Chapter 9

GEOLOGY OF ISLA DE MONA, PUERTO RICO

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INTRODUCTION

Isla de Mona (18°05'N, 67°53'W) is a carbonate island located in the south-central Mona Passage between Puerto Rico and Hispaniola in the northeastern Caribbean Sea (Fig. 9-1). It is located 72 km west of Puerto Rico and covers an area of 55 km² (Fig. 9-2). Isla de Mona and its small neighbor, Isla Monito, are part of the Mona Platform, a bathymetric high bounded to the north by a major northwest-trending fault zone of unknown displacement (Rodríguez et al., 1977). Isla de Mona is subject to uninterrupted easterly trade winds throughout the year (Calvesbert, 1973). The small land mass of Isla de Mona and its low elevation of <100 m result in a climate similar to that of the surrounding ocean. Specific climatic data on Isla de Mona are restricted to reports on daily rainfall. The climate of Isla de Mona is considered semi-arid with very little or no water surplus based on moisture-index calculations by Calvesbert (1973). Mean annual rainfall for the island is 809 mm with the greatest amount of rainfall occurring during October and November. Temperatures range from 24°C in January to 28°C in July and August, with a mean annual temperature of ~26°C.

Tectonic and geologic setting

The northeastern margin of the Caribbean Sea consists of a complex plate boundary dominated by strike-slip motion (Burke et al., 1978; Masson and Scanlon, 1991). The region is bounded by the Puerto Rico Trench on the north and by the Muertos Trough on the south (Fig. 9-1); both are characterized by oblique underthrusting (Schell and Tarr, 1978; Biju-Duval et al., 1983; Mason and Scanlon, 1991). Pindell and Barrett (1990) suggested that the present tectonic regime of the region reflects a change in Caribbean Plate motion from a northerly to a more easterly direction caused by the collision of the Caribbean Plate with the Bahamas Bank beginning in the Eocene. This change in plate motion in the Eocene resulted in termination of volcanism in the northeastern Caribbean. Reefs have developed in the region since the Oligocene.

Isla de Mona and Isla Monito are part of an upthrown structural block bounded by several nearly vertical faults (Rodríguez et al., 1977) (Fig. 9-3). Monito is separated from Isla de Mona by a shallow graben (Kaye, 1959; Rodríguez et al., 1977). Rodríguez et al. (1977) suggested that normal faulting in the vicinity of Isla de Mona

Fig. 9-1. Location map for Isla de Mona and the Mona Platform area (diagonal hatching). Inset map shows generalized tectonic features of the Caribbean region. Key: PRT, Puerto Rico Trench; MT, Muertos Trough; AT, Anegada Trough; CT, Cayman Trough.

resulted in a general tilting of both islands to the southwest. Seismic activity in the region suggests that some of the faults may still be active today (McCann, pers. comm., 1989).

The coastal plains of Isla de Mona consist of Neogene (Holocene?) carbonate-sand deposits from Playa Sardinera on the west side of the island to Punta Arenas (Fig. 9-2). Holocene beachrock (with the most recent ones containing bricks, bottles, and other artifacts from the last two centuries) is common along the sandy shore. The coastal plain on the west side of the island, North of Playa Sardinera, on the southwest part of the island south of Punta Arenas to Playa del Uvero, and along the southeast side of the island from Playa de Pajaros to Punta Este, is composed of Pleistocene coral-reef terraces covered by a thin carbonate sand layer (Kaye, 1959). The Pleistocene reef terraces are better developed on the southwest coastal plain.

The Isla de Mona plateau is composed of two Neogene lithostratigraphic units, the Lirio Limestone and the Isla de Mona Dolomite (Fig. 9-4A), originally described by Kaye (1959) and later redefined by Briggs and Seiders (1972). Kaye (1959) named the lower unit, which makes up the bulk of the carbonates of the island, the Isla de Mona Limestone; he also named what he considered a significantly thinner upper unit, the Lirio Limestone (after Lirio Cave). The lower unit (Isla de Mona Limestone) was described as thickly bedded, dense, white to light yellow, finely crystalline "exceptionally pure" limestone. Kaye (1959) noted that one sample collected from the base of Punta Este was pure dolomite, but he did not define the nature or lateral extent of dolomitization. The Lirio Limestone was described by Kaye (1959) as a thinly

Fig. 9-2. Generalized topographic and bathymetric map of Isla de Mona. (After Briggs and Seiders, 1972, and Kaye, 1959.).

Fig. 9-3. Simplified structural and bathymetric cross sections of the Mona Platform. (Modified from Rodríguez et al., 1977.).

Fig. 9-4. (A) Cliff outcrops on Punta Este (Fig. 9.2). The lowermost bedded units are backreef facies of the Mona Reef Complex within the Isla de Mona Dolomite, and the uppermost cavernous layers are the reef-core facies of the Lirio Limestone. Two levels of breached flank margin caves are observed in the Lirio Limestone and produce the apparent horizontal bed. Height of the section is approximately 50 m. (B) Aerial view of the southeastern portion of Isla de Mona. Road descends to the coast at Playa Pajaros and follows east (right) to the lighthouse. Note the numerous collapse blocks on the coastal plain and the modern fringing reef delineated by the seaward surf. These cliffs are developed on the reef-core facies of the Mona Reef Complex in the Lirio Limestone. Average elevation of cliffs is approximately 35 m. (C) Cliff exposures at the southernmost tip of Isla de Mona. Note the two well-developed cave levels. These are distal forereef beds of the Mona Reef Complex (Lirio Limestone). Height of section is approximately 25 m.

bedded, dense, finely crystalline limestone. Briggs and Seiders (1972) recognized the extensive amount of dolomite present in the rocks of Isla de Mona and redefined the lower unit as a thick to very thick, locally cross-bedded, well-indurated, finely crystalline calcitic dolomite. The unit was then renamed the Isla de Mona Dolomite.

The Lirio Limestone was redescribed as a cavernous, thickly bedded, locally cross-bedded, chalky, fine-grained limestone. Kaye (1959) reported an early to middle Miocene age for the Isla de Mona Limestone and suggested a Pliocene to Pleistocene age for the Lirio Limestone, on the basis of corals collected from the southwestern corner of the island. Kaye (1959) interpreted both units as being flat-lying with local undulations of as much as 3.5° dip in the lower unit and less than 1° dip in the Lirio Limestone. The Lirio Limestone was interpreted as being deposited on an erosional surface developed on the Isla de Mona Dolomite (Kaye, 1959). Briggs and Seiders (1972) observed that the relationship between the two units was more complex than envisioned by Kaye (1959).

The Isla de Mona Dolomite is exposed in continuous exposures on the northern and eastern seacliffs, in the center of the island at Bajura de los Cerezos (Fig. 9-2), and in discontinuous exposures below the Lirio Limestone along the base of the southern seacliffs. The Isla de Mona Dolomite disappears below the Lirio Limestone along the southwestern and western coasts from Playa Uvero to the area south of Punta Capitán on the west, and in the area between Playa de Pajaros and Punta Este on the southeastern coast (Fig. 9-2). The dolomite attains a maximum exposed thickness of approximately 80 m along the northern coast. These exposures of the Isla de Mona Dolomite gradually disappear towards the southwestern and southern side of Isla de Mona and are replaced by the Lirio Limestone, which has a maximum exposed thickness of 40 m.

The plateau surface of Isla de Mona is characterized by many sinkholes, mostly in the Lirio Limestone. A vast system of NW-SE-trending fractures (Kaye, 1959; Briggs and Seiders, 1972) can be easily detected from aerial photographs. This fracture pattern appears to control major sinkhole development in the central regions of Isla de Mona. On the northern and northeastern sides of Isla de Mona, the vertical seacliffs plunge to 30 m below present sea level (Rodríguez et al., 1977). Seismic reflection studies by Rodríguez et al. (1977) indicate that the seafloor surrounding Isla de Mona ($\sim 400 \text{ km}^2$) is composed of similar, if not identical, lithologies as those exposed on both Isla de Mona and Isla Monito.

Geomorphic features of Isla de Mona

Isla de Mona consists of a relatively flat carbonate plateau, ranging in elevation from 20 m in the southeast to 90 m in the northwest, bounded by vertical seacliffs on its north and east sides and a low-lying discontinuous coastal plain on its south and west sides (Figs. 9-2; 9-4A, B). The surface of Isla de Mona is characterized by well-developed karst. Multiple cave systems are present along the cliffs surrounding the plateau (Fig. 9-4A, C). Sinkholes, depressions and coastal terraces are floored by soils.

The coastal cliffs of Isla de Mona, from Punta Este to Cabo Barrionuevo, are distinguished by the presence of multiple levels of caves that penetrate up to 250 m

into the plateau (Briggs and Seiders, 1972; Frank, 1993) (Fig. 9-4A, C). Caves are more common and better developed within the Lirio Limestone with cave floors extending down into the dolomite in some cases, although some caves are developed completely within the Isla de Mona Dolomite. The caves are preferentially developed with elongated mazework rooms parallel to the cliff faces (Fig. 9-5), and suggest development in flank margins (Frank, 1993; Ruiz et al., 1993; Mylroie et al., 1994) with no contemporaneous openings. Present-day openings of the caves are the result of scarp retreat after uplift of the Mona Plateau.

Dissolution features of various sizes and shapes are widely distributed across the plateau surface. Solution pits are cylindrically shaped, penetrating as much as 20 m deep into the Lirio Limestone and Isla de Mona Dolomite; they frequently become bell-shaped at the bottom (Fig. 9-6). In many areas, the bottom of the solution pits lie within the transition zone between the Isla de Mona Dolomite and the Lirio Limestone and commonly continue down several meters into the dolomite.

Fig. 9-5. Map of Cueva de los Pajaros (Cueva Caballo). The cave is typical of the many caves on the southeast side of the island, elongated parallel to the cliff face with a mazework formed by residual limestone pillars. (Modified from unpublished map of Ramon Carrasquillo, 1992.).

Fig. 9-6. Cross section of selected solution pits along the trail to Bajura de los Cerezos. Note that most of the pits have enlarged, bell-shaped bottoms.

Commonly, small passages, always choked with sediment, branch out from the bottom. Shallow bowl-shaped depressions, 1–5 m deep and 10–20 m wide, are also common. These shallow sinks commonly have small caves with very short lateral extension or have well-developed solution pits. Most solution pits and shallow sinkholes have bottoms filled with reddish sediments (soils). Along the coastline, collapse sinkholes related to the extensive coastal cave system are common.

A large-scale NW-SE-trending fracture system originally described by Kaye (1959) appears to control the development of sinkholes in some areas of the plateau, especially along Bajura de los Cerezos. Originally interpreted as a fault zone by Briggs and Seiders (1972), Bajura de los Cerezos consists of a zone of collapsed blocks of interbedded dolomite and limestone. This linear NW-SE-trending depression extends down into the Isla de Mona Dolomite. A thin layer of Lirio Limestone is present around the periphery of this collapse sink.

The central interior portions of Isla de Mona are characterized by the presence of residual soils (Rivera, 1973) indicating that local drainage was directed toward those

areas. The average thickness of these soils in Bajura de los Cerezos is 60 cm (Rivera, 1973). Lowlands and shallow sinkholes in other parts of the island also are covered with these red soils. The coastal terrace on the southwestern side of Isla de Mona is overlain by thin, sandy soils. The western portion of the coastal terrace at Playa Sardinera is overlain by calcareous soils and carbonate sand deposits, which are up to 1.5 m thick and are derived from the modern reef developed along this coast (Rivera, 1973).

REVISED STRATIGRAPHY AND SEDIMENTARY FRAMEWORK OF THE MIOCENE CARBONATES

In the course of diagenetic studies on Isla de Mona (Monell, 1988; Ruiz, 1989, 1993; González et al., 1990, 1992; Ruiz et al., 1991; Ruiz et al., 1993), numerous stratigraphic sections have been measured and sampled along the cliffs, sinkholes, and caves of Isla de Mona (Fig. 9-7). Data from measured sections have been supplemented by numerous observations and samples from the rock exposure on the plateau surface. The observed stratigraphic relationships, lithologic variability, and fossil faunas of the Lirio Limestone and Isla de Mona Dolomite reveal that their general lithologies and the depositional relationships are much more complex than envisioned by Kaye (1959), Briggs and Seiders (1972) and Aaron (1973).

A prominent zone of differential weathering is exposed along the cliffs bounding the northern half of Isla de Mona and is accentuated by the coincidence of numerous cave bottoms. Briggs and Seiders (1972), in mapping the contact between the Isla de Mona Dolomite and Lirio Limestone along the cliffs, identified this zone of differential weathering as an erosional surface on the Isla de Mona Dolomite. Although, from a distance (Fig. 9-4A), the cavernous Lirio Limestone does appear to be deposited over an erosional surface on the Isla de Mona Dolomite, close examination along measured sections and samples from cliff outcrops (Fig. 9-7) reveals a transitional change in lithology from almost pure dolomite at the base of the sections (e.g., Punta Este, Punta Capitán) to almost pure limestone at the top. The dolomitized units in many areas extend several meters above this apparent surface, whereas cave bottoms extend several meters below the limestone-dolomite transitional contact. In some solution pits along the trail to Bajura de Los Cerezos, the dolomite-to-limestone transition occurs within a few meters and, in one instance, within a single bed. In most places, there is no evidence of an erosional surface separating the dolomitized carbonates (Isla de Mona Dolomite) and the limestone (Lirio Limestone). For example, the contact between the Isla de Mona Dolomite and the Lirio Limestone in Punta Este (Fig. 9-4A) and along the western and northern cliffs is marked by a lithologic transition upsection from pure dolomite, calcitic dolomite, dolomitic limestone, and limestone. This lithologic transition also coincides with a gradual facies transition from backreef (packstones to wackestones) to reef flat and reef crest (packstones to boundstone). Differential weathering (Fig. 9-4A) has accentuated this transition zone which resulted from diagenetic processes leading to preferential dolomitization below and calcitization and

Fig. 9-7. Selected measured sections of pre-Pleistocene carbonates of Isla de Mona along the coastal cliffs. Sections are hung on the base of a 6-m wave-cut notch above the Pleistocene reef tract or beach deposits.

dissolution above this transition zone. All the observations indicate that the contact between the Isla de Mona Dolomite and the Lirio Limestone is diagenetic and not a primary depositional or erosional feature.

Although evidence for periodic subaerial exposure is present throughout the island, no islandwide erosional surface can be recognized. The only extensive exposure surfaces that can be recognized are present in the central lowland of Bajura de los Cerezos (Fig. 9-8). In Bajura de los Cerezos, three distinct paleosol horizons containing freshwater and brackish-water snails and vadose pisoliths have been identified. These paleosols are very similar in appearance to the modern red residual soils present throughout the lowlands of Isla de Mona. These paleosols are separated from each other by at least 0.5 meter of marine carbonates consisting of lagoonal and backreef sands. The carbonate beds underlying and overlying the lowermost paleosol horizon, as well as the paleosol horizon itself, are completely dolomitized. The youngest paleosol contains dolomitized grains and is overlain by nondolomitized marine carbonates. Similar paleosols can be found at scattered localities throughout the island. It is possible that a greater number of exposure surfaces are recorded by paleosols, but the highly dissected nature of the outcrops prevents the differentiation between paleosols and protosols (Carew and Mylroie, 1991).

The carbonates of Isla de Mona contain an abundant coral fauna partially obscured by extensive diagenetic alteration (González et al., 1992). Four major reef facies (distinct biofacies and lithofacies) have been recognized: forereef, reef core, backreef, and lagoon and have been referred to as the Mona Reef Complex by González et al. (1992) (Figs. 9-9, 9-10). Forereef deposits dominate the southwestern side of the island (e.g., Cuesta Geña, Cueva Negra). The reef core is exposed at Playa de Pajaros and Cueva de la Escalera along the southeastern side of the plateau and along the Los Caobos trail on the western side of the plateau. Backreef deposits are exposed in Punta Este and near Playa Sardinera. The northern and central sections of the Isla de Mona plateau consist mostly of lagoon deposits and scattered patch

Fig. 9-8. Paleosol horizons in Bajura de los Cerezos. These paleosols are the uppermost nondolomitized horizons developed on lagoon facies of the Mona Reef Complex within the Lirio Limestone.

Fig. 9-9. Interpreted distribution of the Miocene Mona Reef Complex. Filled circles indicate locality of measured sections. Inset is idealized block diagram through the reef complex.

reefs. The coral fauna of the Mona Reef Complex indicate a late Miocene to earliest Pliocene age for the reef (Budd et al., 1994).

Mona reef complex

Forereef facies. The lithology on the southwestern side of Isla de Mona is predominantly fine-grained carbonates, commonly wackestones and rarely packstones and mudstones. At Cuesta Geña (Fig. 9-7), the rocks contain small amounts of encrusting red algae, benthic foraminifera and minor occurrences of small echinoid fragments, surrounded by a matrix consisting mainly of pelleted mud. Planktonic foraminifera are locally abundant, especially in the upper 5 m of this section. The absence of corals combined with the abundance of planktonic foraminifera support the interpretation that these are distal forereef deposits at Cuesta Geña. At Potugués Well near Playa Sardinera, thinly bedded deposits dipping as much as 21° to the southwest are exposed (Fig. 9-10A). At this locality, the Lirio Limestone contains abundant coral debris, minor isolated corals in growth position (commonly preserved as moldic porosity), and small amounts of planktonic foraminifera. *Stylophora granulata*, *Undaria agaricites*, and *Acropora panamensis* are recognized as the most common corals at this locality (Fig. 9-7). Higher in the section, at nearby

Fig. 9-10. (A) Steeply dipping forereef beds of the Mona Reef Complex at the Portugués Well. Approximate height of section is 20 m. (B) Backreef facies of the Mona Reef Complex north of Playa Sardinera (at section of Fig. 9.4). Note the thinly bedded coral-rich units at the base that grade upward into medium- to thick-bedded backreef sands. Massive-looking beds are flowstone-covered limestone. (C) Exposure of the reef-core on the cliffs at Playa Sardinera. Corals, *Stylophora*, have been preferentially dissolved and infilled by soil materials frequently containing root casts. These are the “vermicular structures” described by Kaye (1959).

Cueva Negra, the lithology consists of medium-bedded, coral-rich grainstones at the base of the cliff grading to packstones at the top of the plateau (Fig. 9-7). Both green and red algae, as well as minor amounts of benthic foraminifera and echinoderm fragments floating in a pelleted-mud matrix, are also present. To the south, these beds grade to wackestones with the relative abundance of coral debris decreasing markedly. This locality has been interpreted as a proximal forereef facies.

Reef-core facies. The cliffs along the southeastern coast of Isla de Mona (Figs. 9-4A, B; 9-7, 9-9), from Playa de Pajaros to the upper 5 m of Punta Este, expose a thick accumulation of the coral *Caulastrea portoricensis*. These corals are commonly preserved as moldic porosity. Near the surface of the plateau, coral molds are frequently filled by calcite-cemented red soil material (Fig. 9-10B). Land gastropod fragments are locally abundant within these soils. Kaye (1959) reported *Lucidella umbonata*, *Chondropoma turnerae*, *Bulimulus diaphanus*, *Cerion monaense*, *Suavitas* cf., and *Lacteoluna selenina* as the six gastropod species present in these cemented soils. A similar lithology is exposed on the plateau surface along Los Caobos Trail near Playa Sardinera. Abundant benthic foraminifera of the genus *Archaias*, as well as minor amounts of echinoid fragments and planktonic forams, (locally common at Playa de Pajaros) are also present. The grains are mostly suspended in a pelleted-mud matrix. Lithologies vary from wackestones to packstones. The abundance of corals increases toward the northeast with the thickest accumulations occurring at Cueva de la Escalera where the exposed thickness reaches approximately 20 m. The Pleistocene reef terrace fringing the cliffs includes remnants of collapsed cliff blocks of the same material, indicating that the thick accumulation of Miocene corals extended southeast at least to the edge of the Pleistocene terrace.

Backreef facies. Along the cliffs north of Playa Sardinera, the Lirio Limestone grades from medium-bedded units (up to 30 cm thick) at the base of the exposure to interbedded coral-rich and sandy units toward the top of the plateau (Figs. 9-9, 9-10C). The base of the cliff is covered by collapsed blocks of this material. The medium-bedded units exposed at the base of the cliffs are mainly wackestones and locally boundstones. The presence of thickets of *Stylophora minor*, abundant benthic foraminifera, red algae fragments and abundant echinoderm fragments and spines characterize these beds. The coral-rich layers are commonly composed of packstones with occasional boundstones and wackestones. The most common corals found in these beds include *Montastraea trinitatis*, *Mussa* cf., *M. angulosa*, *Stylophora affinis*, and *Acropora saludensis*. The sandier beds contain abundant benthic foraminifera (*Nummulites* and *Amphistegina*) as well as branching red algae. These rocks represent a transition between a reef-flat facies at the base of the section to a backreef facies closer to the top. A similar facies transition also is present at Punta Este, where the thickly bedded backreef sands in the Isla de Mona Dolomite give way to the coral-rich, reef-core facies developed in the Lirio Limestone.

Lagoon facies. The cliff face at Punta Capitán exposes both the Lirio Limestone and the Isla de Mona Dolomite. Packstones and minor amounts of wackestones

composed of abundant encrusting red algae, benthic foraminifera and echinoderm fragments as well as minor amounts of green algae, mollusks and occasional coral fragments encrusted by algae characterize both units. Allochems commonly float in a matrix of pelleted mud. In Cueva de la Esperanza, 0.5 km to the north of Punta Capitán, algal mats composed of filamentous green algae are locally abundant in the Lirio Limestone.

Patch-reef facies. A minor accumulation of corals within backreef deposits in the Lirio Limestone is exposed in shallow caves along the northern side of the island. The localized nature of this buildup indicates the presence of small patch reefs in the area. Measured sections in caves and sinkholes on the trail to Bajura de los Cerezos shows marked similarity to the backreef facies rocks of Punta Capitán. Lithologies are mainly wackestones with some sections showing varying degrees of dolomitization ranging from dolomite at the base to dolomitic limestone at the top. These rocks contain abundant red algae, corals and minor amounts of echinoid fragments. The local abundance of corals indicates that many of these sites were patch reefs that have been preferentially dissolved.

QUATERNARY REEF DEPOSITS

In addition to the Miocene Mona Reef Complex, extensive late Pleistocene fringing-reef deposits occur on the coastal terrace bounding the southern and western sides of the island. Scattered throughout the plateau surface there are smaller Pleistocene fringing reefs associated with escarpments easily recognized in aerial photographs and mapped by Kaye (1959).

Upper Pleistocene and Holocene reef deposits

Isla de Mona is bounded by a narrow and discontinuous Pleistocene reef terrace along its south and west coasts from Punta Capitán to Punta Este (Fig. 9-2). This terrace, which is up to 1 km wide, rises from an elevation of 0.5–2 m above sea level at the shoreline to a maximum of 10 m against the paleo-seacliffs. The terrace consists of Quaternary reef-tract deposits, reef-rubble deposits, reef-rubble ramparts, reef-rock boulders, and carbonate sands. Vertically continuous reef-tract deposits extend as much as 6 m above and to an unknown depth below present sea level. They are overlain by reef-rubble deposits that reach elevations of 10.2 m at the base of the paleo-seacliff at distances of several hundred meters from the present shoreline. Soil and vegetative cover progressively conceal the terrace surface landward of the shoreline exposures of boundstone and calcirudite. The upper surface of the coastal exposures of the reef terrace are commonly overlain by a dense laminated algal crust and/or caliche layer 1–6 cm thick. This crust, previously described by Kaye (1959), largely covers the upper surface of all observed inland exposures of the terrace.

Eleven corals retrieved from the reef terrace deposits north of Playa Sardinera, near Piedra del Carabinero, and southwest of Punta Este at elevations ranging from

2–6.5 m above present sea level have yielded $^{230}\text{Th}/^{234}\text{U}$ alpha-spectrometric ages between 107–128 ka. Because sea level 125 ka was approximately 6 m higher than present (e.g., Mesolella et al., 1969; Bloom et al., 1974; Ku et al., 1974; Neumann and Moore, 1975) these data indicate that Isla de Mona has been tectonically stable during the last 125 ky. Uranium-series thermal ionization mass spectrometry (TIMS) ages (Lundberg, J., unpub. data, 1993, Carleton University, Ottawa, Canada) for two samples collected from a 4-m-thick *Montastraea annularis* Pleistocene reef-tract exposure indicate that the rate of vertical reef accretion between 122–126 ka was about 0.75 m ky^{-1} . None of the colonies in this exposure are more than 20 cm in diameter (average 8–10 cm), but they are densely packed, like circular flagstones. When observed in plan view these colonies exhibit a multilobate columnar growth form, indicating a shallow-water origin (Roos, 1971; Smith, 1976; Kaplin, 1982).

An unconsolidated Holocene reef-rubble rampart has been deposited at the shoreline seaward of the northwestern tip of the airfield, about 1 km northwest of Piedra del Carabinero (Fig. 9-2). This rampart, which is located about 5 m behind the beach at an elevation of 3 m, is oriented parallel to the shoreline and is approximately 0.5 m high, 20 m long, and 5 m wide. A second more extensive unconsolidated reef-rubble rampart, located on the small Pleistocene reef terrace to the southwest of Punta Este, is approximately 30 m behind the coastline at an elevation of 7 m and is more than 50 m long. These unconsolidated deposits probably resulted from a storm event that occurred during the last 5 ky.

Many boulders of reef-rock, as much as 5 m in diameter, and a large amount of reef-rock debris, as much as 1 m in diameter, lie scattered about on the southwestern coastal plain. Several of these boulders are located within 30 m of the shoreline near Piedra del Carabinero, and many others are found as much as 600 m inland. The 100-m shelf break surrounding Isla de Mona is less than 300 m offshore along the south coast at Piedra del Carabinero. Beyond this point, depths of 1,300 m are attained within 8.5 km of the shoreline. The reef tract on the insular shelf south of Piedra del Carabinero is the only reasonable source for these boulders. A coral sample from the stratigraphic top of one of the inland boulders produced a TIMS age of 4800 y B.P.. TIMS ages of coral samples from the stratigraphic middle and top of one of the shoreline boulders are 5,376 y B.P. and 4,176 y B.P., respectively. These two samples are separated by a distance of 1.7 m, suggesting a net rate of vertical reef accretion of 1.4 m ky^{-1} during this period of time. This rate compares favorably with those determined for other Holocene reefs (Morelock et al., 1977; Shinn et al., 1977; Lighty, 1985; Macintyre et al., 1985). The size of these reef-rock boulders is such that they could have been transported to their present locations only by a seismic seawave or an extreme storm such as a hurricane. Their ages indicate that they were transported to their present locations sometime after 4,176 y B.P.

The age of the Pleistocene reef terrace places its growth at the height of the Sangamon interglacial sea-level highstand. The age of the late Holocene stranded reef-rock boulders correspond to an early stage in the growth and development of the currently active fringing reef during the present interglacial sea-level highstand. The net rates of vertical reef accretion and reef morphology of these Isla de Mona

reef tract exposures and boulders indicate that (1) the Pleistocene reef tract of 122–126 ka was able to maintain a shallow-water position relative to sea level during a period of slowing rising or stable sea level, and (2) that the Holocene reef tract was accreting at a greater rate in response to the rapid rise in sea level that took place during the Holocene (Neumann and Macintyre, 1985).

Lower Pleistocene reef deposits

Pleistocene coral assemblages on the plateau surface itself (Fig. 9-8; sites M9, M12, M13, M14) occur at elevations ranging from 20 m to as much as 70 m above present sea level. These assemblages have not been studied in detail but do include *Acropora palmata*, which is known to occur in the Caribbean only since the early Pleistocene (Budd et al., 1994). These assemblages are associated with escarpments of 1–5 m relief that can be detected from aerial photography of the plateau surface and were first described by Kaye (1959). These lower Pleistocene fringing-reef deposits were most likely the source of corals which led Kaye (1959) to assign a Pliocene-Pleistocene age to the Lirio Limestone. All sampled corals are recrystallized, with only minor aragonitic patches remaining. Attempts to radiometrically date the recrystallized corals utilizing U-series alpha spectrometry produced $^{230}\text{Th}/^{232}\text{Th}$ and $^{234}\text{U}/^{238}\text{U}$ ratios that were equilibrium values, indicating that these corals were recrystallized prior to 350 ka and possibly before 700 ka. One nearly completely recrystallized coral at 70 m yielded a recrystallization age of 192 ka. A travertine deposit developed on Pleistocene corals recovered from the plateau surface at 60 m above mean sea level has been dated at 287 ka. The presence of these early to middle Pleistocene features indicates that Isla de Mona was submerged during the early Pleistocene.

DIAGENESIS OF THE MONA REEF COMPLEX

The carbonates of Isla de Mona have been subjected to a variety of diagenetic environments. In general, diagenetic events can be divided into: (1) early submarine diagenesis manifested by the development of micritic envelopes, and marine cementation by fibrous and botryoidal cements; (2) mixed freshwater-seawater diagenesis manifested by preferential dissolution of aragonitic components followed or accompanied by extensive dolomitization in some areas and calcitization in other areas; and (3) repeated periods of meteoric diagenesis indicated by extensive calcitization and dedolomitization and cementation by equant calcite spar with karstification and travertine precipitation.

Submarine diagenesis

Micrite envelopes document a period of alteration concurrent with deposition. The micritized surfaces of grains commonly survive dissolution and provide a surface

for later precipitation of cements. In Isla de Mona, micrite envelopes are common in all sections and environments, although they are more prevalent in the lagoonal facies. Syndepositional cementation by fibrous calcite is limited to coral grainstones in forereef facies in the Lirio Limestone (Fig. 9-11A). Fibrous calcite cement consists

Fig. 9-11. Thin-section photomicrograph of a variety of diagenetic features found in Isla de Mona carbonates. All views are crossed polars. (A) Fibrous calcite cements, interpreted as marine, on coral grains of the Cueva Negra forereef deposits (Lirio Limestone). (B) Backreef packstone from Cueva del Esperanza. The cavities are molds of aragonitic component. The mud matrix has been replaced by microcrystalline calcite. (C) Dolomitized wackestone from Cuesta Geña. Note the fabric preservation of the dolomitized planktonic foraminifera test. A late calcite spar fills some of the early moldic porosity. (D) Dolomitized echinoderm grains and pellets. Note the clear (limpid) dolomite overgrowth followed a late calcite spar. (Slide stained with alizarin red.) (E) Cloudy-centered dolomite rhombs. (Slide stained with alizarin red.) (F) Pervasive dissolution of limpid dolomite cements in packstones from the lagoonal facies at ACBC within the limestone-dolomite transition. (Slide stained with alizarin red.)

of elongate nonluminescent fibers, 240 μm in length, forming continuous isopachous layers around skeletal fragments and thin linings inside foraminifera tests.

The occurrence of cements with botryoidal fabrics in deposits on Isla de Mona is very limited. Development of this type of cement is restricted to areas with limited primary porosity (<20% by volume) on distal forereef deposits on the southern coast of the island. In thin section, botryoidal cements consist of groups of densely packed, nonluminescent, radially oriented fibers 190 μm long showing undulatory extinction under crossed polars.

Fabric-selective dissolution

The dissolution of skeletal components in carbonates of Isla de Mona is mostly fabric-selective. Aragonitic grains such as corals and gastropods are most affected, and grains such as red algae and echinoderm fragments are least affected (Fig. 9-11B). Aragonite dissolution is widespread across the Isla de Mona plateau. Unstable skeletal components are commonly preserved as moldic porosity.

Calcitization

Microcrystalline calcite replaces most of the pelleted muds that form the matrix of the Lirio Limestone (Fig. 9-11B). Skeletal grains are also subject to alteration to microcrystalline calcite, especially in rocks that have been subjected to intense meteoric diagenesis, resulting in a rock where mostly ghosts of the original grains remain. The distribution of this type of replacement calcite is widespread across the Lirio Limestone, but is especially prominent in rocks of the reef-flat and backreef facies. Microcrystalline calcite in Isla de Mona carbonates is nonluminescent.

Bladed calcite cements are often found in the Lirio Limestone. Nonluminescent, bladed (96 μm) calcite cement is found lining interparticle and moldic porosity on coralgal packstones and grainstones of both forereef and reef-flat facies. This cement is characterized by thick and stubby blades forming an irregular layer.

Equant calcite spar is widely distributed among the rocks of the Lirio Limestone. This type of cement is composed of nonluminescent, equant crystals of 20–280 μm . Equant calcite is found associated with a variety of other cement types and fills both primary and secondary porosity (Figs. 11B, C, D, E). Near the top of the plateau, this type of cement locally fills intracoralline as well as vuggy porosity. At the dolomite-limestone transition zone, equant calcite spar postdates dolomitization and appears to be related to dolomite dissolution.

Dolomitization

Dolomite forms the bulk of the carbonates of Isla de Mona. Samples from a number of localities contain varying amounts of dolomite. A vertical transition from pure dolomite at the base of the seacliffs to pure limestone at their top is

present along the eastern and northern sides of the island from Punta Este to Punta Capitán.

Fabric-retentive microcrystalline dolomite is the most common and widely distributed type of dolomite in the island. The fine grain size of these crystals makes it difficult to distinguish them from calcite in thin section without the aid of staining (Fig. 9-11C). This type of dolomite replaces both the abundant pelleted muds as well as skeletal grains that characterize the backreef facies of Isla de Mona. The extent of replacement is variable. Rocks from the lower part of the Isla de Mona Dolomite are pervasively dolomitized including originally high-Mg calcite components such as red algae. At higher elevations, dolomitization mostly affects matrix material whereas red algae remain partially calcitic. Dull luminescence is characteristic of replacive dolomite. Nonluminescent dolomite overgrowths around dolomitized echinoderm fragments are present within the limestone-dolomite transition zone (Fig. 9-11D). The absence of overgrowths on echinoid fragments in the lower part of the measured sections of the Isla de Mona Dolomite, contrasting with their abundance in the upper Isla de Mona Dolomite and the lower Lirio Limestone, suggests that dolomititic overgrowths resulted from replacement of a calcitic precursor.

Euhedral, limpid dolomite spar commonly fills interparticle porosity in the Isla de Mona Dolomite. It commonly fills late vugs and some moldic pores. This cement nucleated around dolomitized grains as well as around areas of dolomitized matrix and increases in size toward the center of the cavities. This nonluminescent cement is commonly associated with grainstones in the Isla de Mona Dolomite.

Dolomite rhombs with cloudy centers and clear rims are also common in the Isla de Mona Dolomite. Cloudy-centered dolomite rhombs are commonly found related to the limestone-dolomite transition zone (Fig. 9-11E). Staining indicates that the center of the rhombs are calcitic. Dull luminescence is characteristic of this type of dolomite.

Zoned dolomite cements are found lining secondary porosity in the Isla de Mona Dolomite. The distribution of this cement is restricted to the lower part of the unit. Its abundance decreases upward toward the zone of transition between dolomite and limestone where it is mostly absent. This type of dolomite consists of alternating dark and light zones that are visible under both transmitted light as well as under cathodoluminescence. Commonly this dolomite cement contains an early nonluminescent inner zone followed by a single brightly luminescent outer zone. Samples from various localities, including Punta Este and Punta Capitán, contain multiple generations that are locally well developed.

Dolomite dissolution and dedolomitization

Evidence of dolomite dissolution (Fig. 9-11F) is present at several localities across Isla de Mona. Partially dissolved dolomite rhombs are locally present within the dolomite-limestone transition zone. Dissolution affects both the cloudy-centered rhombs as well as the limpid dolomite spar that are so common within this zone. Corroded crystal outlines are commonly observed in the limpid dolomite spar. Dissolution of the calcitic centers is evident in many cloudy-centered dolomite rhombs.

Karst and paleosol development

The most prominent dissolution features in Isla de Mona are the extensive caves along the coastal cliffs and the numerous sinkholes and solution pits on the plateau. Frank (1993) presented a complete and detailed description of numerous caves and some sinkholes in Isla de Mona and concluded that cave features conform to those of flank margin caves, as defined by Mylroie and Carew (1990). Several of the caves described by Frank (1993) and smaller caves we have visited along the northern cliffs show evidence of at least two episodes of phreatic dissolution as indicated by dissolution features on subaerial speleothems. In many of the deeper solution pits (>10 m), there appears to be a relict bell-shaped bottom present about 6–10 m from the pit entrance. Elliptical sinkholes, depressions and solution pits commonly are developed preferentially along fractures on the plateau surface. Many of the solution pits and depressions are developed preferentially on what are interpreted as patch reefs of the Mona Reef Complex. In caves and sinkholes, numerous paleosols and/or protosols can be identified. Paleomagnetic analysis of paleosols in Isla de Mona caves indicates that soil development was occurring prior to 780 ka (Matuyama Reversal) (Mylroie et al., 1994). Ongoing magnetostratigraphic work by Bruce Panuska and his students suggests that paleosol accumulation in the caves began no later than 1.0–1.8 Ma and possibly began in the Pliocene (USGS CDO, 1994b).

In addition to the paleosols present in Bajura de los Cerezos, karstic breccias are common throughout most caves and sinkholes. These breccias consist of limestone fragments in a matrix of reddish soil and are commonly cemented by calcite. At a few isolated sites, such as the base of the cliffs at Punta Capitán and in Punta Este, breccias consist of dolomite clasts (dolomitized prior to dolomitization of matrix) in dolomite-cemented residual soil.

Stable isotopes

Stable isotopic analyses were performed on samples of <0.2 mg, extracted with a 500- μ m dental drill. Mineralogy was identified by standard staining techniques using alizarin red and potassium ferricyanide. All data presented here are for samples with >90% dolomite or calcite.

Dolomite isotopic compositions range from +4.3 to -4.4‰ for $\delta^{18}\text{O}$ and from +3.4 to -8.3‰ for $\delta^{13}\text{C}$ (Fig. 9-12), although the bulk of the dolomite components are greater than 0.0‰ for $\delta^{18}\text{O}$ and -4.0‰ for $\delta^{13}\text{C}$. In general, dolomite from the outer fringes of the island, such as Punta Este and Punta Capitán, has relatively greater oxygen and carbon values (average $\delta^{18}\text{O}$ values of 3.6‰ and $\delta^{13}\text{C}$ values of 2.7‰) than those of the interior portions of the island. Dolomite spar and clasts have a narrower range of isotopic values than dolomitized red algae and matrix, and all are greater than -1.0‰ for $\delta^{18}\text{O}$ and -6.0‰ for $\delta^{13}\text{C}$.

Calcitic components also exhibit a broad range of values ranging from +3.6 to -5.7‰ for $\delta^{18}\text{O}$ and from +3.1 to -11.63‰ for $\delta^{13}\text{C}$ (Fig. 9-13). In contrast to the dolomite, the bulk of the calcitic components have isotopic values less than -1.0‰ for

Fig. 9-12. Stable isotope composition of dolomitic (dolomite $\geq 90\%$) components of the Isla de Mona Dolomite.

$\delta^{18}\text{O}$ and -2.0‰ for $\delta^{13}\text{C}$. Microcrystalline calcite replacing the pelleted-mud matrix has $\delta^{18}\text{O}$ values ranging from -4.5 to -1.0‰ , and $\delta^{13}\text{C}$ ranges from -6.9 to -4.3‰ .

Strontium isotopes

Only two strontium isotope values have been obtained on dolomites with the heaviest $\delta^{18}\text{O}$ (Ruiz et al., 1993). Two samples from the lower section of Punta Capitán and Punta Este have $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.708915 ± 11 and 0.708829 ± 10 respectively. These data constrain dolomitization of the lower portions of the Isla de Mona Dolomite (if effected by marine fluids) to late Miocene (Tortonian to Messinian).

HYDROGEOLOGY

Modern freshwater resources of Isla de Mona

Hydrogeologic information about Isla de Mona is very limited, although a number of hydrogeologic investigations are being conducted under auspices of the

Fig. 9-13. Stable isotope composition of calcitic (calcite $\geq 90\%$) components of the Lirio Limestone.

U.S. Geological Survey Water Resources Division in San Juan, Puerto Rico. Historic accounts indicate that freshwater was abundant 400 years ago when the island was discovered. At that time, freshwater resources were sufficient to sustain a small population of Taino Indians living on the island. During the period of Spanish colonization in the sixteenth century, the island was denoted on nautical charts as an important watering port (Wadsworth, 1973).

Today, freshwater is in short supply in Isla de Mona. A 5-m² brackish-water pond (apparently of human origin) and a small mangrove swamp exist on the reef terrace at the foot of the cliff at Punta Arenas (Jordan, 1973). The evident lack of response of these two features to tidal cycles led Jordan (1973) to suggest that the pond did not have a hydraulic connection to the sea. He attributed water-level fluctuations to evapotranspiration processes and groundwater inflow (approximately 855 L d⁻¹) from the upper plateau.

Recent geophysical reconnaissance by Martínez et al. (1993) suggests that there are two separate freshwater lenses, one developed under the Pleistocene coastal plain, and one under the plateau (i.e., Exuma-type island; Vacher and Wallis, 1992). Four dug wells tapping brackish water exist on the Pleistocene reef terrace on the southwest side of the island (Jordan, 1973). Two wells near Playa Sardinera penetrate sand deposits, and both the well near the airstrip and the one near Playa del

Uvero penetrate the Pleistocene reef deposit. At present, only one of the wells near Playa Sardinera (Pozo del Portugués) is being actively used. Limited sampling by Jordan (1973) indicates that these wells tap a zone of freshwater-seawater mixing. The freshwater lens under the Pleistocene coastal plain is at least 13 m thick (Martínez et al., 1993), and it thins towards the ocean and towards the cliffs of the plateau. Data from a well at the Mona airstrip, 200 m from the shoreline, indicates that groundwater level has a daily tidal cycle with a 7-cm range as compared to the 30-cm ocean tidal cycle (USGS, CDO, 1994).

Though initial work by Martínez et al. (1993) suggested the freshwater lens under the plateau was at least 25 m thick, recent geophysical surveys (transient electromagnetic) by Martínez and others suggests that the thickness of the freshwater lens under the plateau has a maximum thickness of 10 m (USGS, CDO, 1994). These recent estimates are in marked contrast with the hypothetical freshwater lens of over 75 m calculated by Jordan (1973).

The freshwater-saltwater boundary of the freshwater lens beneath the plateau can be found in the caves along the southern side of the island near Punta Los Ingleses in Playa Brava, in a cave developed within the reef-core facies of the Lirio Limestone and infilled by Quaternary reef rubble (mostly *Acropora palmata*). A 1.5-m-diameter hole in the floor of the cave provides access to a 1.0-m-diameter pit that leads to a cave developed within the Quaternary reef rubble and Miocene reef-core facies. The cave has been surveyed by A.M. Nieves of the Puerto Rico Department of Natural Resources, and information on this cave is presented in Frank (1993). The chambers of this cave are partially to completely filled with brackish water. The cave extends at least 30 m north under the plateau, and a sloping tunnel extends south (seaward) for an undetermined distance. An increase in salinity and turbidity can be easily detected in the water in the sloping tunnel. According to statements by commercial fishermen (Tres Hermanos) who have been visiting the island since the 1940s, freshwater is available in some of the lowermost caves from Punta los Ingleses to Punta Caigo no Caigo. According to these accounts, freshwater could be obtained by carefully skimming the top of the water column in these water-filled caves.

Geologic controls on groundwater

Differences in lithology, porosity, and permeability between the Lirio Limestone and the Isla de Mona Dolomite must play a role in groundwater migration. Well-developed interconnected channel porosity contributes to the excellent permeability of the limestone as evidenced by the lack of well-developed surface drainage. Extensive dolomitization combined with equant calcite precipitation has significantly contributed to the reduction of both primary and secondary porosity in the Isla de Mona Dolomite. As a result, permeability of the Isla de Mona Dolomite is significantly lower than that of the Lirio Limestone, and so the dolomite could be an effective permeability barrier for water moving down the rock column. The many fractures present throughout the island must play a definite role in groundwater movement by providing surface runoff with direct access to the subsurface. Although

the depth of these fractures is not known, there is reason to believe that they may extend deep down into the Isla de Mona Dolomite, providing an underground channel system for water flow through the dolomite body.

The fact that no evidence of freshwater discharge can be seen along the northern and eastern cliffs, coupled with the thinness of the freshwater lens under the plateau surface, argues for structural control on groundwater distribution under the plateau. The limited thickness of the freshwater lens under the plateau surface suggests that either freshwater discharge around the periphery of Isla de Mona is much greater or infiltration rates are much smaller than those estimated by Jordan (1973). The postdepositional dip of several degrees to the southwest and the many fractures might also play an important role in groundwater distribution.

Ongoing research by the U. S. Geological Survey Caribbean District Office is aimed at providing essential data to properly evaluate groundwater distribution and its controls in Isla de Mona.

CASE STUDY: EVOLUTION OF THE MONA REEF COMPLEX

Episodic exposure

The depositional and diagenetic history of Isla de Mona is not one of simple continuous carbonate sedimentation followed by a simple sequence of diagenetic events. The Mona Reef Complex is a complex backstepping reef which was responding to episodic sea-level rise (tectono-eustatic) through the life of the complex. Portions of the Mona Reef Complex were periodically exposed allowing development of vadose and meteoric phreatic zones in the central portions of the plateau and mixed freshwater-seawater zones in the periphery of the plateau.

Although in nearby Puerto Rico the northern Oligocene-Miocene limestone belt remained exposed during late Miocene to early Pliocene (Moussa et al., 1987; Seiglie and Moussa, 1984), the events that resulted in the exposure of the limestone belt of northern Puerto Rico led to the shallowing of the Mona Platform and the initiation of reefal carbonate deposition. The repeated late Miocene to early Pliocene sea-level oscillations recorded through the Caribbean region and Florida (e.g., Pleydell et al., 1991; Mallinson et al., 1994) resulted in the frequent changes in diagenetic environments observed in the Isla de Mona Miocene carbonates.

The paleosols in the central portions of the island indicate that at least three periods of exposure of the lagoon and backreef facies took place towards the final episode of deposition of the Mona Reef Complex. Dolomitized karstic breccias and travertines in the lower portions of the Isla de Mona Dolomite indicate that a minimum of two exposure episodes occurred in the earlier stages of development of the Mona Reef Complex before dolomitization. It is likely that numerous exposure events took place through the history of deposition of the Mona Reef Complex.

The relatively large sea-level drop in the late Miocene recorded in other Caribbean localities (e.g., Lidz, 1984; Jones and Hunter, 1994) also resulted in exposure of the Mona Reef Complex. Whereas northern Puerto Rico (Moussa et al., 1987) and

Grand Cayman (Jones and Hunter, 1994; Pleydell et al., 1991) underwent Pliocene submergence, the absence of definite Pliocene fauna indicates that Isla de Mona was exposed through much of the Pliocene.

The presence of early to middle Pleistocene fringing reefs coinciding with escarpments indicate that Isla de Mona remained at or near sea level during the first half of the Pleistocene. The position of escarpments and fringing reefs on the plateau surface indicates that during the early to middle Pleistocene Isla de Mona underwent three, and possibly more, relatively rapid episodic uplift events. The lowest fringing-reef deposits of the escarpment occur at 20 m above present sea level. Several wave-cut notches and/or breached flank margin caves, the most prominent at 6, 10 and 20 m above mean sea level, are present in the cliffs. These data, in conjunction with radiometrically dated late Pleistocene reef-tract deposits, indicates that Isla de Mona underwent episodic uplift during most of the Pleistocene and has remained stable since 125 ka.

Environments of diagenesis

All of the existing data indicate that the diagenetic alteration of the Isla de Mona carbonates resulted from alteration in four distinct and frequently coeval diagenetic environments. Significant carbonate dissolution and development of paleosols and travertines took place predominantly in the meteoric vadose environments. Carbonate dissolution, particularly fabric-selective dissolution of aragonitic components and the replacement of original marine components by calcite or dolomite, took place in phreatic environments. During lowstands of sea level, the topographic highs in what is now the plateau surface were above sea level and acted as catchment areas for meteoric waters resulting in development of an extensive freshwater lens that graded downward and laterally into a marine phreatic environment. The selective dissolution of lagoon patch reefs resulting in the formation of solution pits and sinkholes suggests that these areas, because of the higher permeability relative to surrounding calcareous sands and mud, acted as conduits for aragonite and calcite-undersaturated fluids into the phreatic environment.

The presence of fabric-selective aragonite dissolution in calcitized and dolomitized rocks indicates that throughout the diagenetic history of the Miocene carbonates of Isla de Mona diagenetic fluids remained undersaturated with respect to aragonite. The preferential calcitization or dolomitization of matrix carbonate and the delicate fabric-retentive calcitization or dolomitization of skeletal components indicate that most of the observed fabrics are primary diagenetic features, although complete replacement of individual units might have required repeated exposure to the same diagenetic environment.

Zoned dolomite cements showing alternating bright and nonluminescent bands are locally abundant. Similar cements have been interpreted to form under alternating oxidizing and reducing conditions such as those found in mixed freshwater-seawater zones (e.g., Mussman et al., 1988). The presence of cloudy-centered dolomite rhombs indicates that the initial dolomitizing fluids were saturated with respect to calcite that forms the inclusion of calcitic material at the center of the dolomite

crystals. At a later stage when water became undersaturated with respect to calcite but supersaturated with respect to dolomite, continued precipitation formed inclusion-free crystals. Such evolution of porewaters is consistent with the mixed freshwater-seawater hypothesis of dolomite formation and has been suggested by Sibley (1980) to explain the cloudy-centered dolomite rhombs of Bonaire and similar features observed in Grand Cayman (Pleydell et al., 1990).

The petrographic properties are consistent with alteration in the mixed freshwater-seawater zone. The broad range of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ isotopic values also indicate that the bulk of the replacement fabrics, dolomitic and calcitic, were formed in meteoric-marine mixed fluids. Considered together, the isotopic data can best be described by hyperbolic trends that are characteristic of mixing of fluids with different concentrations of dissolved CO_2 (Lohmann, 1988) (Fig. 9-14). The isotope data of the red algae argue against these trends being the result of mechanical mixing of components with two different isotopic compositions for two reasons: (1) mechanical mixing should result in a linear trend (Lohmann, 1988); and (2) all the data are for components with >90% calcite or dolomite, the observed range in $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values is much greater than can be attributed to 5–10% contamination. The endmember compositions can be inferred to be meteoric and marine fluids. The relatively high isotopic values of dolomite ($\delta^{18}\text{O} \geq 0.0\text{‰}$; $\delta^{13}\text{C} \geq -4.0\text{‰}$) suggest that the bulk of the dolomitization occurred in fluids containing over 50% seawater. The lighter values for the calcitic components ($\delta^{18}\text{O} \leq -1.0\text{‰}$; $\delta^{13}\text{C} \leq -2.0\text{‰}$) indicate that calcitization took place predominantly in fluids containing over 50% meteoric water. The broader range of $\delta^{13}\text{C}$ values of the calcitic components can be attributed to: (1) different degrees of rock-water interaction; (2) a more open system leading to greater variability in PCO_2 ; (3) analyses including samples that have undergone surface evaporation and degassing; and (4) inclusion of modern vadose calcite indistinguishable from Miocene to Pleistocene calcite.

The dolomites from Isla de Mona show a wider range of isotopic values than those reported for other dolomites interpreted to have formed under similar mixed freshwater-seawater conditions. Microcrystalline dolomites replacing carbonate muds show greater $\delta^{18}\text{O}$ values but a similar range of $\delta^{13}\text{C}$ values compared to Pleistocene mixed freshwater-seawater dolomites from the Yucatán (Ward and Halley, 1985). Nevertheless, values are consistent with data for Neogene dolomites from the Bahamas reported by Supko (1977) and mixed freshwater-seawater dolomites reported from Mururoa Atoll in the Pacific (Aïssaoui et al., 1986) [q.v., Chap. 13]. $\delta^{18}\text{O}$ values greater than $+2\text{‰}$ have been considered to indicate precipitation from a fluid with a similar or greater isotopic value than seawater (Supko, 1977). The isotopic compositions of most Isla de Mona dolomites fall between 0 to $+4\text{‰}$ suggesting that either seawater or evaporation-concentrated freshwater could have been involved in dolomitization.

Other alternative dolomitizing fluids (e.g., pure seawater and hypersaline water) and mechanisms (e.g., burial dolomitization and thermally driven circulation of interstitial water) are judged not to be responsible for dolomitization at Isla de Mona for several reasons. Although seawater dolomitization cannot be discounted in distal portion of the mixed freshwater-seawater environment, the range of dolomite

Fig. 9-14. Stable isotope composition of calcite (C) and dolomite (D) components. Hyperbolic trends generated by utilizing a marine endmember composition with a $\delta^{18}\text{O}$ of +2.2‰, $\delta^{13}\text{C}$ of +3.5‰ and a ΣCO_2 of 2.5 mmol L^{-1} at 24°C, and the freshwater endmember with a $\delta^{18}\text{O}$ of -3.75‰, $\delta^{13}\text{C}$ ranging from -3.8 to -14.1‰ and a ΣCO_2 ranging from 5.0 to 8.0 mmol L^{-1} at 6°C. The $\delta^{18}\text{O}$ composition of modern precipitation for this region of the Caribbean ranges from -2.0 to -5.7‰ (Rozanski et al. 1993). The $\delta^{18}\text{O}$ of coastal aquifers in southwestern Dominican Republic (with a climate similar to Isla de Mona) range from -3.2 to -4.0‰ (Febrillet et al., 1987).

isotopic composition is greater than can be accounted for by mechanical mixing of components produced by marine fluids of slightly different isotopic composition or by contamination with calcite. It is unlikely that massive dolomitization in Isla de Mona was achieved solely by circulating seawater. There is no evidence that hypersaline or evaporite depositional environments have been developed at Isla de Mona and, although the relatively heavy $\delta^{18}\text{O}$ values of the marine endmember

calcite and dolomites would suggest some evaporative enrichment of seawater, no evaporite minerals, primary or secondary, have been identified. The absence of major compaction features; the dolomitization of paleosols, karstic breccias, and travertines; the development of multiple levels of flank margin caves; and the absence of highly negative $\delta^{18}\text{O}$ values ($<8\text{‰}$) — all do not support diagenetic alteration in the burial environment. Finally, the absence of highly negative $\delta^{18}\text{O}$ argues against anomalous geothermal gradients to drive seawater or brine circulation. The lightest observed $\delta^{18}\text{O}$ values in Isla de Mona can be attributed to precipitation from normal freshwater, (assuming the $\delta^{18}\text{O}$ range observed for modern freshwater in the region (Rozanski et al., 1993; Febrillet et al., 1987) at temperatures ranging of 22–27°C.

The diagenetic alteration of Isla de Mona carbonates probably began shortly after the formation of reefal deposits near sea level which could be easily exposed to meteoric fluids during minor sea-level falls. Diagenetic alteration occurred in episodic fashion, and in discontinuous areas throughout the life of the Mona Reef Complex. Sustained exposure of late Miocene limestones occurred during the Pliocene and throughout the episodic uplift events that affected Isla de Mona throughout the Pleistocene. The recurrent exposure led to development of multiple cave levels in Isla de Mona where discharging groundwater reached the coast and mixed with seawater resulting in extensive dissolution of the limestone in some areas and dolomitization and calcitization in others. Analogs for the cave system of Isla de Mona are the caves of the Yucatán peninsula (Back et al., 1986) and the Bahamas (Mylroie and Carew 1990; Mylroie et al., 1991; Frank 1993). The extent of dolomitization of the Mona Reef Complex, relative to the Pleistocene analogs, is the result of repeated exposure to a mixed freshwater-seawater dolomitizing environment. The larger size of the Isla de Mona flank margin caves, surface dissolution features (kaminitzas), depth of solution pits, and solution depressions and sinkholes, when compared to Bahamian carbonates, is also a result of the repeated re-establishment of an environment of carbonate dissolution and not solely a function of the larger size of the island as suggested by Mylroie et al. (1994). The contact between the dense Isla de Mona Dolomite and the cavernous Lirio Limestone — a gradual transition from nearly pure dolomite to pure limestone — preserves the time-averaged boundary of the late Miocene mixed freshwater-seawater environment below which dolomitization took place and above which calcitization and dissolution took place.

CONCLUDING REMARKS

The carbonate buildup of Isla de Mona is the result of the development of a barrier reef of middle Miocene to earliest Pliocene age. Four reef facies have been identified in the Neogene deposits of the island. Forereef deposits characterized by muds, pelagic foraminifera, and steeply dipping strata are present on the southwestern cliffs. Reef-core deposits are exposed along the southeastern coast near Playa de Pajaros and in the western tip of the island near Playa Sardinera. A transition between reef-flat and backreef deposits is present to the north of these reef-core deposits. Lagoon deposits composed of pelleted muds, benthic foramini-

fera, and coralline algae comprise the bulk of the island's carbonates. Scattered patch reefs are locally developed in the lagoon facies. During the reef development stage, marine diagenesis caused micritization of some reefal components and the reduction of primary porosity through cementation. Recognition of the abundant coral fauna in these deposits by previous workers was obstructed by extensive diagenetic alteration.

Reef development was followed by an extended period of intermittent exposure resulting from the interaction of glacioeustasy and tectonoeustasy. Freshwater lenses developed during periods of platform exposure. Seawater and freshwater mixing resulted in the formation of flank margin caves and the dissolution of aragonitic components within the platform. Platform exposure was accompanied by multiple periods of karstification and soil formation. Calcitization of the limestone involved multiple periods of meteoric diagenesis as a product of oscillating sea levels. Extensive dolomitization followed aragonite dissolution in most of the island carbonates. The association of dolomite with aragonite dissolution combined with the abundance of cloudy-centered and zoned dolomite cements and the carbon and oxygen isotopic trends of dolomite and calcite point to a mixed freshwater-seawater origin. During the Pleistocene, carbonates of Isla de Mona were exposed to vadose diagenesis. During this period of emergence, abundant precipitation resulted in the development of cave speleothems.

Episodic uplift of the island led to development of a series of escarpments during sea-level stands along which fringing-reef deposits were formed. Isla de Mona has been relatively stable since 125 ka when an extensive fringing-reef tract developed along the cliffs of the island.

Hydrogeologically, Isla de Mona can be described as an Exuma-type island (Vacher and Wallis, 1992). Two separate freshwater lenses are developed, one under the Pleistocene coastal plain, the other under the Miocene plateau carbonates. The abundant fractures, sinkholes, and solution pits result in rapid percolation of water preventing development of surface drainage system. The thin freshwater lens under the plateaus surface suggests strong structural and lithologic control on the shape of the freshwater lens and the discharge of freshwater in periphery of the island.

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