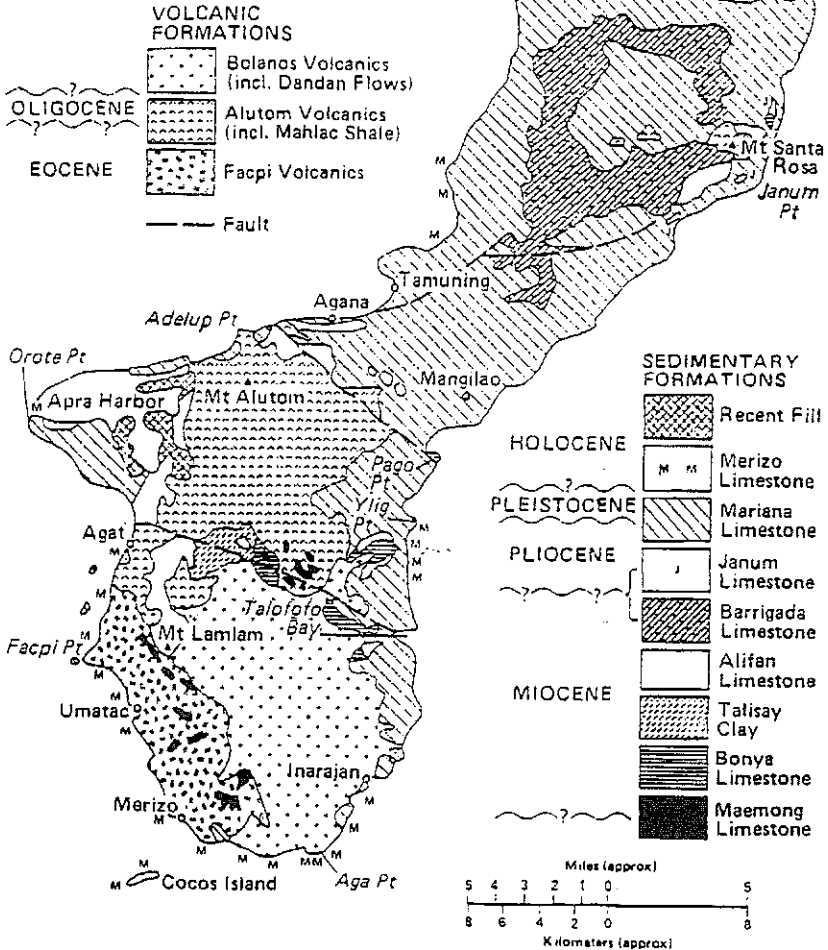


Fig. 2 Generalized geologic map of Guam (after Tracey et al. (1964) and Reagan & Mcijer (1984); from Siegrist & Randall (1992)).

Miocene or early Pliocene time, allowing reef formation on the underlying volcanic (Alutom) formation (Tracey et al., 1959; Siegrist & Randall, 1992).

Overlying the Barrigada Limestone is the younger Mariana Limestone (late Pliocene to Pleistocene time; 3.4–1.6 m.y.b.p.) which overlies most of the surface area of the northern plateau and onlaps the Barrigada Limestone as a vertical and transgressive facies, changing from a deep to a shallow water depositional sequence. The four reef-associated facies of the Mariana limestone, includes the reef facies, the fore-reef facies, the detrital facies, and the molluscan facies. The reef facies are massive, generally compact, porous and cavernous, white coralline and corallgal

boundstones, coarse grainstones, packstones, and wackestones of reef origin (Tracey *et al.*, 1959; Siegrist & Randall, 1992). The detrital facies are friable to well cemented, coarse to fine-grained, generally porous and cavernous, white detrital coralliferous rudstone, micritic wackestone and mudstones mostly of lagoonal origin. The molluscan facies are fine-grained, white to tan detrital limestone of lagoon origin containing casts and moulds of molluscs. The fore-reef facies consist of well-bedded, friable to indurated, white foraminifera packstones and wackestones deposited as a fore-reef sand (Tracey *et al.*, 1964; Siegrist & Randall, 1992).

GEOMORPHOLOGY

Karstification of the limestones on Guam, resulting in formation of caves, cenotes and sinkholes have developed over much of the northern plateau. These features have formed from the chemical dissolution of limestone by weak carbonic acid derived from the atmosphere and soils (Palmer, 1991). In addition to the surface and near surface weathering, the mixing of two contrasting water types (fresh and marine) has resulted in the dissolution of limestone at depth, particularly occurring at the vadose/phreatic interface and in the transition zone—the zone where freshwater is in contact above the denser marine water (Bögli, 1980; Palmer, 1991; Esteban & Wilson, 1993).

The emerged caves found along the margins of the limestone plateau are the result of this mixing zone dissolution process. Along the margins of the island, the freshwater lens is thin in comparison to the lens thickness inland. The thinning of this lens and the influences from tides and storm surges, create a chemically aggressive mixture that produces dissolution porosity and in some cases, caves. Drilling of several deep boreholes inland and along the coastal areas help support this theory. Another dissolution process may result from the introduction of organic material into the aquifer with oxidation of organic carbon. Oxidation/reduction reactions involving sulphur can produce acidic waters capable of phreatic dissolution (Mylroie *et al.*, 1995).

GROUNDWATER

The Barrigada and Mariana Limestone formations are the primary water bearing aquifers and drinking water supply on Guam. The aquifer is recharged by rainfall which generally exceeds 200 cm (80 inches) annually on the northern portion of the island (Mink, 1976). Selected geochemical parameters and tritium concentrations were evaluated by Mink & Lau (1977) in a study conducted in 1976 to more fully understand the hydrologic cycle on the island and to identify prospects for additional water yield. Tritium analysis of groundwater samples were compared to rainwater data monitored at Taguac by the International Atomic Energy Agency (IAEA) from December 1961 to December 1972, and a groundwater age date of “about five or less years old” (circa 1972) was determined by their study (Mink & Lau, 1977).

The groundwater exhibits a relatively flat hydraulic gradient resulting from the high permeable limestones, and the elevation of the water table ranges from sea level

at the coastal areas to approximately 1.8 m (6 feet) above sea level. Throughout northern Guam, fresh groundwater floats on denser marine water and forms a freshwater lens that approximates the Dupuit-Ghyben-Herzberg model (Vacher, 1988). Based on this model, for every one foot of water above sea level, 40 feet of freshwater will extend below sea level. The observed boundary, however, is usually diffuse in nature because of hydrodynamic dispersion induced by movements of the interface from tidal changes, seasonal differences in recharge rates, and withdrawals of freshwater by pumping (Mink, 1976). This diffuse zone of brackish water between the marine water and freshwater is referred to as the transition zone, and the thickness of this zone is dependent on the dynamics of flow and potential for mixing with the freshwater portion of the lens. Observed freshwater thickness on Guam, based on geophysical logs (fluid conductivity) is approximately 37 m (120 feet). The depth to the water table across the northern plateau generally approximates sea level, and groundwater exists as seeps and submarine springs as the lens thins along the coast.

DISCUSSION

Hydrogeologic investigations included: measuring water levels in existing monitoring wells; borehole drilling around landfill areas and along the northern coast; downhole and surface geophysical surveys; and performing a dye trace. The resulting water levels indicated a relatively flat groundwater gradient sloping toward the northern coastal area. Borehole drilling 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 to place boreholes on natural potential anomalies (Lange & Barner, 1994). Geophysical and borehole video logging of the boreholes suggest that most of the caverns, vugs and dissolution porosity occurs at the vadose/phreatic interface and at the freshwater/salt water interface.

A dye trace was initiated to determine groundwater flow direction and estimated flow velocities within the freshwater lens and to simulate release from a landfill area. The tracer study monitored over 70 locations that included existing wells and boreholes around the landfill area, boreholes along the beach area drilled on natural potential anomalies, and in caves that contained freshwater sumps discovered along the base of the northern cliff face. One month of background results were collected prior to the dye placement to establish background fluorescence of the aquifer. Background fluorescent conditions of the aquifer and dye standards were used to compare data during the evaluation of sample analysis.

Three dyes were used consisting of: rhodamine WT, Uranine, and Phorwhite BBH Pure. The dyes were placed in boreholes drilled around the existing landfill area and were at depths of 15 and 60 m (50 and 200 feet) below ground surface. The third injection was directly into the groundwater, approximately 137 m (450 feet) below land surface. Samples collected from these sampling locations consisted of activated carbon and undyed cotton samplers.

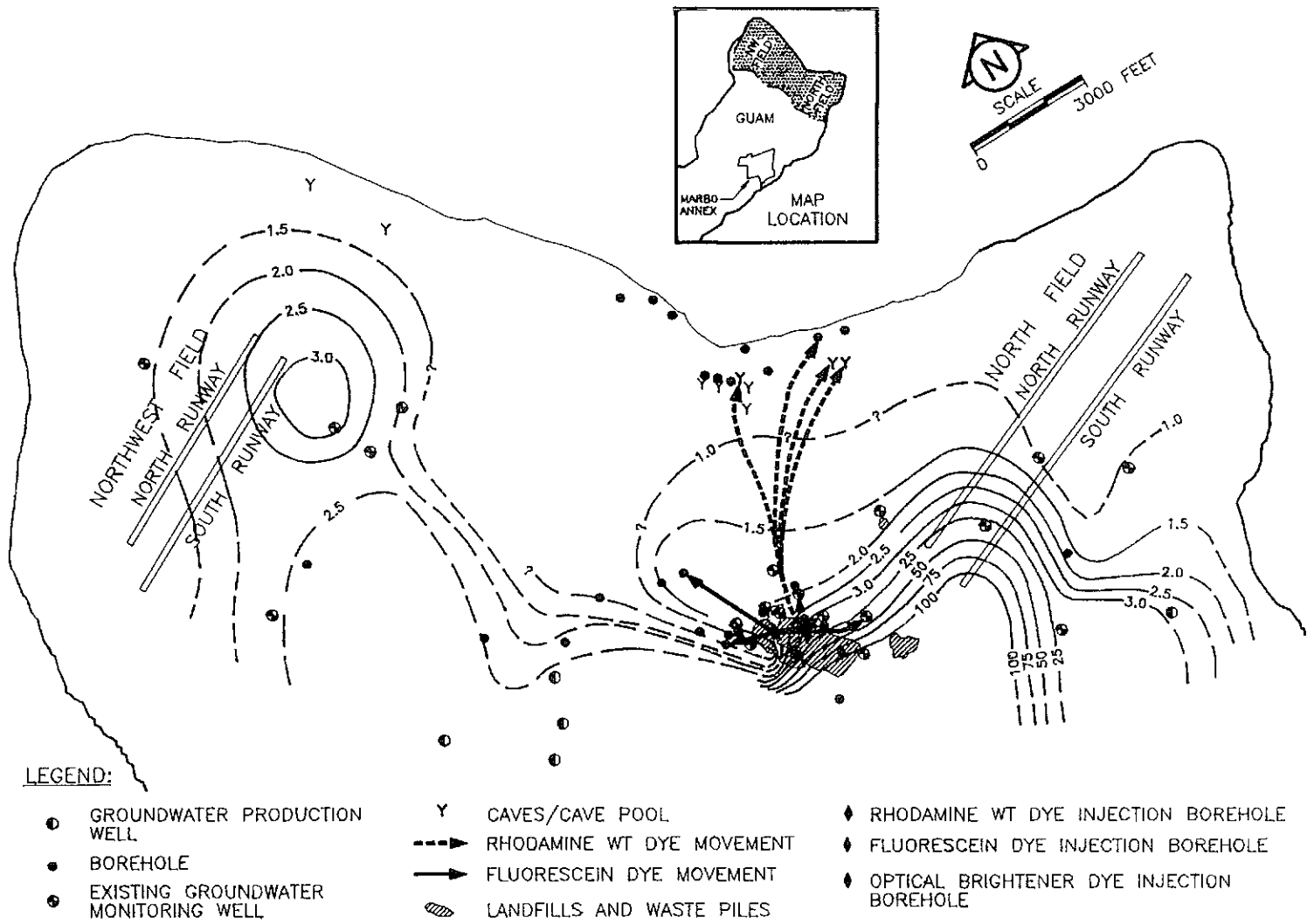


Fig. 3 Dye trace results and flow directions in the vadose and phreatic zones.

The dye trace programme lasted 15 months and was terminated with positive results (Fig. 3) 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 the porous nature of the limestone, the numerous caverns and other karst features located, and previous tritium studies showing relatively young water, it was anticipated that groundwater movement would be very rapid. However, saturated flow was not as rapid as originally anticipated, and the combined vadose and saturated flow near the landfill area indicated more rapid movement in the vadose zone prior to reaching the water table. Flow within the groundwater system is essentially advective flow along the hydraulic gradient and is indicative of diffuse transport with the average flow velocity calculated to range from 6–11 m (20–36 feet) day⁻¹.

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 due to the deposition and stratigraphic relationship of the reef limestone, and fracturing and faulting of the bedrock associated with island arc tectonics. When the water flows through the vadose zone, velocity is abruptly reduced when the water table is encountered. Travel time for the combined vadose and saturated flow ranged from 91 m (300 feet) day⁻¹ to over 244 m (800 feet) day⁻¹. The combined flow regime includes approximate 76 m (250 feet) of vertical movement through the vadose zone to the water table before the saturated flow condition predominates.

The dye trace results indicate two distinct flow characteristics. Flow within the vadose zone is very rapid and the pathway direction is tortuous. Flow within the groundwater system essentially flows with the subtle hydraulic gradient and slower velocities. These findings and the limestone aquifer of Guam are similar to other recent limestone systems such as provided in the literature for the Yucatan (Back *et al.*, 1986), Florida (Beck, 1986), and the Bahamas (Mylroie *et al.*, 1995). These aquifer systems are characteristic of young limestone formations, with relatively flat groundwater gradients, and highly diffuse permeability.

CONCLUSION

The geology of northern Guam is characterized by porous reef deposited limestones on an active volcanic seamount. The two primary limestone formations: the Barrigada and Mariana Limestones, contain the primary drinking water source for the island of Guam. Geologic and hydrogeologic investigations conducted on the northern portion of the island demonstrate that water moves rapidly through the vadose zone, but is then slowed when reaching the water table. Groundwater flow direction in the vadose zone is unpredictable because of the thick sequence of the reef limestone which the water drains through under geologic structural influence before reaching the water table. Groundwater flows along the subtle hydraulic gradient and is several times less rapid than flow in the vadose zone. The groundwater is also transported vertically downward through the aquifer, and eventually exits at seeps and possible submarine springs located along the coastal regions of the island.

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