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Front Cover: Close-up view of a patch-reef coral head in Grahams Harbor, north of Dump Reef. As shown here, Caribbean shallow-water reefs have declined since the mid-1980s and are now largely overgrown by fleshy green macroalgae and a variety of encrusting organisms. See Curran et al., "Shallow-water reefs in transition," this volume, p. 13. Photograph by Ron Lewis.

Back Cover: Dr. A. Conrad Neumann, University of North Carolina, Chapel Hill, NC, Keynote Speaker for the 11th Symposium and author of "Cement loading: A carbonate retrospective," this volume, p. xii. Photograph by Mark Boardman.

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PETROLOGY OF LIMESTONES FROM GUAM, U.S.A.: A PREDICTABLE PATTERN OF DIAGENESIS?

Toni Reale, James L. Carew, Charity Thomas, and Anton Dumars
Department of Geology and Environmental Geosciences
College of Charleston
Charleston, SC 29424
treale@geo.umass.edu

Galt Siegrist
Water and Environmental Research Institute of the Western Pacific
University of Guam
Guam, U.S.A.

ABSTRACT

Miocene-Pleistocene limestones of Guam were studied to determine whether the diagenetic condition of the rocks is related to their age, stratigraphic position, or proximity to karst features or soils/paleosols. Analyses of more than 100 samples from outcrops and quarries revealed that diagenetic alteration is advanced; however, there is no apparent relationship between degree or style of alteration and the stratigraphic position of the rocks, or their proximity to karst features or paleosols.

Fifty-one thin sections were obtained from a deep core (EX-5) that was drilled to 280 meters depth in the Miocene-Pliocene Barrigada Limestone in northern Guam. Point counts of the thin sections reveal a general trend of greater porosity and less diagenetic micrite with depth. However, the trend is not statistically significant. Preservation of allochems is greatest in samples from near the top and bottom of the core. Moldic porosity produced by dissolution of corals and foraminifera plays an important role in secondary porosity development, but vuggy and interparticle porosity is also common. It is only in the middle of the core that void infilling by precipitation of spar is evident, which is most likely the result of greater exposure to the freshwater vadose environment resulting from fluctuations of the freshwater lens position.

Generally, the degree of diagenesis is likely related to the amount of time the rock has spent in the freshwater/marine mixing zone, and the freshwater phreatic and vadose environments. Lesser diagenesis of the rocks of the upper core may have resulted from rapid uplift early in the island's exposure history that quickly moved those rocks above the zone of diagenesis near and within the freshwater lens. However, because of episodic uplift of the island, glacio-eustatic fluctuations of the freshwater lens position, and widespread karst development (from micropores to caves), the degree of alteration is not simply a function of depth.

The results of this study indicate that one cannot predict the degree or style of diagenetic alteration of the rocks of the Northern Guam aquifer by determining their stratigraphic position, their age, or their proximity to a karst feature or soil horizon. The porosity and permeability are not simply related to any known variables, and there are no recognized horizons that reflect past stillstands of sea level that might be expected to exhibit greater karst development and greater micro- and macroporosity. Preferred pathways for infiltration of freshwater, the rate of infiltration, and the rate of discharge from the margins of the freshwater lens are probably locally controlled and highly variable. A significant conclusion of this study is that in order to protect the water resources of the Northern Guam Aquifer, all of Northern Guam should be developed in an environmentally conservative manner.

INTRODUCTION

Guam is the southern-most island of the Marianas chain (Figure 1) and is centered at approximately 13°27' N and 144°47' E. The island is approximately 48 km from north to south and is about 13 km at its widest point, which is in northern Guam. Guam is a tectonically uplifted island that is bordered in places by near-vertical cliffs up to 183 meters high. According to the classification of carbonate islands by Mylroie and Carew (2000), southern Guam is a carbonate-rimmed island (later renamed composite island by Mylroie and Jenson, 2001, based on a classification proposed by Vacher, 1997). Northern Guam is generally a carbonate-cover island with only limited areas (e.g., Mount Santa Rosa) where the underlying volcanics reach the surface. In those areas, the island behaves as a composite island with localized allogenic freshwater recharge. Because of the great thickness of limestone over much of northern Guam, hydrologically most of northern Guam probably behaves as a simple carbonate island as described in the Carbonate Island Karst Model (CIKM) (Mylroie and Jenson, 2001).

This study was conducted as part of a larger, USGS-funded project aimed at understanding the hydrogeology of Guam. The aim of this study was to determine whether petrologic evidence can be used to identify horizons of greater porosity/karst development that may have resulted when sea-level stillstands perched the freshwater lens in the same position for extended times. Such zones of preferred or diagnostic diagenesis might greatly influence the hydrogeology of the Northern Guam Aquifer, which provides most of the water that supports the large tourist economy of Guam.

GENERALIZED GEOLOGY OF GUAM

The earliest geologic investigation of Guam was a study of coral reefs reported by Agassiz (1903). Studies of the general geology of Guam were conducted by Stearns (1937, 1941), Cloud (1951), Tracey et al. (1964), Schlanger (1964), Ward et al. (1965), and Siegrist and Randall (1992). The hydrogeology of Guam has also been studied by Mink (1976), Mink and Lau (1977), Ayers and Clayshulte (1984), Lange and Barner (1995), Barner (1997), and Mink and Vacher (1997). Tracey et al. (1964) is generally regarded as the primary reference for the geology of Guam, and the premier studies of the petrology of the limestones are those by Schlanger (1964) and Siegrist and Randall (1992). A good synopsis of the geologic history of Guam is presented in Mink and Vacher (1997).

The limestones of northern Guam consist primarily of two formations, the Mio-Pliocene Barrigada Limestone and the Plio-Pleistocene Mariana Limestone. The Barrigada Limestone represents the early stages of a shallowing-upward sequence of an emerging volcanic submarine plateau (Siegrist and Randall, 1992).

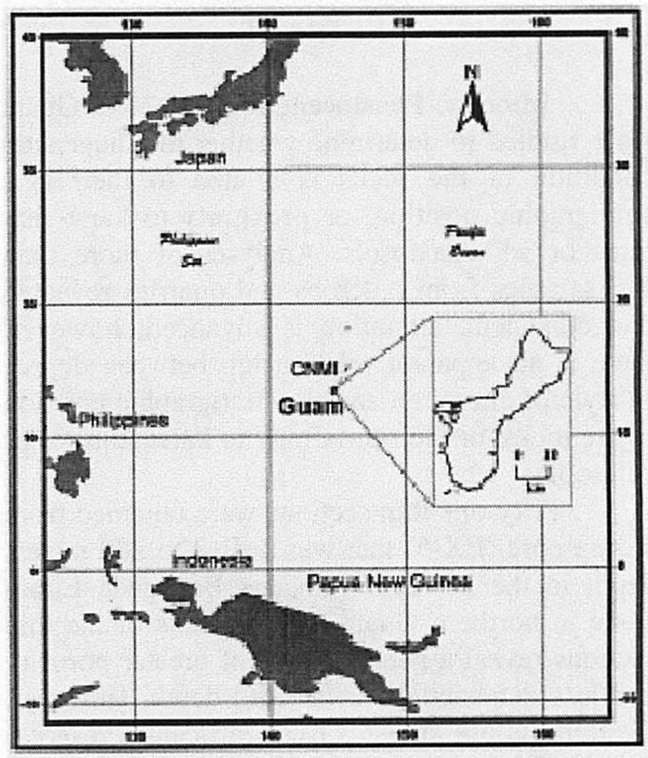

Figure 1. Location and outline map of Guam. From Mylroie et al, 2001.

The Mariana Limestone represents the later stages of shallow-water deposition and includes abundant reefal facies (Tracey et al., 1964; Siegrist and Randall, 1992). These limestones comprise the Northern Guam Aquifer, which holds the primary water supply for the island.

METHODS

For this study, hand samples and short, one-inch diameter cores were obtained from out

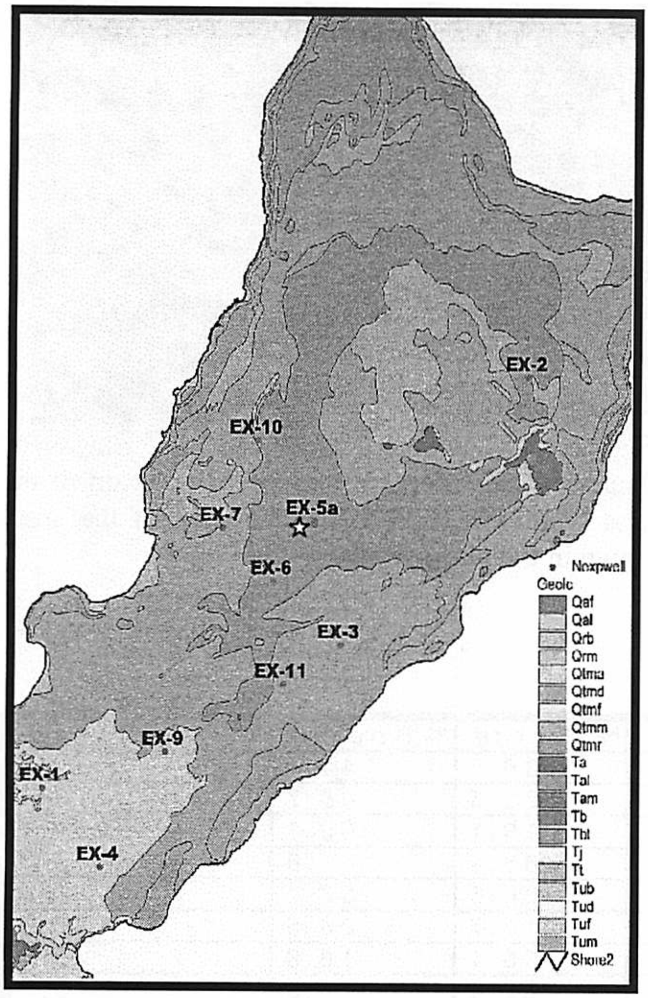

Figure 2. Geologic map of northern Guam showing the location of surface rock samples and one core (star).

crops of the Barrigada, Mariana, and other limestones. Exposures included natural outcrops, roadcuts, quarries, and cave interiors. Samples were also obtained from one (EX-5) of the two cores that were drilled a few meters apart in the Barrigada Limestone in the south central portion of northern Guam (Figure 2). The more than 100 thin sections taken from the rocks of the Northern Guam Aquifer were point counted and analyzed to determine the relationship, if any, between diagenesis (e.g., porosity and micritization) and stratigraphic position or proximity to karst features and soils/paleosols. It was of interest to selectively sample rocks in proximity to karst features and soil horizons in order to determine whether there were predictable diagenetic signatures associated with those locales. Thin sections from the hand samples, short cores, and deep core EX-5 were analyzed for allochem content, matrix/cement type, and porosity.

Fifty-one thin sections, on loan from the Water and Environmental Research Institute of the Western Pacific (WERI), came from USGS core EX-5, drilled in 1993. The core was drilled in the south-central portion of Northern Guam through what appears to be homogenous Barrigada Limestone. The elevation of the drill site was 118 meters above sea level and the core extended to 162 meters below current sea level. Thin sections analyzed for this study range from 106 meters above sea level to 135 meters below sea level.

Analysis of the core thin sections began by recording a qualitative description of percent pore space, cement, and type of allochems present in each thin section to ensure that the area to be point counted reflected the overall content of the thin section. Point count analyses consisted of 350 counts per thin section, and were carried out using a Swift Automated Point Counter mounted on a Nikon Microphot petrographic microscope. Each thin section was point counted for type of matrix/cement (sparite or micrite), pore space (type of pore space was noted), and allochem content (ooid, coral, foraminifera, algae, mollusk, echinoderm, peloids, and unidentified bioclasts). These data were then analyzed for any linear relationship between depth and porosity, or depth and cement type.

Thin sections were cut from all of the hand samples and short cores, and these were analyzed and point counted. In order to determine whether there are any discernable patterns of diagenesis in proximity to karst features or soil horizons, some outcrops were sampled in an organized fashion. Samples were drilled at the margin of, and at increasing distance from karst features and soil horizons (Figure 3).

RESULTS

Point counts of allochems, porosity, and matrix/cement in the thin sections from core EX-5 reveal general trends of increased porosity and decreased micrite with depth (Figures 4 and 5). The percent of micrite in the thin sections ranges from near 20% to 72.2%, with an average value of

52.2%. These data show that the rocks throughout the core contain significant micrite. However, that micrite is not primarily in the form of original muddy matrix, but instead represents diagenetic micrite. So, these data indicate that all rocks show significant micritization. The data show that there is a general decrease in micrite (and therefore diagenesis) with depth (Figure 4), but the distribution of data points about the trend line (r^2=0.3232) is such that no reliable prediction can be made about the level of micritization versus depth.

Sparite cement is generally uncommon in the core samples. Sparite was encountered in only 23% of the thin sections, and ranges from 0.2% to 14.5% of the points counted in those samples. Large, secondary spar crystals infilling vuggy porosity (Figure 6) were found in only two thin sections.

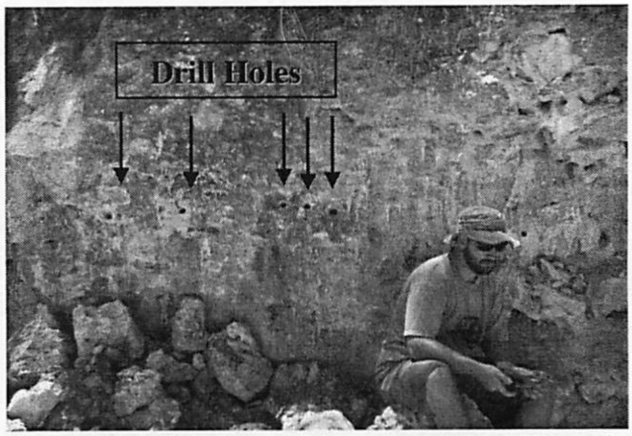

Figure 3. Mariana Limestone in Hawaiian Quarry. Cores were drilled in the proximity of karst feature located to the far right of the area shown in the photograph.

Sample #	Formation and Location	% Micrite	% Sparite	% Pore Space
GU99-5	Mariana/Awesome Cave	36.5	41.1	2
GU99-1A	Argillaceous Mariana	20.5	65.7	13.7
GU99-1B	Argillaceous Mariana	19.1	59.1	21.1
GU99-36	Alifan Ls	85.4	8	5.4
GU99-35	Mariana/Talofofo Cave	30.5	57.4	12
GU99-32	Mariana epikarst/Hawaiian Q	11.7	26.5	12.2
GU99-34	Mariana Upper/ Hawaiian Q	55.1	18.8	5.7
GU99-33	Mariana Mid/Hawaiian Q	39.4	6.5	5.7
GU99-31	Mariana Lowest/Hawaiian Q	23.1	70.5	6.2
GU99-15	Barrigada Ls/Perez Q	57.4	1.1	43.8
GU99-16	Barrigada Ls/Perez Q	71.4	3.1	18.5
GU99-17	Barrigada Ls/Perez Q	44.5	22.5	32.5
GU99-18	Barrigada Ls/Perez Q	65.4	2.2	21.4
GU99-23	Mariana/Tarague Cliff	20.5	5.1	27.7
GU99-20	Mariana/Tarague Cave S	15.4	11.4	10.5
GU99-21	Mariana/Tarague Cave N	43.4	7.4	19.7
GU99-19	Mariana/Pagat Cave	31.1	32.8	14.8
GU99-13	Mariana/Hawaiian Q	30	42	17.1
GU99-12	Mariana/Hawaiian Q	1.7	84	14.2
GU99-11A	Mariana/Hawaiian Q	30	61.2	8.8
GU99-10	Mariana/Hawaiian Q	13.8	77.6	8.5
GU99-9	Mariana/Hawaiian Q	48.1	21.7	8.2
GU99-8	Mariana/Hawaiian Q	42.5	47.1	6.8
GU99-7	Mariana/Hawaiian Q	27.1	61.7	11.1
GU99-14	Mariana/No Can Fracture	27.7	21.4	0.8
GU99-27	Janum Ls	25.3	29	26
GU99-26	Janum Ls	15.7	0	1.1
GU99-30	Janum Ls	12.5	0	?
GU99-25	Janum Ls	21.3	0	0

Table 1. Percent micrite, sparite, and pore space from thin-section analysis of limestones taken from various outcrops in Northern Guam. Samples GU99-7 through GU99-13 were taken at increasing distances from a karst feature, with GU99-7 being the closest.

Porosity measured in the thin sections from the core range from a maximum of 44% to a minimum of 5.4%. The average porosity is 27.3%. The porosity data reveal a general trend of increased porosity with depth (Figure 5); however, the r^2 value (0.2298) indicates that there is a large spread within the data, and the trend is not statistically significant.

The thin section analyses of core EX-5 also made note of the types of porosity such as moldic, interparticle, intraparticle, and vuggy. The data indicate that regardless of depth, vuggy or non-fabric-selective porosity dominates and accounts for most of the point-counted pore space. The second most common type of porosity is moldic porosity. Essentially all of the coral and some of the foraminifera found in the core samples are represented by molds (Figure 7). Most of the remainder of the foraminifera bioclasts have been diagenetically altered to micrite, but even those fossils the inner-most portions were usually dissolved out to form intraparticle porosity (Figure 8).

Overall, bioclasts seem to be better preserved near the top of the core and near the bottom of the core, with the exception of coral, which is represented almost exclusively by molds. The most abundant identifiable bioclasts are foraminifera, which averaged 9.1% of the core samples. Several species of algae, echinoderm fragments, bryozoans, mollusc fragments, and some fecal pellets were evident in some samples. Due to the intense diagenesis in some areas of the core, many bioclastic allochems were unidentifiable.

Interestingly, there are erosional notches seen in coastal outcrops in northern Guam that show evidence of at least 4 sea-level stillstands, now exposed above modern sea level. However, those sea-level stillstands have not left a detectable diagenetic signature in the rocks of core EX-5.

Results from the analyses of the hand samples and short cores are shown in Table 1. Note especially the data from the Hawaiian Rock Quarry samples that were taken at increasing distance from a karst void. Clearly there is no trend in porosity or diagenesis. Overall, these results

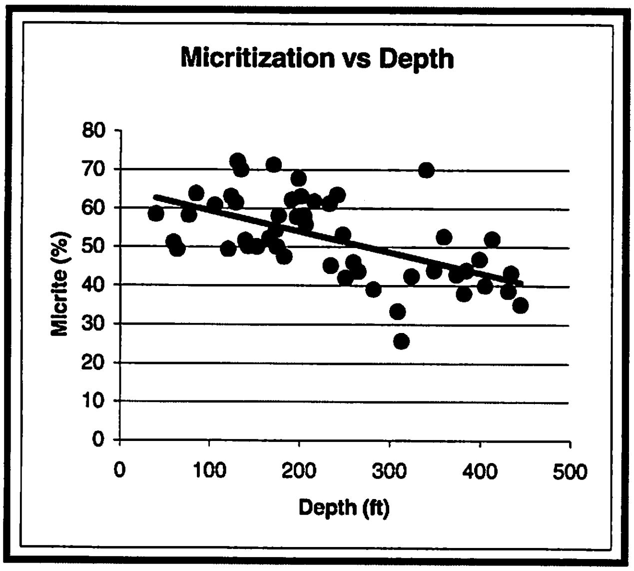

Figure 4. Graphical represntation of percent micrite as a function of depth; the r^2 is 0.3232.

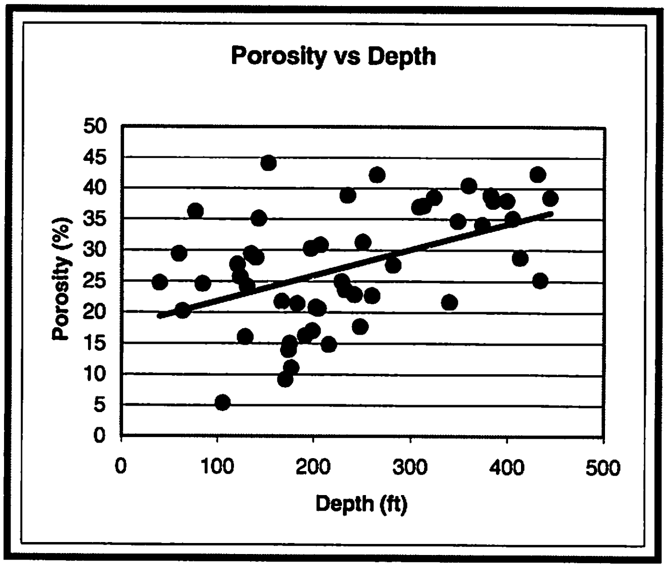

Figure 5. Graphical representation of percent pore space as a function of depth; the r^2 is 0.2298.

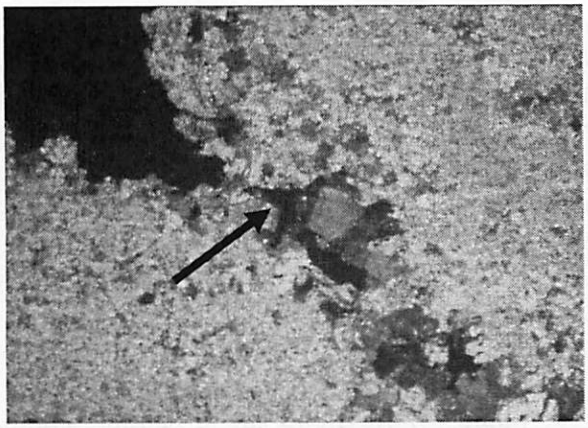

Figure 6. Photomicrograph from a thin section taken at 39m depth showing a void that is infilled with secondary spar. Field of view = 2mm.

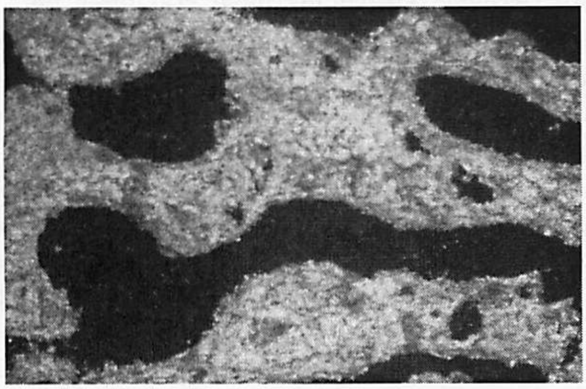

Figure7 Evidence of moldic porosity of a coral skeleton. Thin section is from a depth of 131.5m Field of view = 2mm.

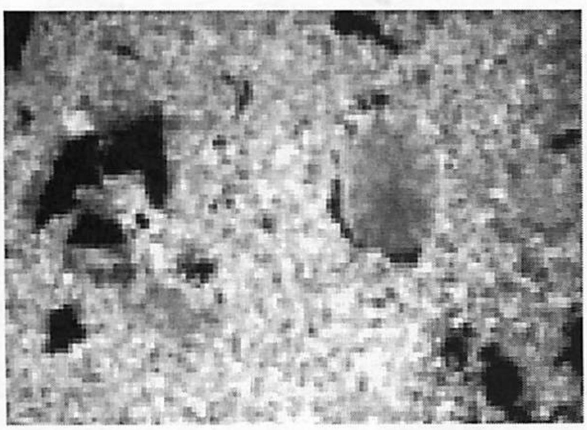

Figure 8. Photograph of a foraminiferan that has intraparticle porosity. This thin section is from 55.5m depth. Field of view = 2mm.

reveal that there is no predictable diagenetic signature in Guam limestones with reference to karst features, nor is there any predictable pattern associated with proximity to soil horizons. In addition, there is no apparent relationship between the age of the rock and the degree or style of diagenesis. Interestingly, three of the four samples of the Janum Limestone, which is thought to be a deep-water equivalent to the Barrigada Limestone, have no porosity at all, and show the greatest preservation of unaltered fossil allochems (mostly foraminifera).

DISCUSSION AND CONCLUSIONS

The data obtained from this study indicate that the degree and style of diagenetic alteration of the carbonates housing the Northern Guam Aquifer cannot be predicted based upon stratigraphic position, age, or relationship to karst features or soils/paleosols. This study does reveal a general trend of decreased micritization and increased porosity with depth in core EX-5 of the Barrigada Limestone. However those trends are not statistically significant. Another interesting observation is that bioclasts are better preserved in both the top and bottom portions of the core, while the allochems in the central region are more diagenetically altered. This may reflect the greater amount of time that the rock in the central part of the core has been in the freshwater vadose zone and/or in the zone of intense diagenesis associated with the freshwater lens and mixing zone. When the rocks at the top of the core were first uplifted into the subaerial environment, there was limited catchment, and probably little or no freshwater lens. So, the only diagenesis that could occur was during the brief time it took for rainwater to pass through the rock to the closely underlying marine water. With further uplift those rocks spent most of the time in the driest portion of the vadose zone.

Diagenesis of carbonates is largely a direct result of the hydrogeology, which is quite complicated on carbonate platforms; that is, the amount of exposure to pore waters of various chemistries. Guam is located in the tropical North Pacific where the amount of precipitation exceeds the amount of evaporation (Lander, 1994), which means that Guam has a robust freshwater budget. The input of water into the subsurface is largely a result of autogenic recharge from meteoric water over most of the northern plateau. There is also some allogenic recharge in areas where volcanics are exposed (e.g., Mt. Santa Rosa). Northern Guam contains no natural surface water drainage system, and closed depressions tend to collect water, which is transported to the vadose zone via diffuse flow. Pit caves, banana holes, and fractures also capture water, which is delivered to the subsurface as quasi-point-source recharge.

At the surface, meteoric water accumulates CO_2 from the soil, thus enhancing the acidity of the water and increasing its dissolving power near the surface. However, with depth, as it interacts with the limestone it is buffered and it quickly looses its ability to dissolve more limestone. As a result of this near-surface dissolution, the landscape is dominated by epikarst.

It is interesting that near the top of the core (~12 m depth) bioclasts such as foraminifera are recrystallized to micrite, but are better preserved than those occurring farther down the core where the preservation is mostly as molds. It may be inferred that the development of the epikast and intense diagenesis of the top few meters of the limestone creates a type of barrier that protects the immediately underlying rock from some diagenesis. This may happen because the epikarst is capable of storing a large quantity of water, which loses much of is aggressivity as it dissolves rock that enhances the epikarst. Also, through the recrystallization of matrix and allochems to micrite, there may be a resulting decrease in permeability. This decrease in permeability may result in the collection of water in the micropores, leading to further diagenesis of the limestone.

Sea-level flucuations throughout the Quaternary have had the largest impact on the degree of alteration of the limestone. When sea level fluctuates, so does the freshwater/saltwater mixing zone that has great dissolutional and diagenetic potential. It is likely that the degree of alteration is a function of the amount of time that the limestone has been in contact with the freshwater lens and the underlying mixing zone. It can be inferred that the rocks in the middle of the core have been in contact with those environments for the longest duration of time.

The tectonic history of the northern Guam plateau also contributed to the degree of diagenesis developed in the rocks. The timing and rate of uplift of the plateau determined the pattern by which the freshwater lens moved through the rock column via glacio-eustatic sea level changes. Pauses in tectonic uplift that were coincident with glacio-eustatic stillstands of sea level should have produced the greatest amount of diagenesis. However, as revealed by this study, there are no apparent horizons with distinctive diagenesis.

Tectonics has introduced yet another variable into the diagenesis equation. Northern Guam has many dip-slip faults, fracture zones, and joint sets that divert meteoric water directly into the subsurface. The rate at which meteoric water flows into the vadose zone via faults and fractures can be assumed as high. This type of input largely bypasses the rocks in the vadose zone except those immediately in contact with the fracture. So, rocks close to the fracture may be heavily altered, while nearby rocks experience little contact with meteoric water, and thereby are less diagenetically altered. It is possible that over time fractures could be lined by relatively impermeable micritized rock. Thereafter, flow at depth may not reach the fracture, and instead may occur as diffuse flow through the nearby, relatively less altered rock.

Considering the many variables that have contributed to the complex pattern of diagenetic alteration of the limestones of northern Guam, one cannot predict water flow paths with any reasonable certainty. With these considerations, the Northern Guam Aquifer should be recognized as a delicate resource that could be damaged by development in any area. Each development project should be carefully scrutinized in order to avoid possible negative impact on the aquifer.

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