Sequence stratigraphy of upper Paleogene to Neogene sedimentary rocks exposed from Guánica bay to Guayanilla Puerto Rico

by:

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ABSTRACT

Detailed stratigraphic columns were measured, analyzed in terms of sequence stratigraphy, and correlated to previous works to produce a sequence stratigraphic model for the upper Paleogene to Neogene carbonate rocks exposed from Guánica Bay to Guayanilla, Puerto Rico. Four depositional sequences and three sequence boundaries were found. Facies analysis of the first depositional sequence of the Juana Diaz Formation, exposed at both sides of Guanica Bay, suggest a left lateral displacement where the west side was deposited in a proximal environment and the east at a more distal environment. Sequence stratigraphic analysis at the west side of Guanica bay showed that Mid-Miocene carbonate sediments of the fourth sequence are uncomformably overlying the first depositional sequence. The Guanica bay east exposure contains all fourth sequences suggesting that displacement occur before deposition of the fourth sequence during the Neogene. The southwestern of Puerto Rico has been of great interest because of its exceptional Outcrops of the Ponce (Mid-Miocene) and Juana Díaz (Oligocene) Formations, and models from these studies are of great value for the analysis of potential hydrocarbon reservoirs.

RESUMEN

Se midieron columnas estratigráficas detalladas, se analizaron en términos de estratigrafía secuencial y se correlacionaron con trabajos previos para producir un modelo de estratigrafía secuencial para los estratos del Paleógeno superior al Neógeno que se encuentran expuestos desde la Bahía de Guánica hasta Guayanilla, Puerto Rico. Se encontraron cuatro secuencias deposicionales separadas por tres límites de secuencia. Las tres primeras parasecuencias forman parte de la Formación Juana Díaz (Oligoceno al Mioceno temprano) y la cuarta de la Formación Ponce (Mioceno medio). El análisis de estratigrafía secuencial en el lado oeste de la bahía de Guánica mostró que los sedimentos carbonáticos del Mioceno medio de la cuarta secuencia están superpuestos sobre la primera secuencia deposicional en una disconformidad angular. El afloramiento en el este de la bahía de Guánica contiene las cuatro secuencias deposicionales, lo cual sugiere que el desplazamiento ocurrió antes de la deposición de la cuarta secuencia durante el Neógeno. Se produjo una curva del nivel del mar para el área de estudio y se comparó con la curva eustática global. Las primeras tres secuencias deposicionales no correlacionan con la curva eustática global, lo que sugiere que el tectonismo local afectó al noreste del Caribe durante el Oligoceno medio al Mioceno temprano. Esto concuerda con trabajos previos que sugieren sindeposición durante eventos tectónicos de ese tiempo. La cuarta secuencia deposicional del Mioceno medio se correlaciona con la curva eustática global, lo que sugiere estabilidad tectónica durante el Mioceno medio. El suroeste de Puerto Rico ha sido de gran interés debido a sus afloramientos excepcionales de las formaciones de Ponce (Mioceno medio) y Juana Díaz (Oligoceno) ya que los modelos derivados de estos estudios son de gran valor para el análisis de posibles reservorios de hidrocarburos.

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ACKNOWLEDGEMENTS

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CHAPTER 1 – INTRODUCTION

Oligocene to Miocene sedimentary deposits cover the north and south coastal areas of Puerto Rico unconformably overlying Cretaceous to Eocene deposits. In south Puerto Rico, this depositional basin extends from west of Guánica to Juana Díaz municipalities (Renken et al., 2002) (Figure 1). Berkey (1915) was the first who recognized these deposits and informally classified the Juan Díaz and Ponce formations as subdivisions of the Arecibo Formation. Berkey (1915) suggested that the Arecibo Formation represents all the deposits from the Paleogene and younger. This study also mentioned that it would take paleontological studies to make the proper subdivisions of the Juana Díaz marls and shales and Ponce chalks (Berkey, 1915).

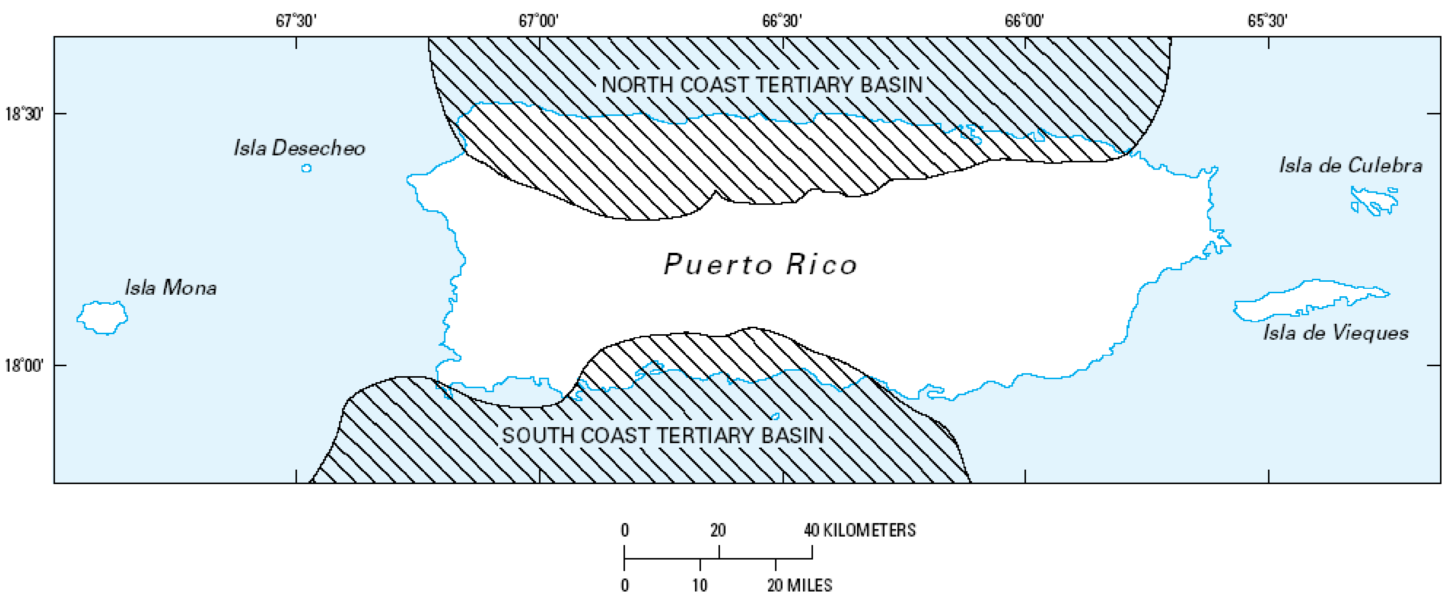

Figure 1.1: Location of Tertiary sedimentary basins of Puerto Rico (modified from Meyerhoff and others, 1983 *in* Ward et al., 2002).

Using biostratigraphic associations of planktonic foraminifera Mousa and Seiglie (1970) designated the Juana Díaz Formation to the Oligocene and the Ponce Limestone to the Miocene

(Figure 1.2). They also informally named the lower Miocene pelagic deposits between the Juana Díaz and Ponce formations as the “Angola Formation.”

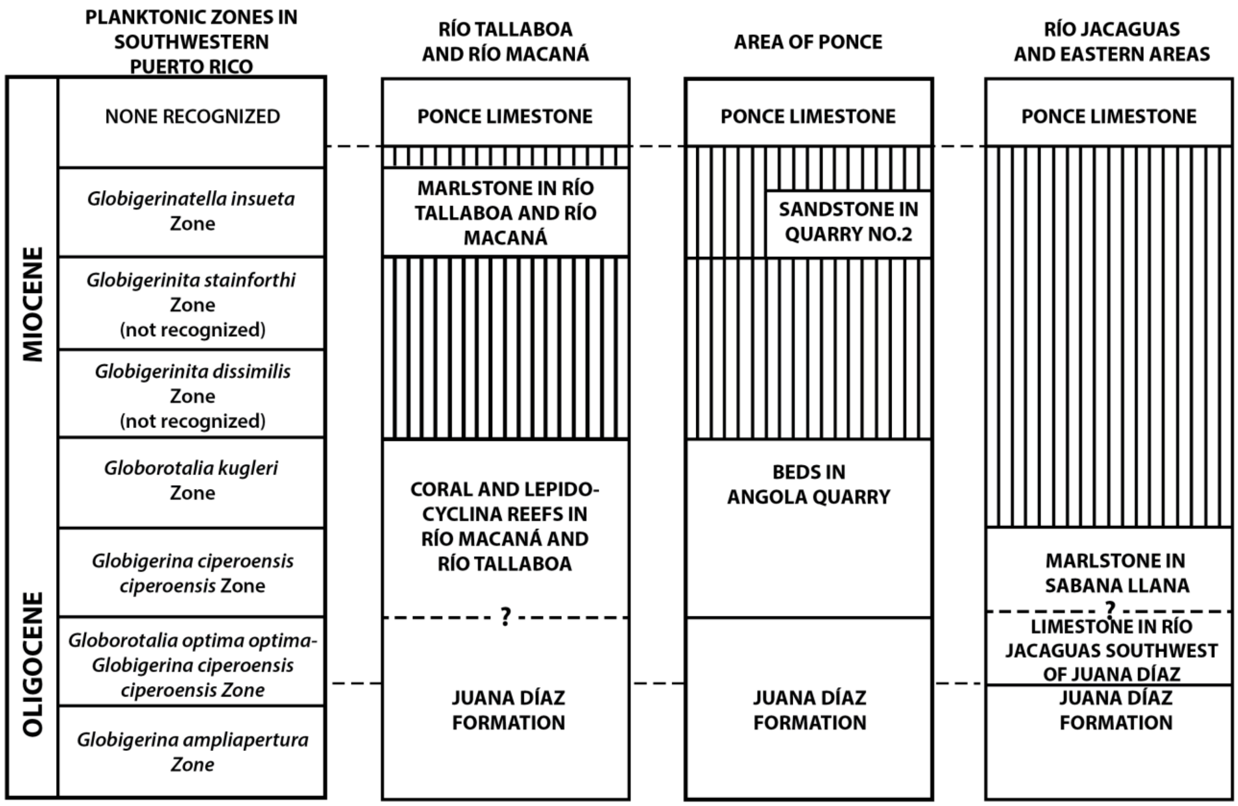

Figure 1.2. Correlation of mid-Tertiary stratigraphic units in southwestern Puerto Rico from Mousa and Seiglie (1970).

Frost et al. (1983) confirmed Moussa and Seiglie’s (1970) findings using coral faunal assemblages from the Oligocene rocks of southwestern Puerto Rico and named the island slope deposits of the late Oligocene as the “New Formation” (Figure 1.3).

Renken et al. (2002) considered the “New Formation” as a part of the Juana Díaz Formation with which this study agrees (See Chapter 5). The lower Miocene pelagic deposits which belong to the *Globorotalia kugleri* zone (Table 1) defined by Mousa and Seiglie (1970) remained unnamed as they were not correlative with other localities in southwestern Puerto Rico.

Addarich (2009) divided the Juana Díaz Formation into two members for the Guánica quadrangle due to a difference in fossil assemblages and siliciclastic content. These two members were referred to as the Juana Díaz Clastic Member, and the Juana Díaz Limestone Member.

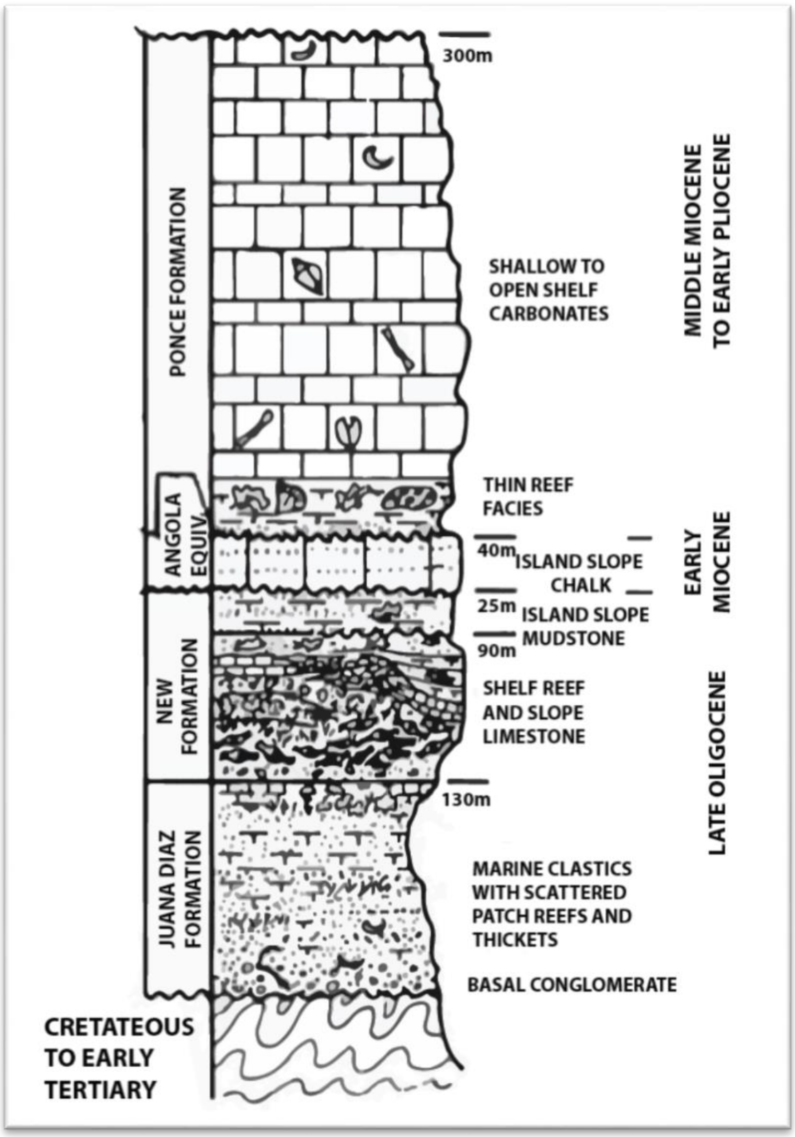

Figure 1.3: Stratigraphic sequence of southwestern Puerto Rico
[modified from Frost et al. (1983)].

1.1 Tectonic Setting

Puerto Rico is the easternmost island of the Greater Antilles arc system, in the northeastern part of the Caribbean Sea (Ortega–Araiza, 2009). The northern segment of the Caribbean island arc became inactive during a Paleocene-Oligocene collision event with a now subducted feature with a crustal thickness greater than normal oceanic crust that lay to the south and southeast of the present-day Bahama carbonate platform. The age of this Paleogene collisional event occurred in late Eocene in Puerto Rico (Mann et al., 2005).

The island is of Puerto Rico is divided into three igneous provinces by two major faults: The Great Southern Puerto Rico Fault Zone and The Northern Puerto Rico Fault Zone (Ruidíaz,2013). Following collision of the Puerto Rico arc and cessation of arc volcanism, most deformation in Puerto Rico was focused on the high-angle Great Northern and Great Southern Puerto Rico fault zones. It is evident that during the Oligocene, the Great Southern Puerto Rico fault zone (Figure 1.4) was comparatively more active than the Great Southern Puerto Rico Fault Zone as Oligocene Carbonate deposits in the north generally show paleoenvironmental consistency along the outcrops, which is not the case of the Oligocene deposits in southwestern Puerto Rico. Monroe (1980) indicates that rocks in the southern limb of the islands arc are broken by many faults and some with displacements that are up to several hundred meters, while in the north, the platform rocks of the gentler-dipping northern limb of the arc are deformed by a few small anticlines and faults having displacements of 35 m or less.

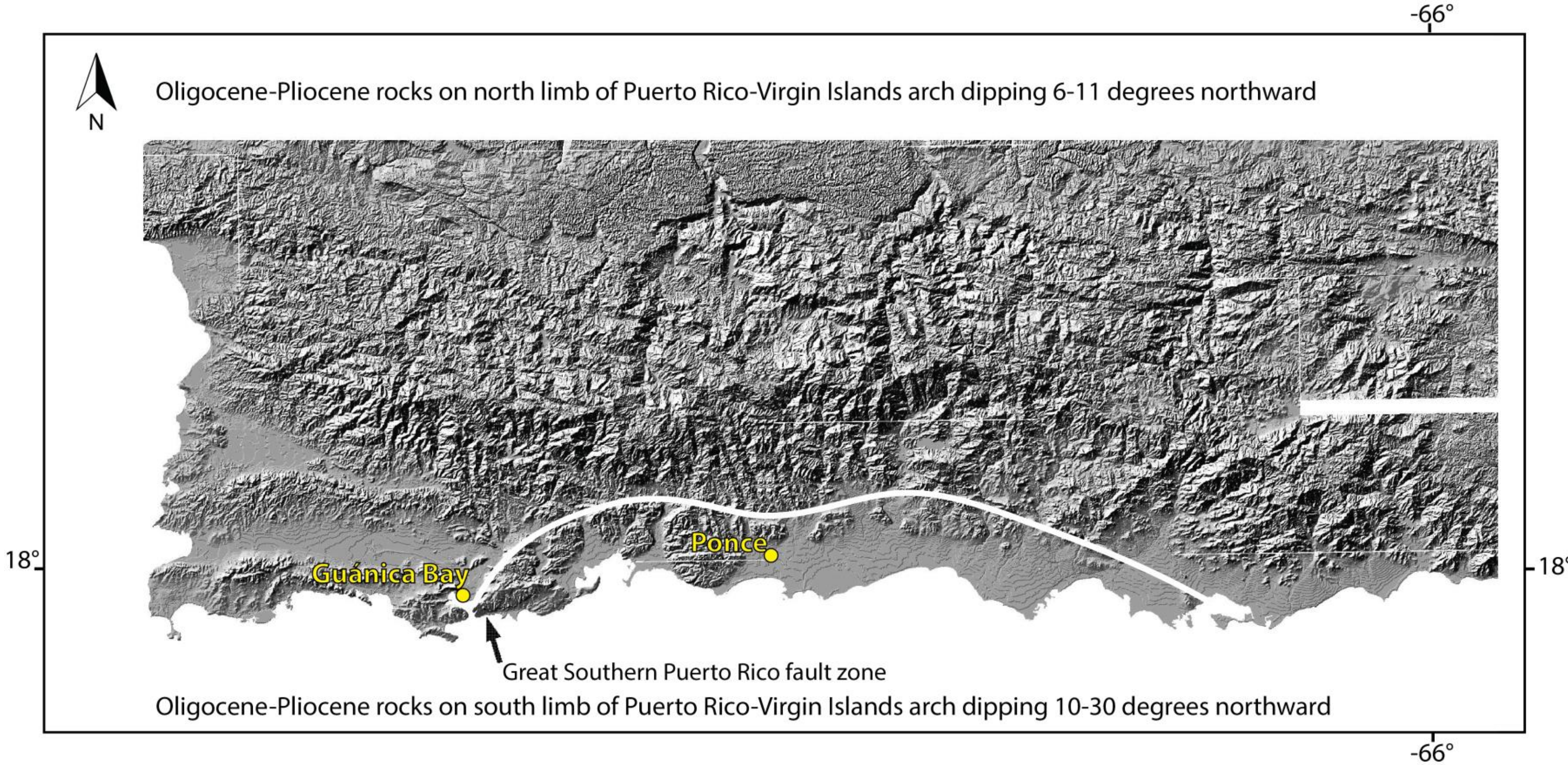

Figure 1.4: Digital elevation model (DEM) of Puerto Rico, showing the Great Southern Puerto Rico Fault Zone (Modified from Mann et al.,2005)

1.2 Purpose

The purpose of this study was to establish a sequence stratigraphy framework for the upper Paleogene to Neogene rocks exposed in southwestern Puerto Rico. To create a comprehensive model, new sections were measured, interpreted and associated with a previous sequence stratigraphy work on east side of Guánica bay by Ruidíaz (2013). The present study also gives continuity to the work of Frost et al. (1983) in the municipality of Guayanilla, while applying modern sequence stratigraphy concepts to his observations and interpretations.

1.3 Introduction to Sequence Stratigraphy

The sequence stratigraphic approach has been embraced by geoscientists as the preferred method of stratigraphic analysis in the field of sedimentary geology (Catuneanu, 2006).

Proposed by Peter Vail in the mid 70's (Vail et al., 1977) this genetic approach gives us an understanding of how stratigraphic units, facies tracts, and depositional elements relate to each other in time and space within sedimentary basins (Catuneanu, 2006). Carbonate and siliciclastic systems are based on the same principle; however, the geometry of each genetically related cycle is different. The models in this summary represent carbonate systems in allusion to the geology of the area of study.

The relationship between space available within a basin for sediment to be deposited and the amount of sediment supplied is termed accommodation space. The amount of marine accommodation space is governed by changes in relative sea level (Figure 1.4) (Coe & Church, 2003).

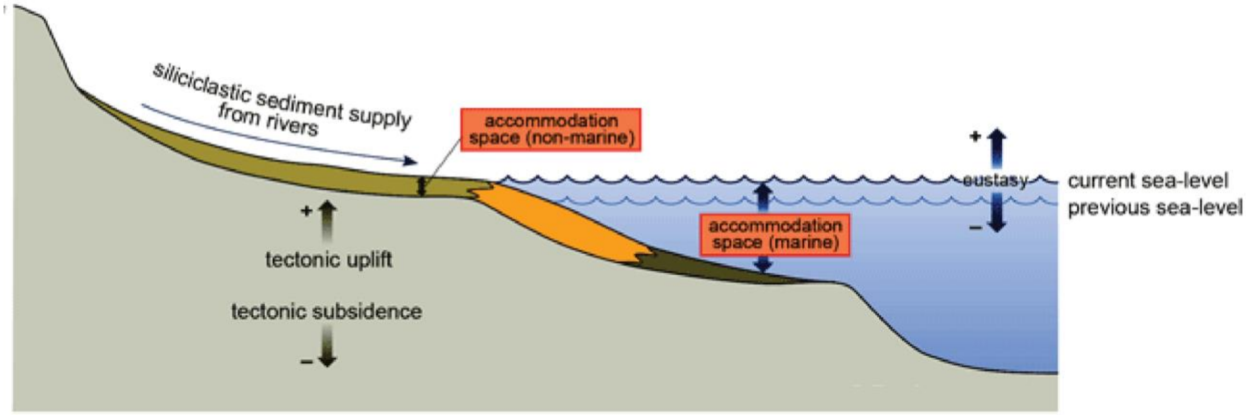

Figure 1.5: Sediment accommodation space and its relationship to eustatic sea level and tectonic uplift and subsidence (Coe & Church, 2003).

Ideally, when accommodation space is created, a shallowing or deepening upward succession of genetically linked facies will develop. These successions, bounded by marine flooding surfaces and their correlative surfaces are known as a parasequences (Emery & Myers, 1996). Parasequences are the building blocks of stratigraphic sequences, and each sequence is composed by system tracts (Figure 1.6), each of which embody a different relation between accommodation space and sediment supply, along third order sea level cycles (Coe & Church, 2003).

A complete sequence is composed by four system tracts, which are described below:

1. Highstand systems Tract (HST). Deposited between the maximum rate of sea-level rise and maximum relative sea-level. Parasequence sets in this systems tract are aggradational to progradational (Coe & Church, 2003). A sequence boundary is generally placed at the subaerial unconformity that forms when the relative sea level drops after the deposition of the HST (James and Dalrymple, 2010).

2. Transgressive systems tract (TST). Deposited when base level rises more rapidly than sediment accumulates, parasequence sets will develop transgressive depositional architecture (James and Dalrymple, 2010). At the time of maximum transgression, a

maximum flooding surface (MFS) will be characterized either by the formation of a condensed bed in distal areas, or by sediments representing the most landward position of the shoreline in proximal areas (Coe & Church, 2003).

3. Falling stage systems tract (FSST). Deposited during a relative sea-level fall, parasequence sets will be aggradational due to a forced regression deposition. Because this system tract is solely a consequence of forced regression it is very common that the FSST is missing in the geological record (Coe & Church, 2003).

4. Lowstand systems tract (LST). After sea-level fall reached its minimum, it will start to rise, creating progressively more accommodation space, generating progradational to aggradational parasequence sets (Coe & Church, 2003).

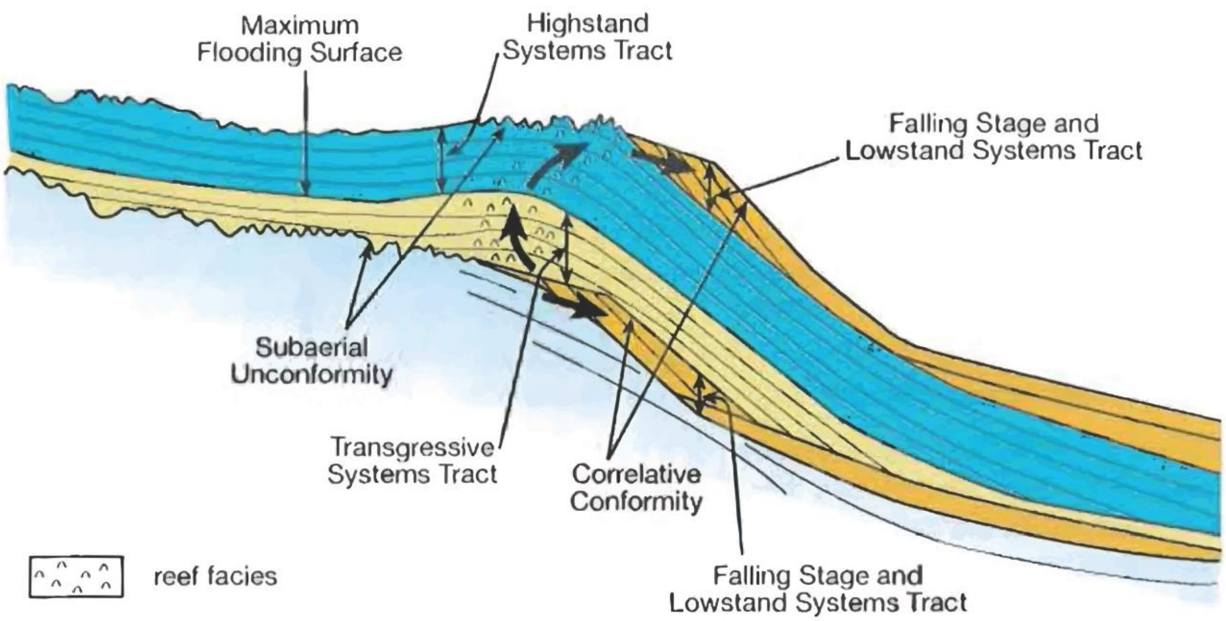

Figure 1.6: Schematic section for a carbonate platform showing the stratal architecture, systems tracts and major surfaces produced over an accommodation cycle. (Modified from James and Dalrymple, 2010).

1.3.1 *Carbonate Platforms*

The term carbonate platform is used to describe recent and ancient thick-deposits of shallow water carbonates (Coe & Church, 2003). The geometry of these deposits will depend on the spatial patterns of carbonate production and sediment redistribution by waves and currents (Schlager, 2005). The commonly occurring patterns in carbonate deposits are: rimmed platforms, unrimmed platforms and ramps (Figure 1.7).

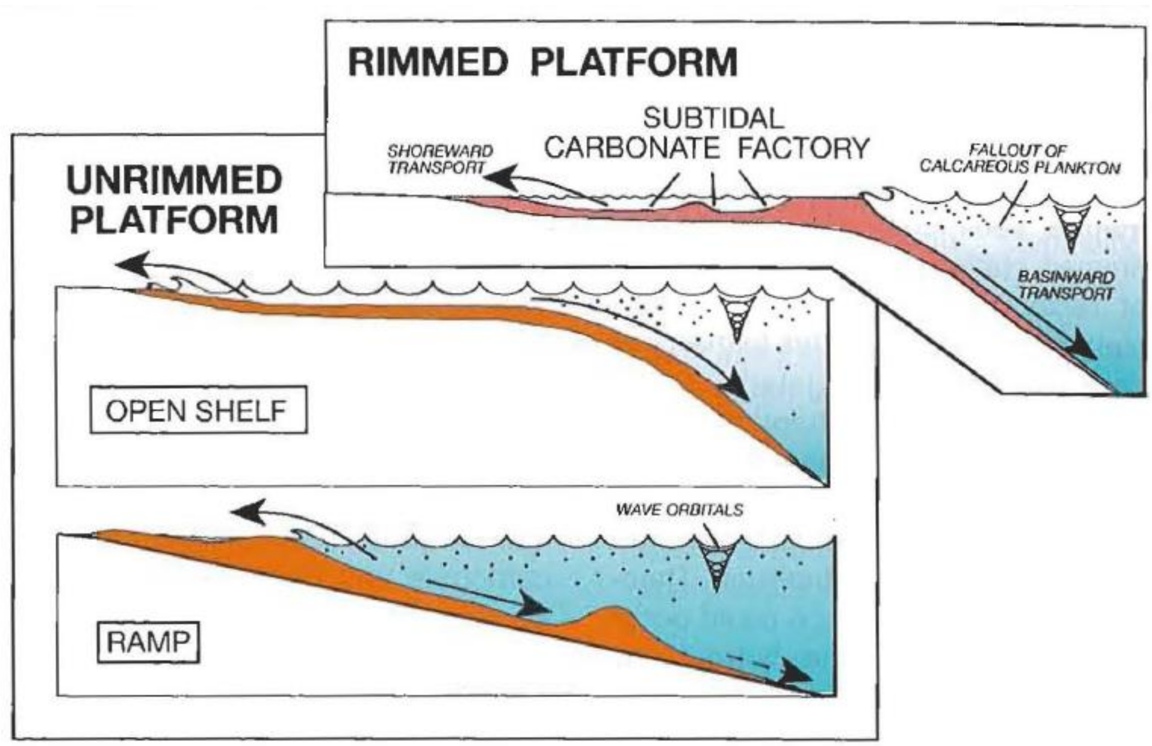

Figure 1.7: Figure showing the differences in geometries. (Modified from James and Dalrymple, 2010)

A rimmed carbonate platform has a segmented to continuous rampart of reefs along its margin, which absorbs the wave energy, allowing a variety of low energy leeward environments. This morphology is common in moden and ancient warm-water carbonate deposits (James and Dalrymple, 2010).

An unrimmed or open platform has no reef barrier. This morphology is common for cool water settings.

A Ramp is a gently inclined platform towards the open sea at generally less than one degree (Coe & Church, 2003). Because there is no barrier for wave action, shallow water environments tend to have high energy.

1.4 Study Area

The major distribution of upper Paleogene to Neogene deposits in south of Puerto Rico is exposed predominantly from Juana Díaz to the southwest of Guánica, comprising an extension of approximately 50 km. This study focus in the stratigraphy from Guánica bay to Guayanilla. Three stratigraphic sections were measured along this area; one at the west side of Guánica bay and two more in Guayanilla, see Figure 1.8

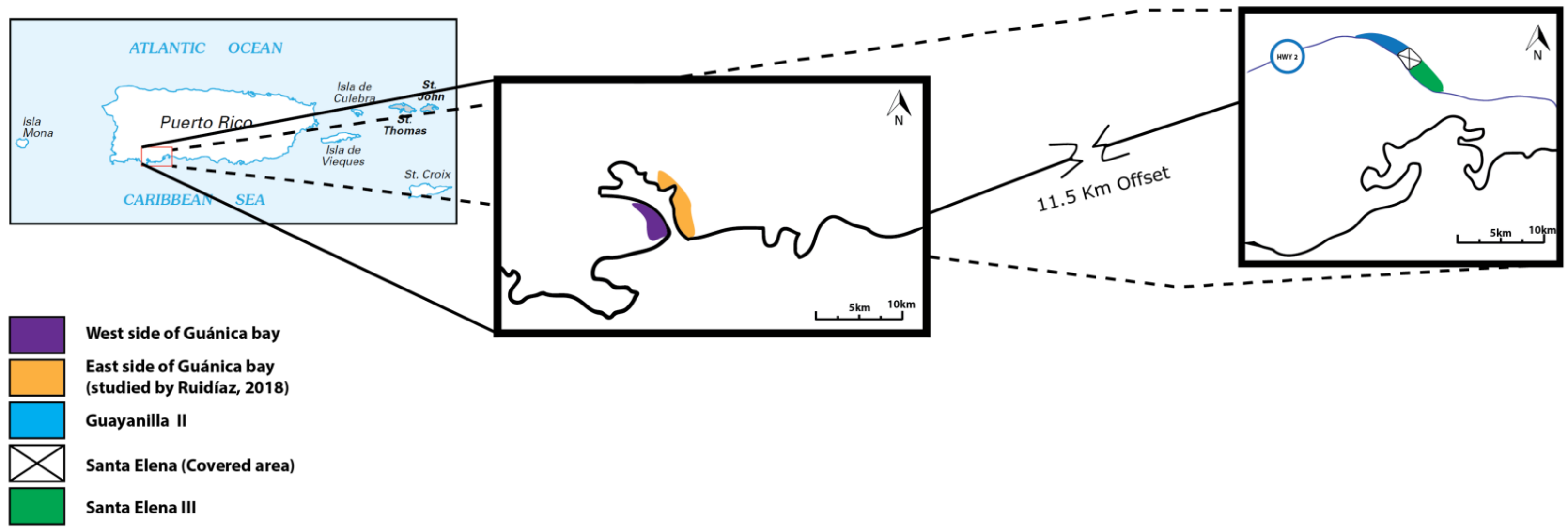

Figure 1.8: Location of the areas of study in the Guánica and Guayanilla municipalities.

CHAPTER 2 – METHODOLOGY

The procedures to create a sequence stratigraphy framework for southwestern Puerto Rico were developed as follows; 1) Field and laboratory analysis; 2) Paleoenvironmental interpretations using facies analysis; 3) Review of previous works for subsequent correlation with field and laboratory work interpretations.

2.1 Field Work and Laboratory Analysis

The fieldwork consisted of measuring three stratigraphic sections at; west side of Guánica bay (Figure 3.1), Guayanilla II on Hwy. 132, and Santa Elena III housing development (Figure 3.11). Stratigraphic sections in Guánica bay are only accessible by water since there are no roads or paths to the designated study area location. On the other hand, Guayanilla II and Santa Elena III sites required climbing gear as full examination was performed by descending the steep outcrop using a rope, also known as “rappelling”. The rocks that make up these sections were classified using the expanded Dunham classification by Embry and Klovan (1971) (Figure 2.1). For these preliminary descriptions, skeletal and non-skeletal components were described by relative fossil abundance as; (1) Scarce (2) Moderate (3) Abundant (4) Very abundant. See Appendix 1 for preliminary descriptions.

<table>
<tr><td colspan="6">ALLOCHTHONOUS LIMESTONE
ORIGINAL COMPONENTS NOT ORGANICALLY ORIGINAL
BOUND DURING DEPOSITION</td><td colspan="3">AUTOCHTHONOUS LIMESTONE
COMPONENTS ORGANICALLY
BOUND DURING DEPOSITION</td></tr>
<tr><td colspan="3">Less than 10% > 2 mm components
contains lime mud (< 0.03 mm)</td><td>no
lime mud</td><td colspan="2">Greater than 10% > 2 mm
components</td><td colspan="3">by organisms
which</td></tr>
<tr><td colspan="2">Mud supported</td><td colspan="2" rowspan="3">Grain-supported</td><td rowspan="3">Matrix-
supported</td><td rowspan="3">> 2 mm
component
supported</td><td rowspan="2">build
a rigid
framework</td><td rowspan="2">encrust
and bind</td><td rowspan="2">act
as bafflers</td></tr>
<tr><td rowspan="2">less than
10% grains
(> 0.03 mm and
< 2 mm)</td><td rowspan="2">greater than
10% grains</td></tr>
<tr><td colspan="3">BOUNDSTONE</td></tr>
<tr><td>MUDSTONE</td><td>WACKESTONE</td><td>PACKSTONE</td><td>GRAINSTONE</td><td>FLOATSTONE</td><td>RUDSTONE</td><td>FRAMESTONE</td><td>BINDSTONE</td><td>BAFFLESTONE</td></tr>
</table>

Figure 2.1: Expanded Dunham classification (Embry and Klovan, 1971)

The laboratory analysis was conducted to verify and complement the field observations with data obtained from fifty thin sections. The samples used to produce these thin sections were collected after the parasequence sets were preliminarily defined for each outcrop. This approach was made to collect samples where most needed and avoid excessive sampling of the same facies within the same parasequence set. Thin sections were also made from areas where recrystallization and diagenetic alteration made it difficult to describe the original rock texture in the field.

Facies Analysis

The sequence stratigraphy model was developed by first dividing sedimentary successions into building blocks, better known as facies (Figure 2.2). Facies attributes like texture, fossil content, and physical structure reflect very important aspects of the origin of a sedimentary succession (James and Dalrymple, 2010).

In order to delineate these facies successions, facies types were made for the Guayanilla and Guánica locations. The facies types were then compared to the Oligocene reef facies model created by Frost (1983) (Figure 2.3). This model was based on data obtained from various outcrops at the municipalities of Guánica, Yauco, and Guayanilla, summarizing the environments in which Oligocene carbonate deposits were formed in southwestern Puerto Rico.

Because the Oligocene reef facies model did not fit the Santa Elena III outcrop at Guayanilla, paleoenvironmental interpretations were made from a modern foraminiferal assemblage model published by Hallock & Charlotte (1986) (Figure 2.4). The *Kuphus incrassatus* mollusk in growth position were used to mark shallow marine deposits because they have been associated with subtidal deposits.

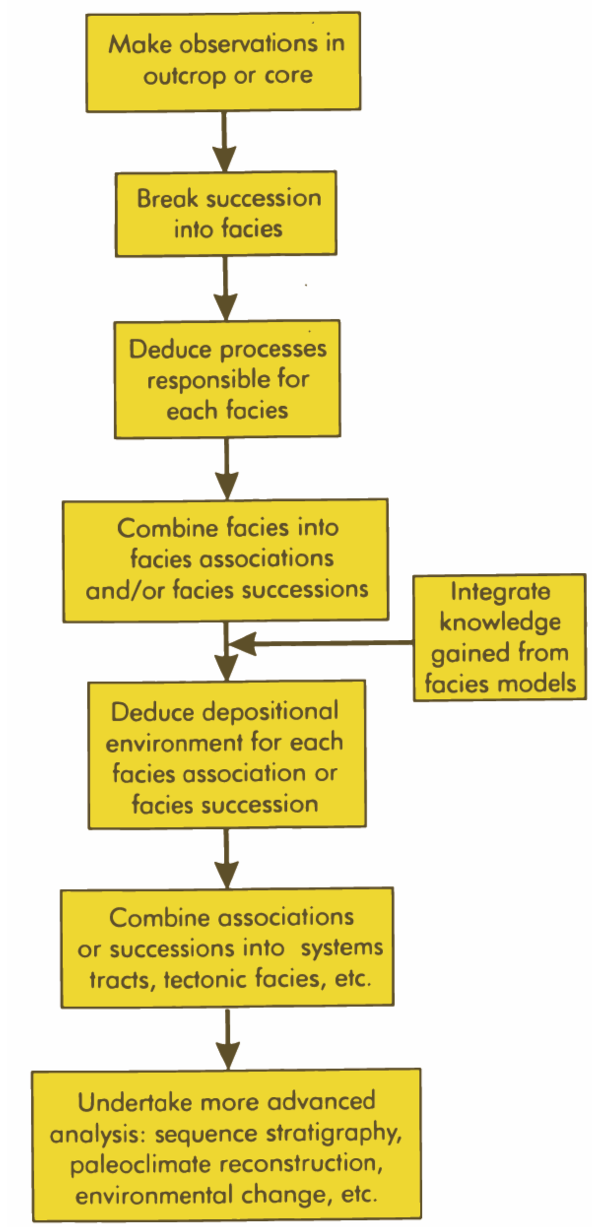

Figure 2.2: Relationship between facies, facies associations, facies successions, depositional environments and systems tracts. (From James and Dalrymple, 2010).

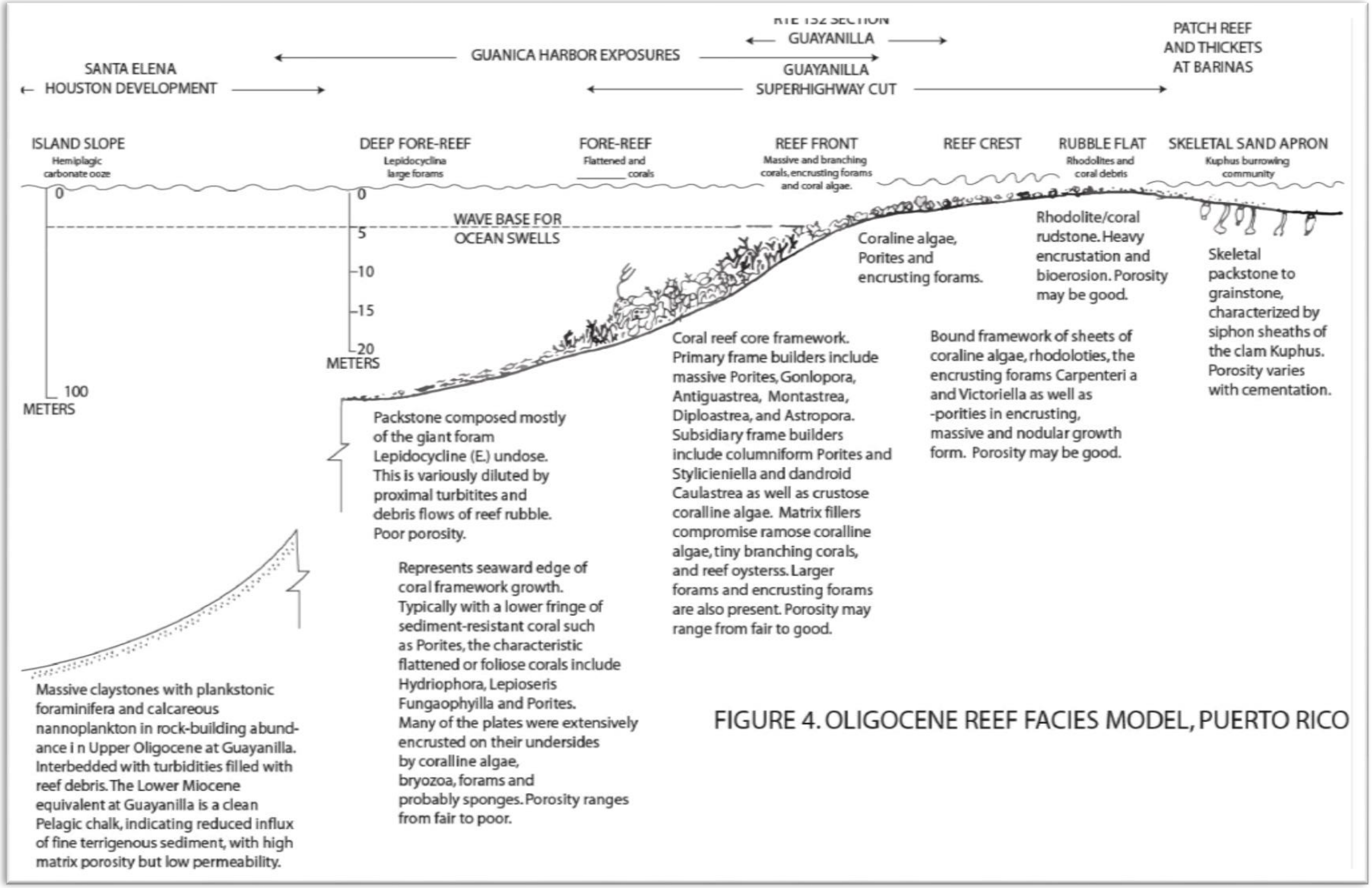

Figure 2.3: Oligocene reef facies model proposed by Frost et al., (1983).

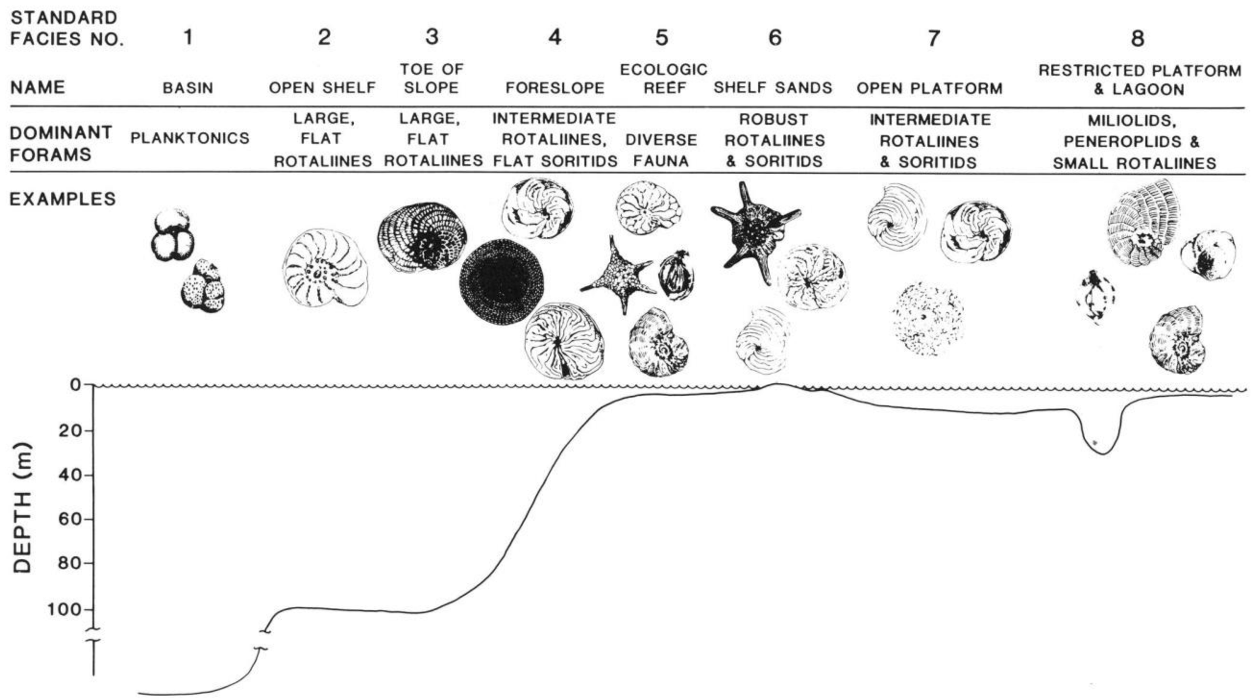

Figure 2.4: Idealized distribution of major foraminiferal groups in reef-associated environments (from Hallock & Charlotte, 1986).

2.2 Review of Previous Works

2.2.1 Oligocene Reef Facies Model (Frost, et al., 1983)

The Oligocene Reef Facies model (Frost, et al., 1983) was developed form the study of various outcrops at the municipalities of Guánica, Yauco, and Guayanilla to explain the processes involved in the development of the Peñuelas-Guánica shelf-reef-slope complex. This facies model is a summary of the spectrum of environments in which late Oligocene deposits were formed over the Peñuelas-Guánica shelf-reef-slope complex.

The two outcrops measured in the Guayanilla municipality (Guayanilla II and Santa Elena III) are separated by an area covered by soil and vegetation which contain an offset section of

Guayanilla II and the Santa Elena section measured by Frost (Figure 1.8). These sections were used to correlate Guánica and Guayanilla depositional sequences.

The Santa Elena stratigraphic section extend form coordinate 18°1'50.76"N 66°47'28.49"W to 18° 1'42.96"N 66°47'14.43"W.

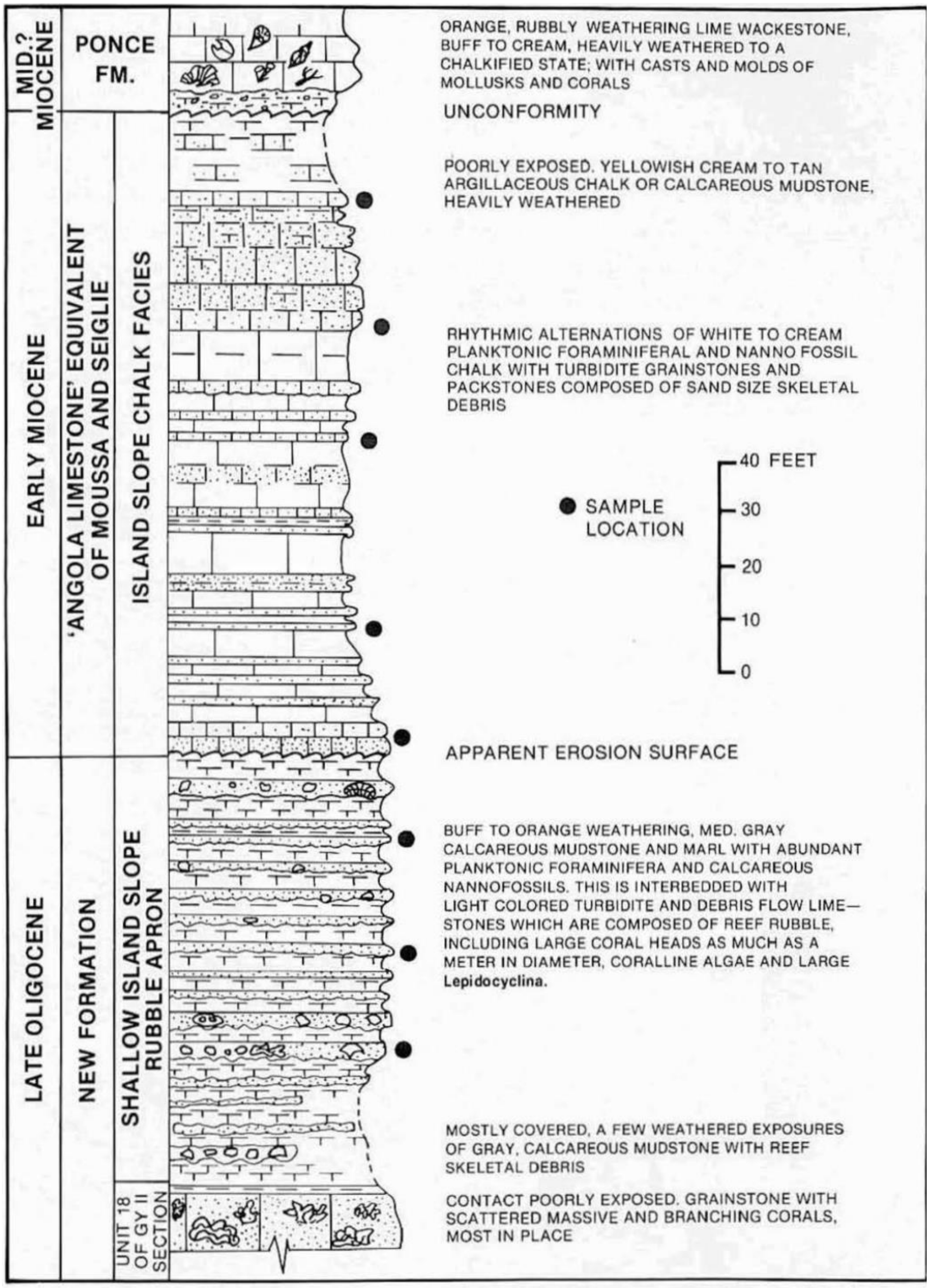

Figure 2.5: Stratigraphic section of Santa Elena locality (from Frost et al., 1983).

The offset section of Guayanilla II is a stratigraphic section of approximately 60m located east of the Guayanilla II outcrop from 18° 1'55.30"N 66°47'37.53"W to 18° 1'54.44"N 66°47'36.41"W (Figure 3.1). Figure 2.6 Shows the stratigraphic column and unit descriptions.

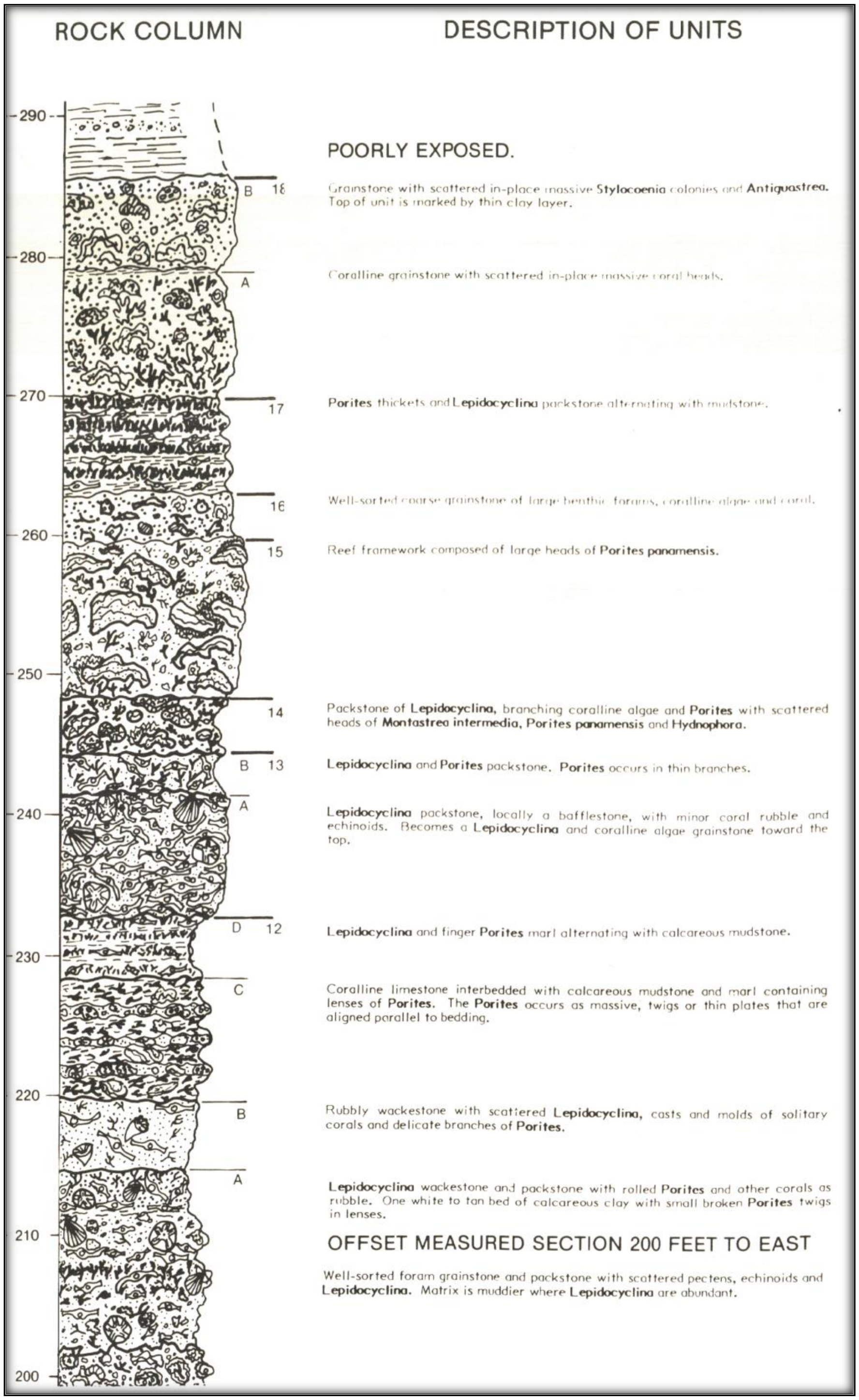

Figure 2.6: Offset section of Guayanilla II (from Frost et al., 1983).

2.2.2 Facies distribution model and sequence stratigraphic model of mid Tertiatry rocks exposed in east side of Guánica bay, Puerto Rico (Ruidíaz, 2013)

Ruidíaz (2013) carried out a sequence stratigraphy study in the east side of Guánica bay, Puerto Rico by measuring and correlating ten stratigraphic sections, (Figure 2.7), (see Apendix II for detailed stratigraphic sections). Nine facies types were identified, and four stratigraphic sequences were interpreted. Also, a strontium isotope analysis confirmed an early Miocene age for the Ponce limestone deposits at Jaboncillo Beach, reporting Sr ages of 13.66 ± 0.16 Ma and 13.79 ± 0.19 Ma (Ruidíaz, 2013).

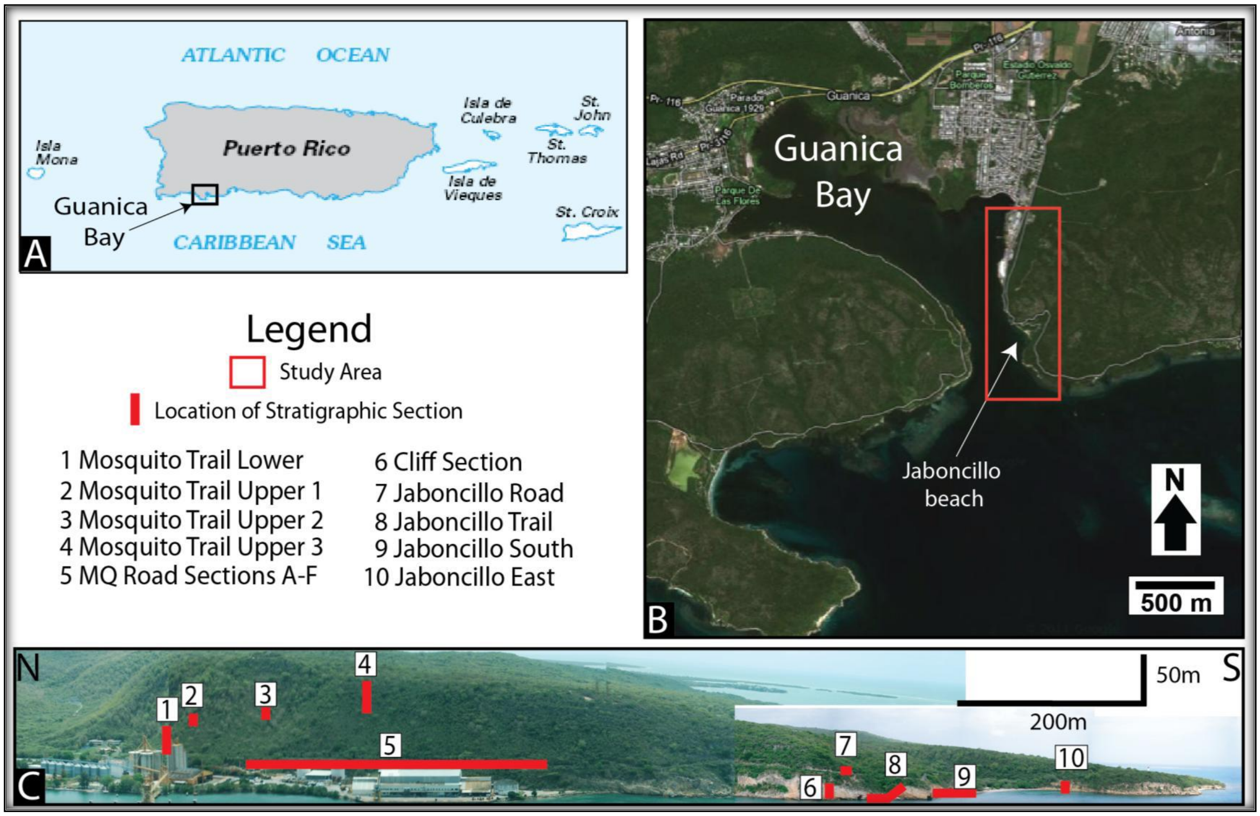

Figure 2.7: Study area. A) Location of Guánica bay in Puerto Rico Map (Renken et al, 2012). B) Satellite imagery of Guánica bay, highlighting study area. C) Cross-sectional view of study area, showing location of measured stratigraphic sections (from Ruidíaz, 2013).

In Figure 2.7 we have a facies distribution model for the east side of Guánica bay showing six shallowing upward cycles. These facies associations from Ruidíaz study (2013) were used to make correlations and paleogeographic interpretations by comparing them with the results of the west side of Guánica bay and Guayanilla outcrops. See Chapter 5.

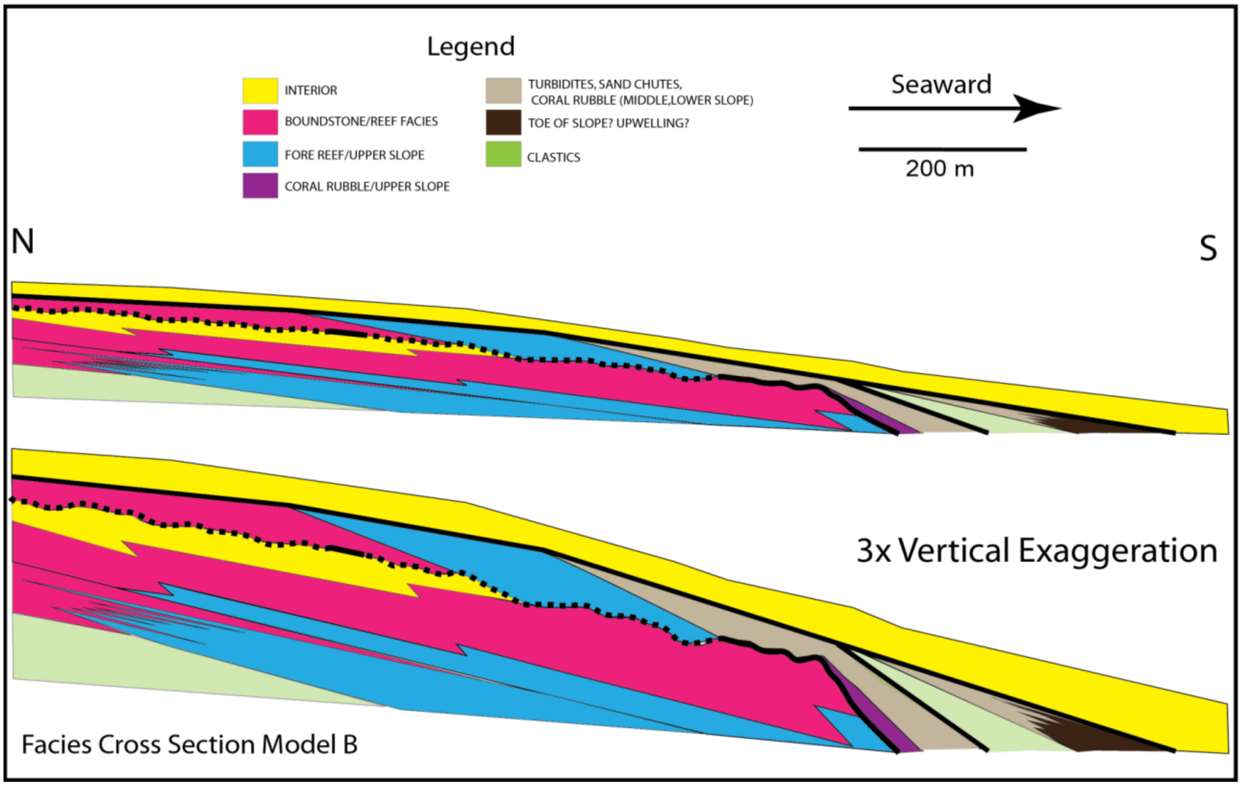

Figure 2.8: Facies distribution cross-section for the east side of Guánica bay. (Form Ruidíaz., 2013)

CHAPTER 3 – RESULTS

3.1 West Side of Guánica Bay

The western section of Guánica bay was measured from 17°57'16''N, 66°54'39'' to W17°57'3''N 66°54'33''W (Figure 3.1). This outcrop has a width of 375 m and was analyzed to better understand the difference in geometries overserved from the west side of the bay, to Ruidíaz (2013) outcrop on the east side and produce a more complete reconstruction of the Guánica bay geological history. In section 3.1.1 are stratigraphic descriptions of the west side of Guánica bay, while section 3.1.2 presents a depositional environment interpretation, and section 3.1.3 a sequence stratigraphic interpretation.

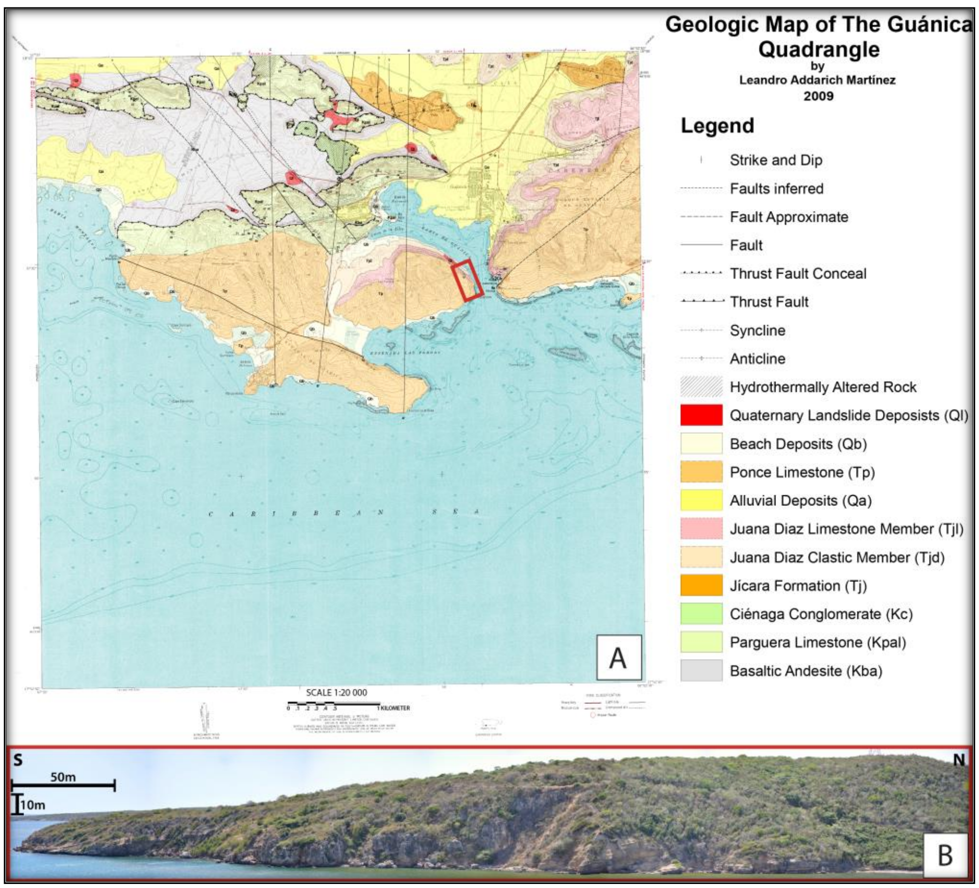

Figure 3.1: Geological map of the Guánica quadrangle by Addarich (2009) showing the area of study inside the red rectangle (A) and photomosaic of the exposed outcrop on the eastern side of the bay (B) (Aerial photograph taken by Dr. Santos).

3.1.1 Stratigraphic Description

A total of 25 units were described for a total of 29 meters. Eleven parasequences were identified and grouped into parasequence sets using their characteristic lithologic patterns, fossil content, and diagenetic features. In sections 3.1.1.1, 3.1.1.2, and 3.1.1.3 are description of the lower, middle, and upper parasequence sets that were characterized for the West side of Guánica Bay.

3.1.1.1 Lower Parasequence Set

The lower parasequence set consists of the first three parasequences which are composed of units 1 to 7, where parasequence 1 is represented by unit 1, parasequence 2 by units 2 to 4, and parasequence 3 by units 3 to 7 (Figure 3.7). The lower parasequence set is composed of mixed siliciclastics and carbonates, where siliciclastics are represented by rounded gravel and pebble size lithic fragments. In general, the facies that conform each of the three parasequences occur in the following order; *Lepidocyclina* Rudstone facies in a marl matrix, massive coral framestone facies and heavily bioturbated packstone to grainstone facies.

Lepidocyclina Rudstone facies have a graded bedding [(Fig. 3.3 (A)] and can show horizons of scarce to moderate abundance of platy coral *Agaricia agaricites.* Siliciclastic content in this rudstone units occur in gravel size or smaller. *Amphistegina sp*., *Clipeaster sp*. and *Porites sp.* fragments are common components in these units.

Coral Framestone facies occur with a similar marl matrix with scarce *Lepidocyclina sp*. fragments. Massive coral heads can reach up to 60 cm in diameter and are in growth position. As siliciclastic decrease towards adjacent units, corals become more abundant and diverse and growth position percentage increase. Branching corals *Caulastrea portoricoencis* and *Porites sp.* are dominant in the topmost parasequence framestone of this set.

Bioturbated packstone to grainstone facies are heavily borrowed, composed of fecal pellets, red algae, fragments of gastropods, bivalves, echinoderms, solitary corals, and siliciclastics, the latter are mostly gravel and pebble size (Figure 3.2). Rodoliths are usually very abundant at the top of these grainstone units.

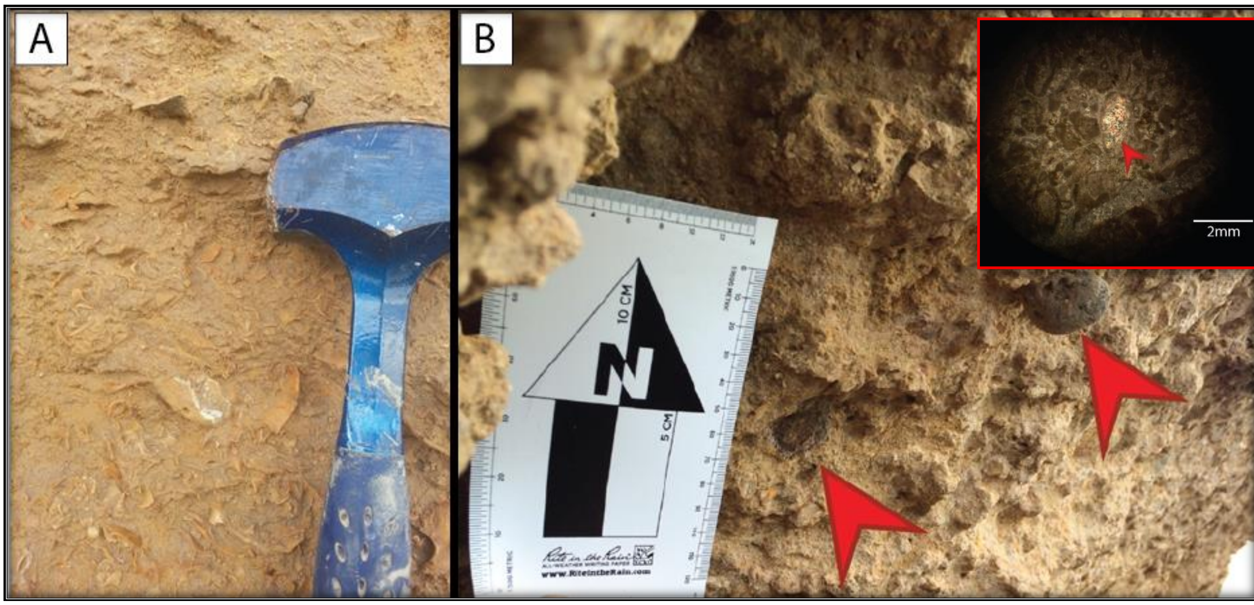

Figure 3.2: A) Graded bedded *lepidocyclina* rudstone. B) Bioturbated pacstone to grainstone showing pebble and gravel size lithoclasts.

3.1.1.2 Middle Parasequence Set

The middle parasequence set is characterized by heavily karstified, clean shallow water carbonates (Figure 3.3). The parasequences here are composed of branching coral framestone facies, were coralline algae increases towards the top, and bioturbated packstone to grainstone facies. These bioturbated grainstone facies represent the top part of each parasequence. The middle parasequence set consists of the fourth to seventh parasequences composed of units 8 to 20, where parasequence 4 is represented by unit 8 to 12, parasequence 5 by units 13 to 15, parasequence 6 by units 15 and 17, and parasequence 7 by units 18 to 20 (Figure 3.8).

Branching coral framestone facies are typically dominated by branching corals that can be found as lenticular accumulations with a micritized wackestone matrix. Despite the degree of recrystallization, coralline algae accumulations can be appreciated as white bands of 40 to 50 cm on the upper part of these units.

Bioturbated packstone to grainstone facies in this middle parasequence set show red algae, fragments of gastropods, bivalves, echinoderms, rotalids, and solitary corals. These grainstones tend to be much thinner than the grainstones in the lower parasequence set and karstification hinders the ability to identify borrowing.

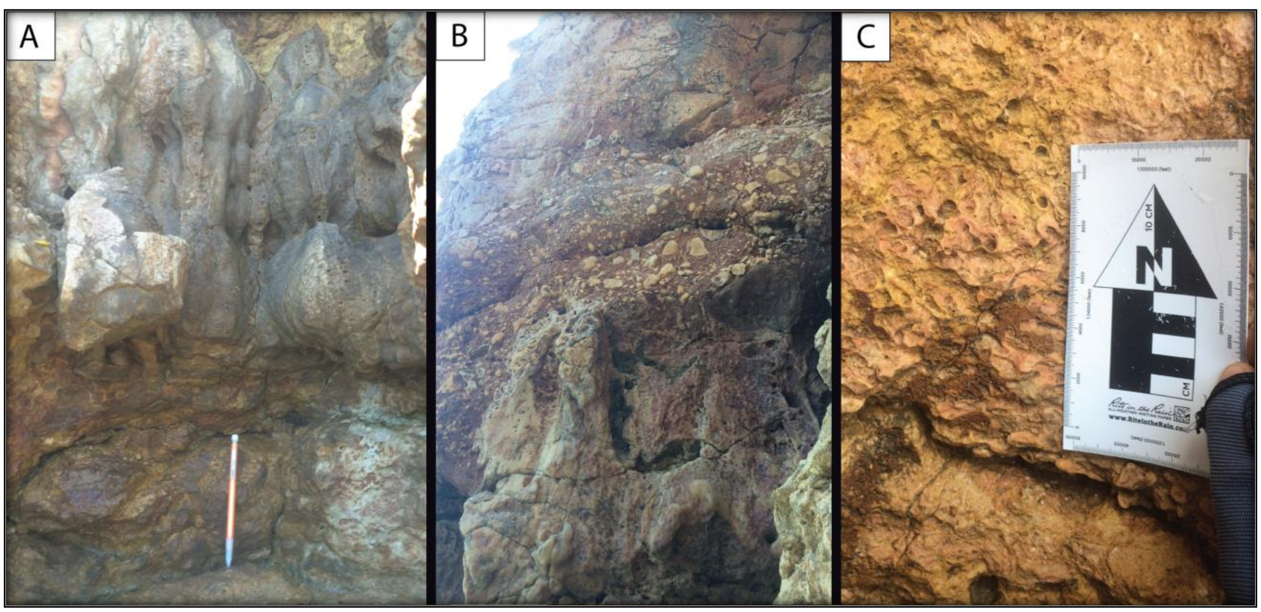

Figure 3.3: A) Speleothems B) collapse breccias C) pink stained and heavily recrystalized colony of *Porites sp*.

3.1.1.3 Upper Parasequence Set

Each of the last four parasequences composing the upper set is represented by a skeletal grainstone unit, separated by a thin paleosol. This upper section is sitting unconformably on top of an exposure surface with reworked coral rubble, caliche nodules and cobble size lithoclasts, (Figure 3.4). The upper parasequence set consists of the eight to eleventh parasequences, composed of units 21 to 25, where parasequence 8 is represented by units 21 and 22, parasequence 9 by unit 23, parasequence 10 by unit 24, and parasequence 11 by unit 25.

Figure 3.4: Reworked clasts of the Ponce Limestone on top of paleosol, separating the middle and upper parasequence sets.

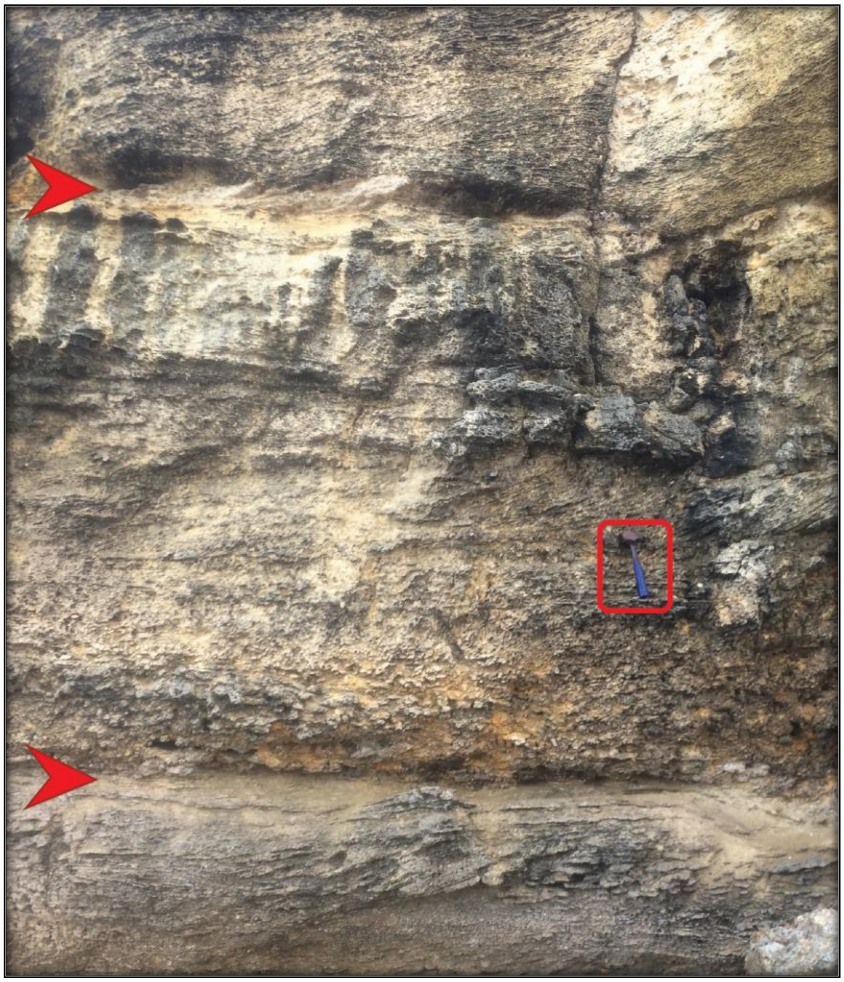

Figure 3.5: Photo of the Ponce Formation cross-bedded grainstones. Red arrows are indicating exposure surfaces on top of plannar bedded grainstones.

These skeletal grainstones are composed of red algae, *Marginopora sp.*, miliolids, *Kuphus incrassatus*, *Clipeaster sp*., large gastropod, and bivalve shells. They show low angle cross-stratification at the base and parallel laminations bedding at the top of the cross-bedded grainstone facies. Theses upper grainstone facies show abundant vuggy porosity. A thin clay layer separates each parasequence (Figure 3.5).

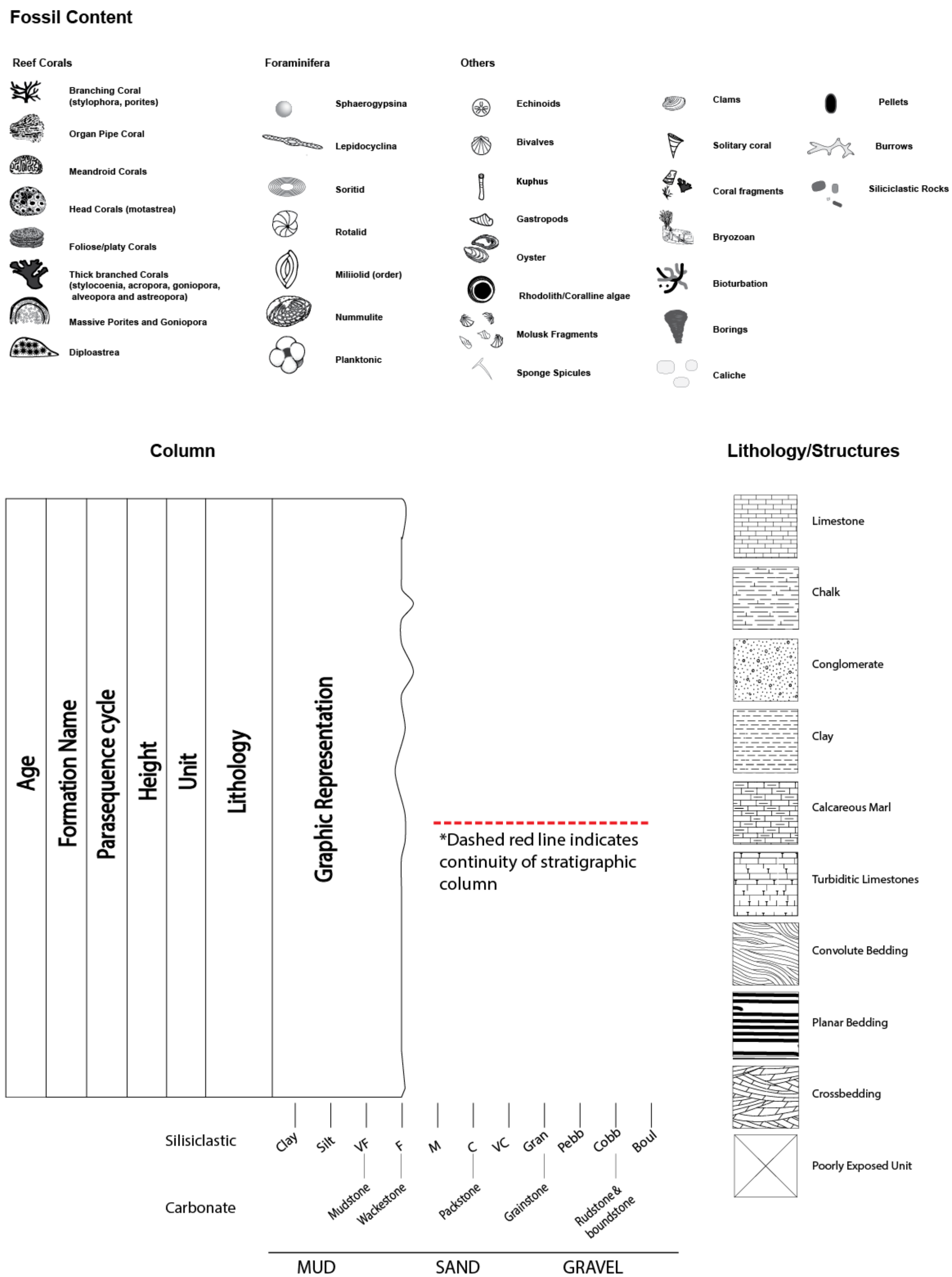

Figure 3.6: Legend for lithology, fossil content and texture of measured stratigraphic sections.

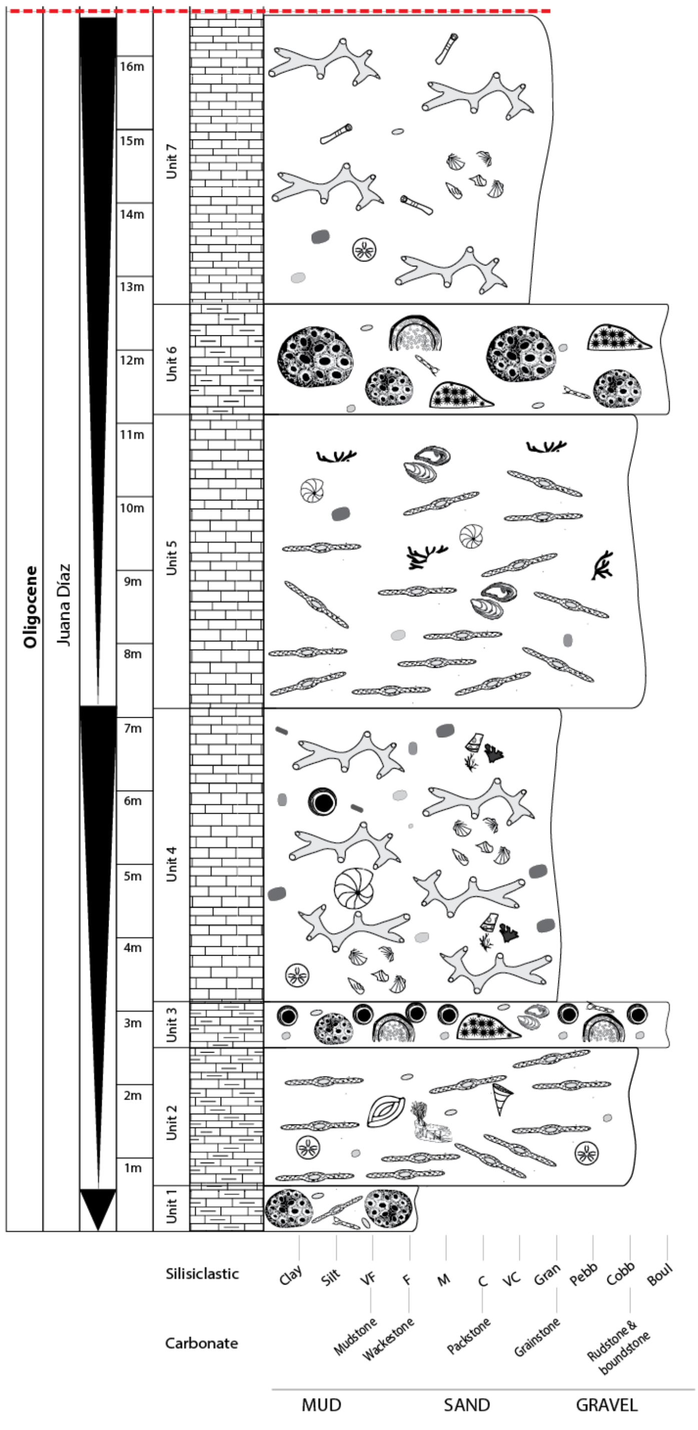

Figure 3.7: Stratigraphic section for the west side of Guánica Bay (from units 1 to 7).

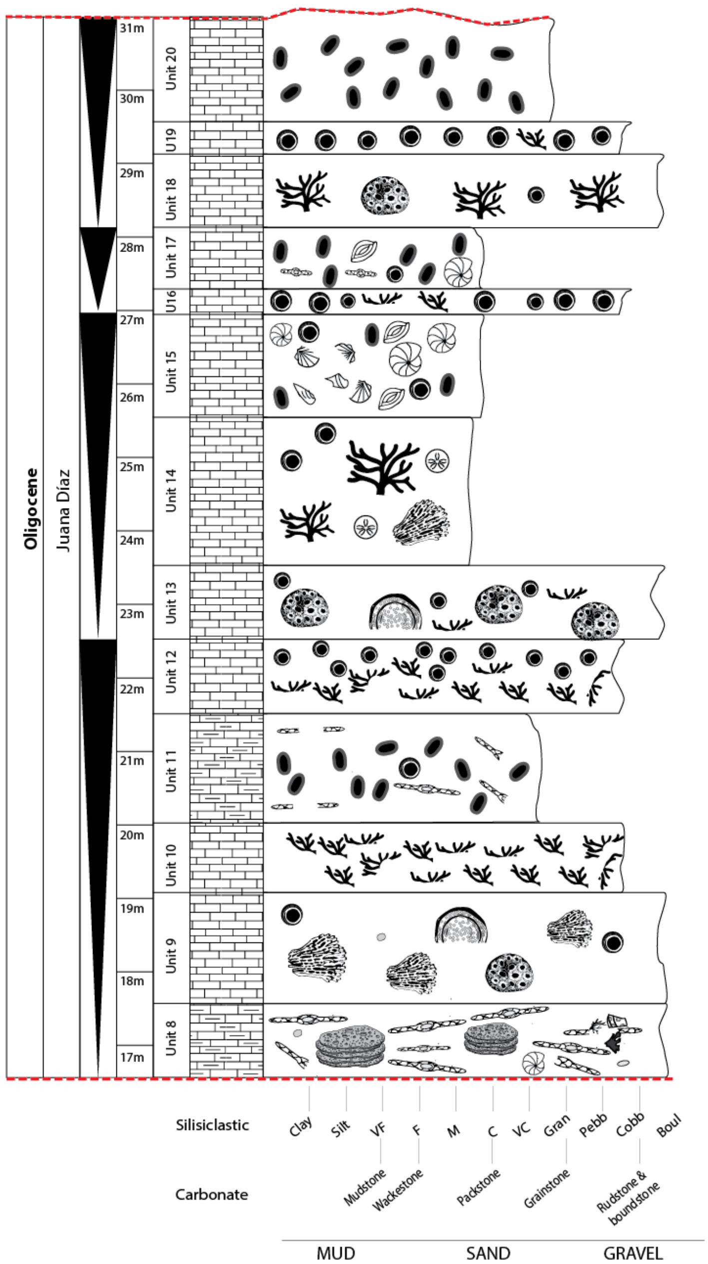

Figure 3.8: Stratigraphic section for the west side of Guánica Bay (from units 8 to 20).

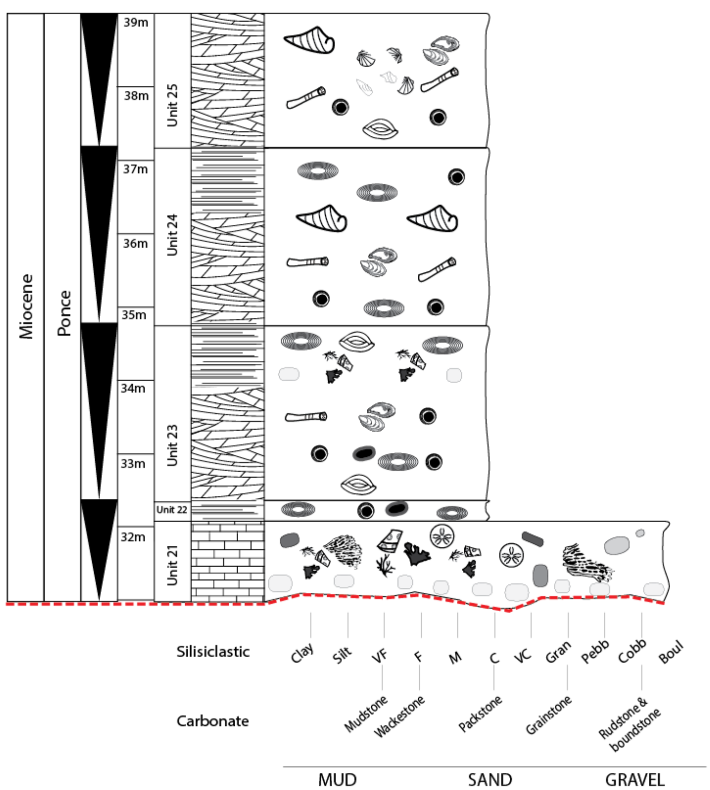

Figure 3.9: Stratigraphic section for the west side of Guánica Bay (from units 21 to 25).

3.1.2 Depositional Environment

The lower and middle parasequence sets portray two different reef cycles that adhere to the Oligocene reef facies model by Frost et al. (1983). These reef deposits are overlain by shallow-water, non-reefal marine deposits of the third parasequence set.

The depositional environments of the lower parasequence set are: fore reef, reef front, and inner shelf lagoonal environment, which are represented by the shallowing upward succession of *Lepidocyclina* rudstones, massive coral boundstones, red algal boundstones and peloidal grainstones at the top.

In the middle parasequence set, the same depositional environments are present, however, the fore reef environment progressively becomes missing. Also, in contrast with the lower parasequence set, lagoonal facies become much thinner than the reef front and reef crest environments.

In the top Parasequence set, the laminated grainstones on top of the cross-bedded grainstone facies indicate a transition between the shoreface and the foreshore in a beach environment (Scholle et al. 1983). The vuggy porosity in these parallel laminated grainstones (Figure 3.10) represents beach wave action, which is followed by thin paleosols that separate each grainstone unit representing exposure.

Figure 3.10. Slab of unit 23. Grainstone with vuggy porosity.

3.1.3 Sequence Stratigraphic interpretation

Each of the three previously mentioned parasequence sets (lower, middle and upper) was interpreted to represent a system tract or part of a system tract of two different depositional sequences.

The lower set of three parasequences represents a transgressive system tract (TST) since we can observe very thick parasequences becoming thinner as the system starts to prograde. However, the massive coral framestone facies do not show an extensive development, which is interpreted here to represent the difficulties of the reefs keeping up with the accelerated increase in the relative sea level rise. The maximum flooding surface is interpreted to be at the top of the third parasequence, from here, the thickness of the units that represent distal environments decrease and parasequences are represented by proximal environments.

The middle set of four parasequences is interpreted to be a high stand system tract (HST) as accommodation space is filled with shallow water deposits (Coe & Church, 2003) in which reefal productivity is higher. Another characteristic that support this interpretation is the parasequences fining upward due to progradation occurring during an HST. This parasequence set are composed mostly by reef front and crest separated by thin back reef deposits at the top of the parasequence.

The last four parasequences of the upper set are interpreted as a transgressive system tract, given that there are beach facies deposited over an unconformity and these parasequences show a constant and ample thickness of at least 2.5 meters in a shallow environment, which suggest retrogradation.

3.2 Guayanilla II and Santa Elena III

In the municipality of Guayanilla, the stratigraphic sections of Guayanilla II and Santa Elena III were measured (Figure3.11). The Guayanilla II section consists of 60m and it extends from coordinate 18° 1'59.75"N 66°47'41.04"W to 18° 1'55.44"N 66°47'37.49"W. The Santa Elena III section consists of 79m an it extends from coordinate 18° 1'42.16"N 66°47'13.60"W to 18° 1'35.97"N 66°47'8.85"W. These two outcrops are separated by the Santa Elena Housing development described by Frost et al. (1983).

Section 3.2.1 show descriptions of Guayanilla II stratigraphy, while section 3.2.2 presents a depositional environment interpretation, and section 3.1.3 a sequence stratigraphic interpretation. In the same order, section 3.2.5 describes the Santa Elena III stratigraphy, followed by a depositional environment interpretation in section 3.2.5, and finally a sequence stratigraphic interpretation in section 3.2.6.

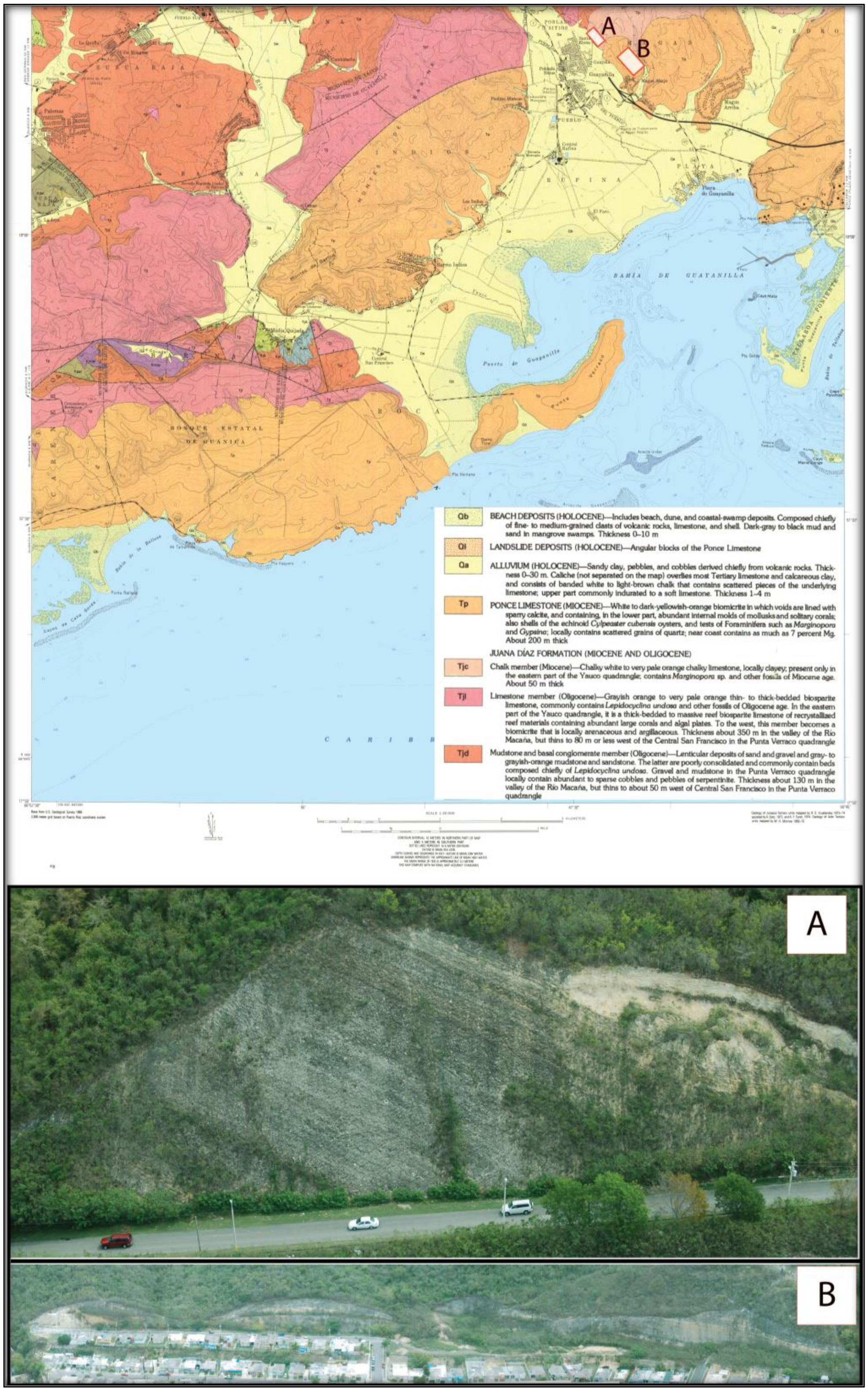

Figure 3.11: Geologic map of Yauco and Punta Verraco Quadrangles, Puerto Rico showing the locations of Guayanilla II (A) and Santa Elena III (B) (modified from Krushensky and Monroe, 1979). (Aerial photographs A and B taken by Dr. Santos.

3.2.1 Stratigraphic Description of Guayanilla II

A total of 21 units with a thickness of 60 meters was described in the Guayanilla II outcrop. These are interpreted here to represent seven parasequences. The first parasequence comprise the initial 20 meters in which skeletal and siliciclastic components are coarsening upwards with *Lepidocyclina* packstones and rudstones at the lower half of the parasequence. The upper half of this parasequence is composed of coral framestones with abundant mollusk and branching coral fragments. The top of this parasequence is represented by a conglomerate of silisiclastics, coral fragments and red algae. This conglomerate unit, with matrix containing clay, weathers more rapidly than the carbonates resulting in a recessive unit with abundant vegetation (Figure 3.12).

The second to sixth parasequences form a parasequence set which is composed of units 9 to 20, where parasequence 2 is represented by units 9 and 10, parasequence 3 by units 11 and 12, parasequence 4 by units 13 and 14, parasequence 5 by units 15 and 16, and parasequence 6 by units 17 to 20 (Figures 3.14, 3.15, and 3.16). Parasequences show a very similar facies pattern of repetition between coral framestone and coralline algae bindstones facies. In this section, siliciclastic components are decreasing progressively until they disappear in the sixth parasequence. Coral framestone and coralline algae bindstones facies alternations become thinner from units 17 to 20, therefore, the sixth parasequence might represent several small parasequences instead of one. The topmost unit of this parasequence is characterized by a foraminiferal grainstone that contains *Kuphus incrassatus* in growth position.

The seventh parasequence is on top of an exposure surface and is composed of *Lepidocyclina* rudstone facies with some overturned massive and platy corals at the top. This parasequence is composed of unit 21 (Figure 3.16). The rest of the outcrop is covered by heavy vegetation.

Figure 3.12: South facing Guayanilla II outcrop along Hwy. 132. Red arrow indicates vegetation line growing on lithoclast conglomerates.

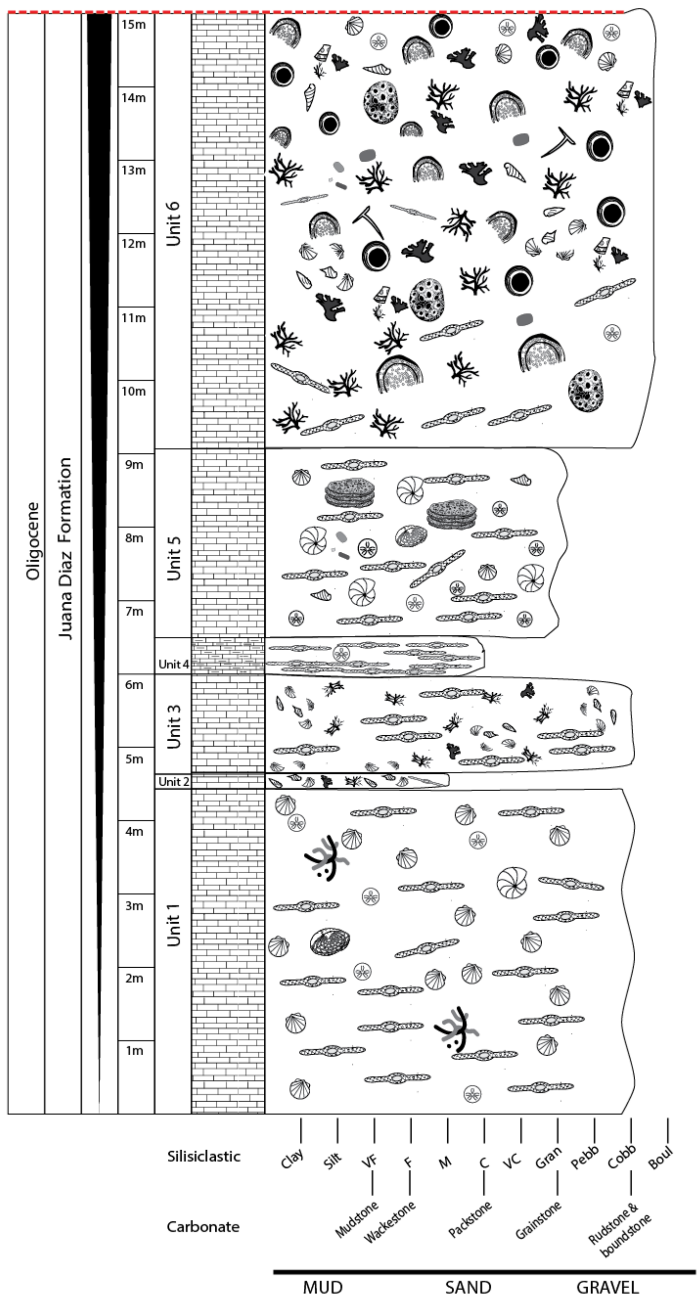

Figure 3.13: Stratigraphic section for Guayanilla II (from units 1 to 6).

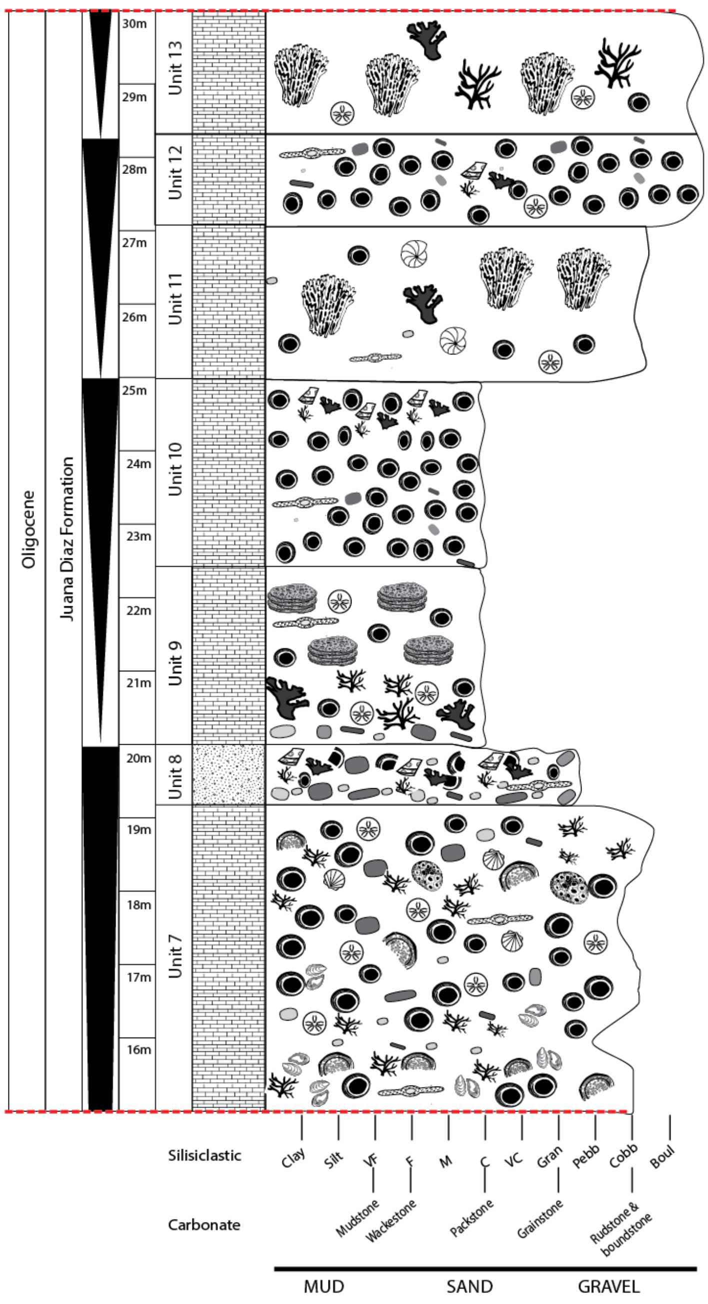

Figure 3.14: Stratigraphic section for Guayanilla II (from units 7 to 13).

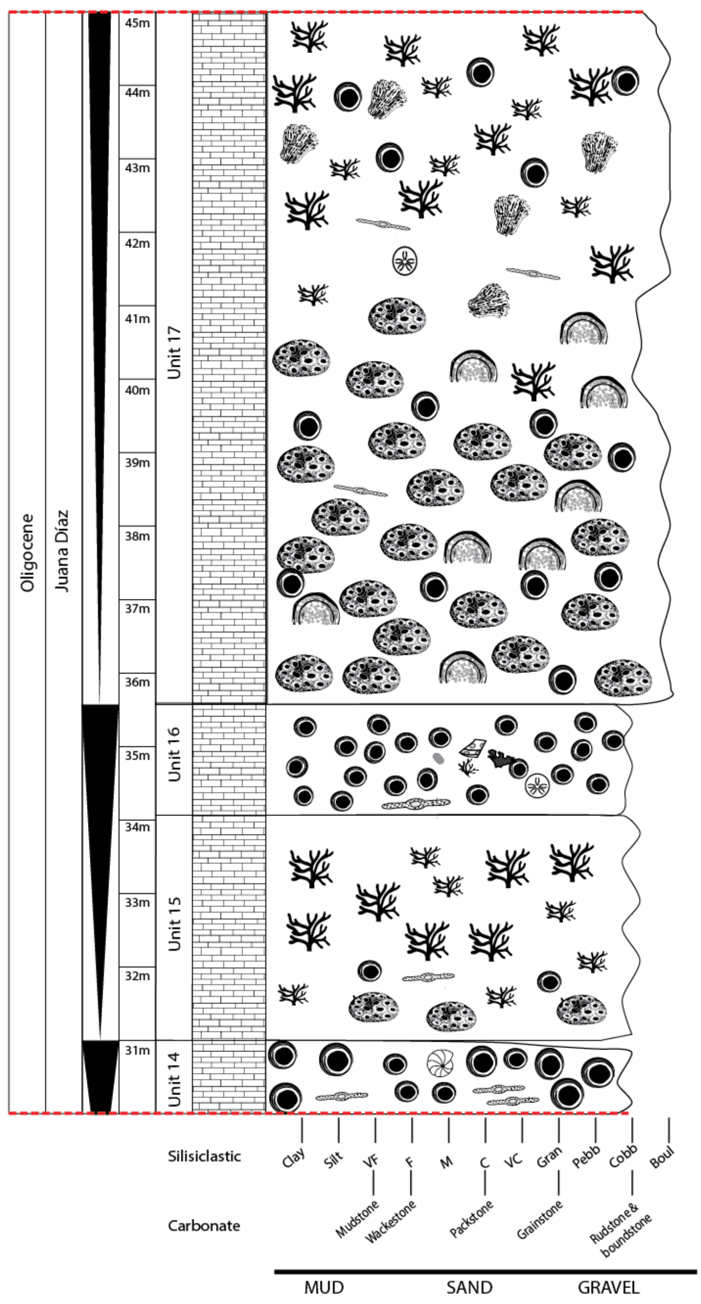

Figure 3.15: Stratigraphic section for Guayanilla II (from units 14 to 17).

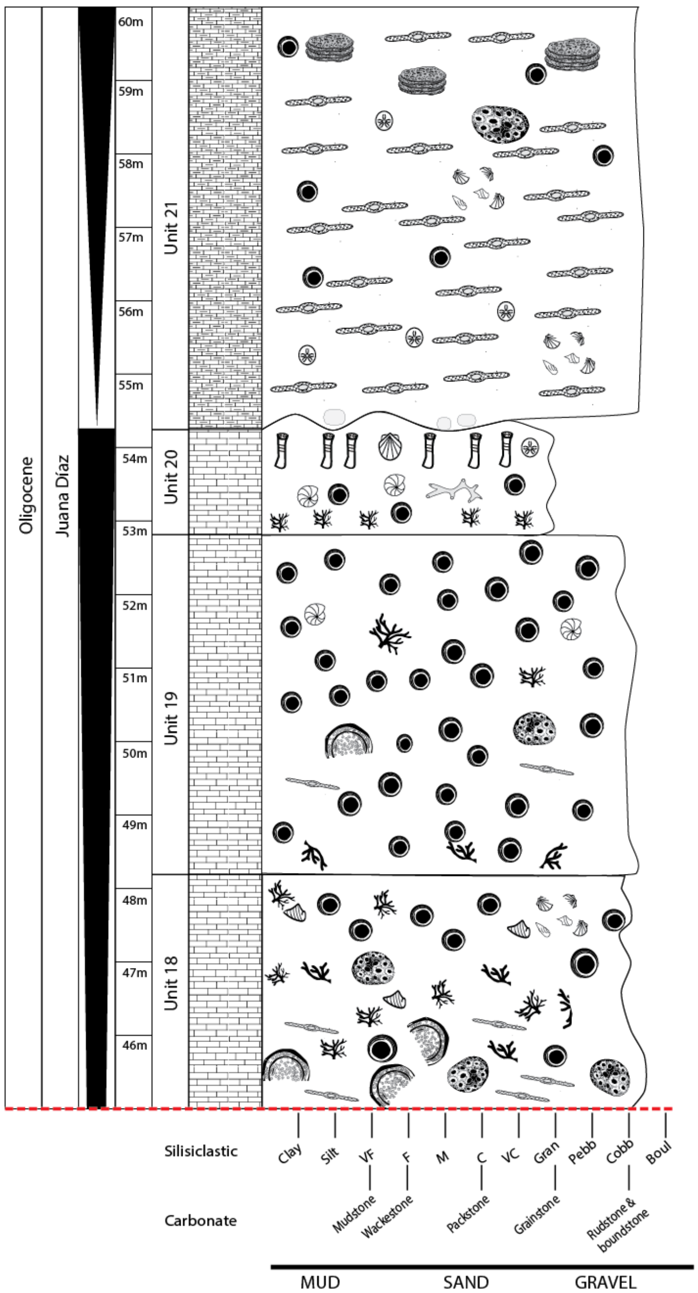

Figure 3.16: Stratigraphic section for Guayanilla II (from units 18 to 21).

3.2.2 Depositional Environment of Guayanilla II

The facies present in the first parasequence are interpreted to represent two main depositional environments; the fore-reef environment and rubble flat environment. The fore-reef environment is represented by the *Lepidocyclina* packstone and rudstone facies, and the rubble flat environment is represented by the coral rubble facies on top.

Coral framestones and rodolith bindsones that compose the second to sixth parasequence are interpreted to represent a cyclicity between reef front and reef crest environment. The sixth parasequence marks the end of the cycle, where a paleosol is on top of peloidal grainstones from the backreef environment.

The seventh (last) parasequence is part of a shallowing upward sequence which starts with deep fore-reef *Lepidocyclina* rudstone facies transitioning to a shallower part of the fore-reef with in-situ platy corals.

3.2.3 Sequence Stratigraphy of Guayanilla II

The first parasequence is interpreted here to represent a transgressive system tract (TST) in which a constant rise of sea level was creating more accommodation space than carbonate sediment production. The thickness of this parasequence is 20 meters. The maximum flooding surface is represented by a conglomerate unit at the top of the first parasequence. The conglomerate unit in top of the first parasequence is interpreted here to represent the maximum flooding surface. This conglomerate suggest that at this point the shoreline was at its maximum landward position and terrigenous sediments were increasing landwards to their source. Parasequences 2 to 6 are interpreted to represent a HST. It is composed by relatively thinner (3 to 5 meters thick) parasequences of framestone facies with corals in growth position from the second to sixth parasequence. The last parasequence show an abrupt facies change from proximal to distal. This is interpreted as a new depositional sequence that become progressively shallower and therefore is defined as a transgressive system tract (TST).

3.2.4 ***Stratigraphy of Santa Elena II***

This section of the Peñuelas - Guánica shelf reef complex is characterized by ten carbonate parasequences uncomformably overlying a white cream unit of planktonic foraminiferal chalk (Figure 3.17). The first parasequence is composed of unit 1, which is an eight-meter exposure that represents the continuation of the poorly exposed argillaceous chalk at the Santa Elena locality, described by Frost (1983) (Figure 3.18).

Each of the following nine parasequences is typically composed of three different units that progressively become more grain-supported (foraminiferal wackestones, packstones, and grainstones). *Kuphus Incrassatus* molluscs are commonly in growth position towards the top of the these soritid wackestone to packstone facies. The second to tenth parasequences which are unconformably on top of the foraminiferal chalk are composed of units 2 to 29, where parasequence 2 is represented by units 2 to 6, parasequence 3 by units 7 to 9, parasequence 4 by units 10 and 11, parasequence 5 by unit 12, parasequence 6 by units 13 to 15, parasequence 7 by units 16 to 19, parasequence 8 by units 20 to 23, parasequence 9 by units 24 to 26, and parasequence 10 by units 27 to 29 (Figures 3.18, 3.19, 3.20, 3.21 and 3.22). Planktonic foraminifers are found at the wackestone base of the last three parasequences. Unit 30 was described and sampled to determine if any evidence of a major depositional change occurred but it is very similar to the units of previous parasequences and not enough exposure is present to make any other interpretation.

Figure 3.17: Unconformity between planktonic chalk facies and coral rubble facies .

The units of first sequence are dipping at an angle of 28 degrees. Unit 13 at meter 14is composed of a creamy, white paleosol with nodular texture. After this paleosol, the remaining four parasequences are very consistent and exhibit dipping angles that range from 12° to an almost completely horizontal stratification. This clearly represent an angular unconformity between the Juana Diaz Formation and the Ponce Limestone.

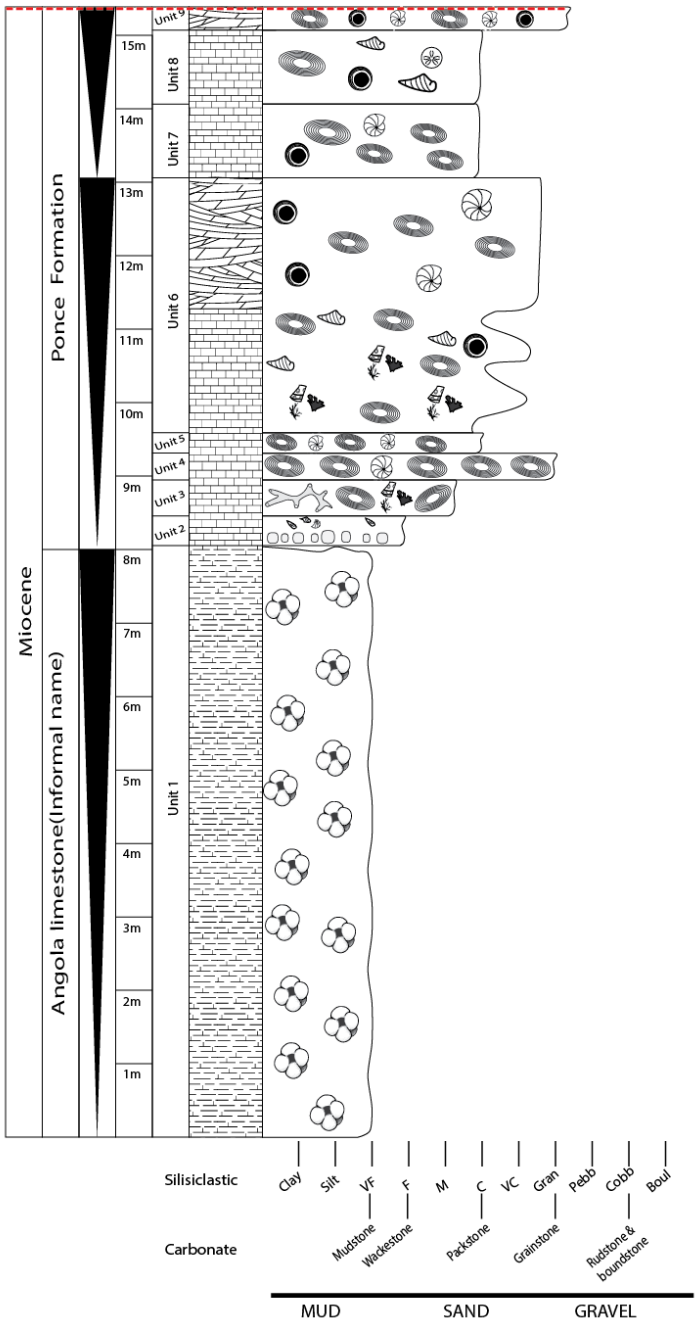

Figure 3.18: Stratigraphic section for Santa Elena III (from units 1 to 9).

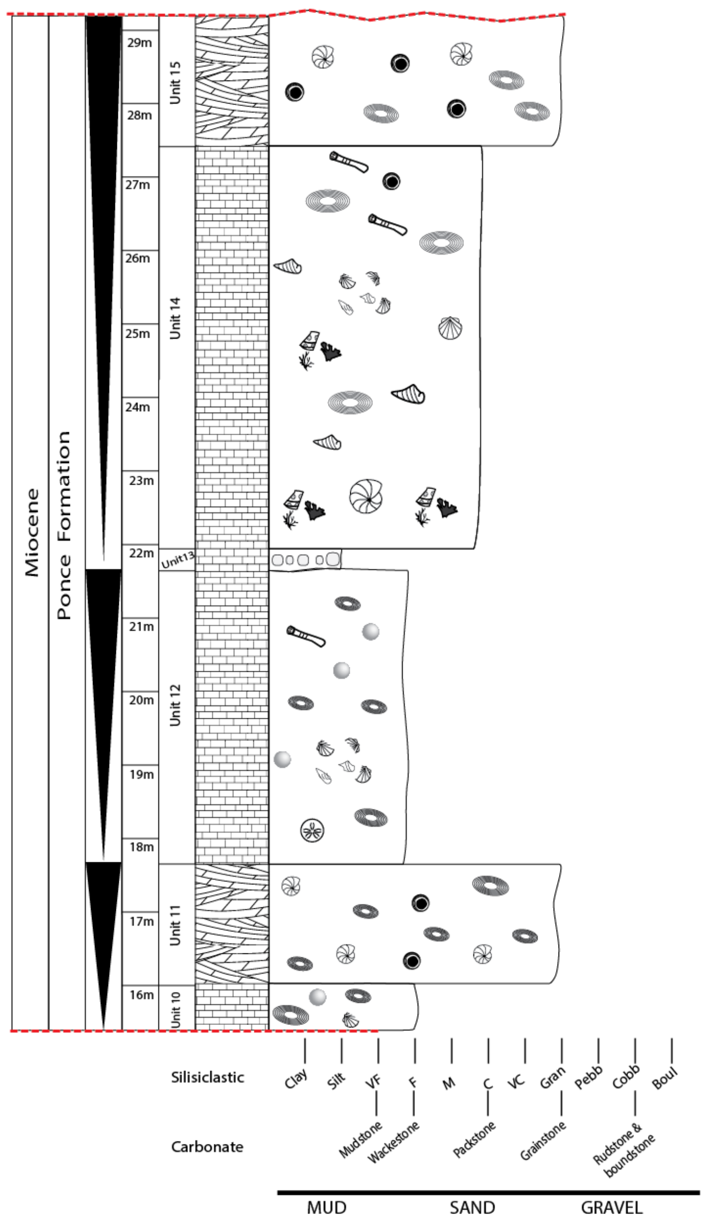

Figure 3.19: Stratigraphic section for Santa Elena III (from units 10 to 15).

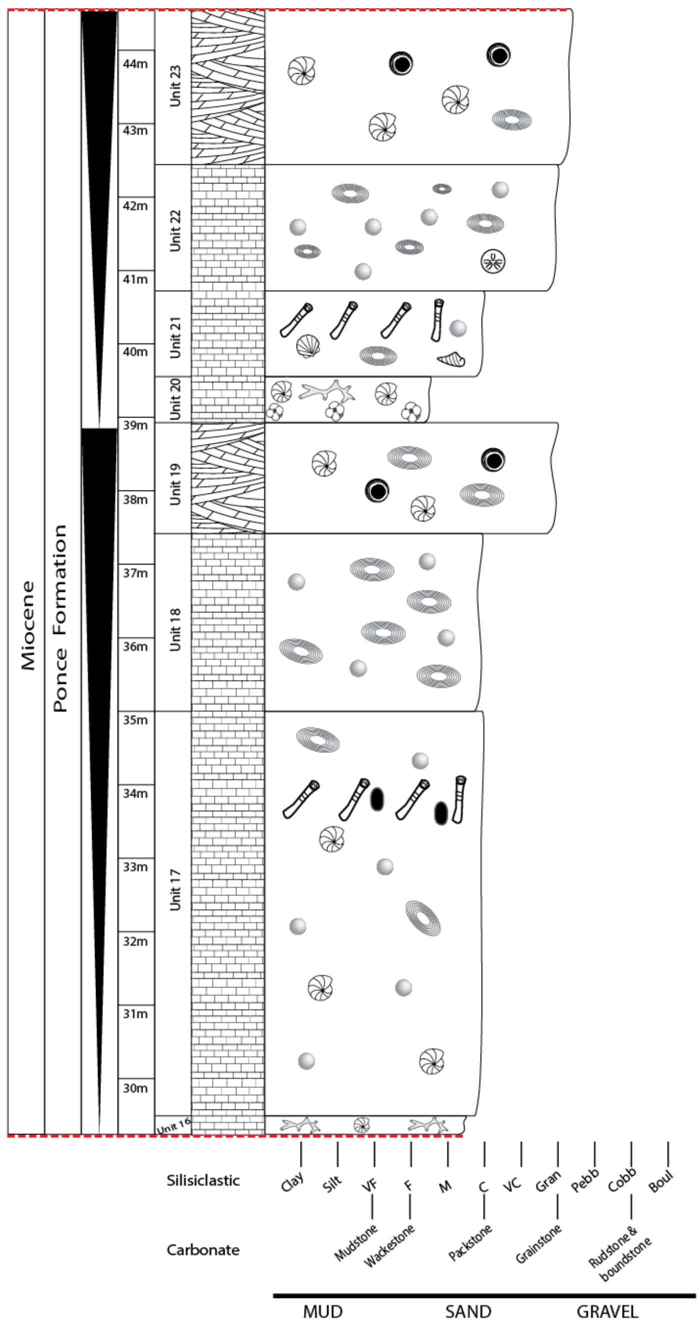

Figure 3.20: Stratigraphic section for Santa Elena III (from units 16 to 23).

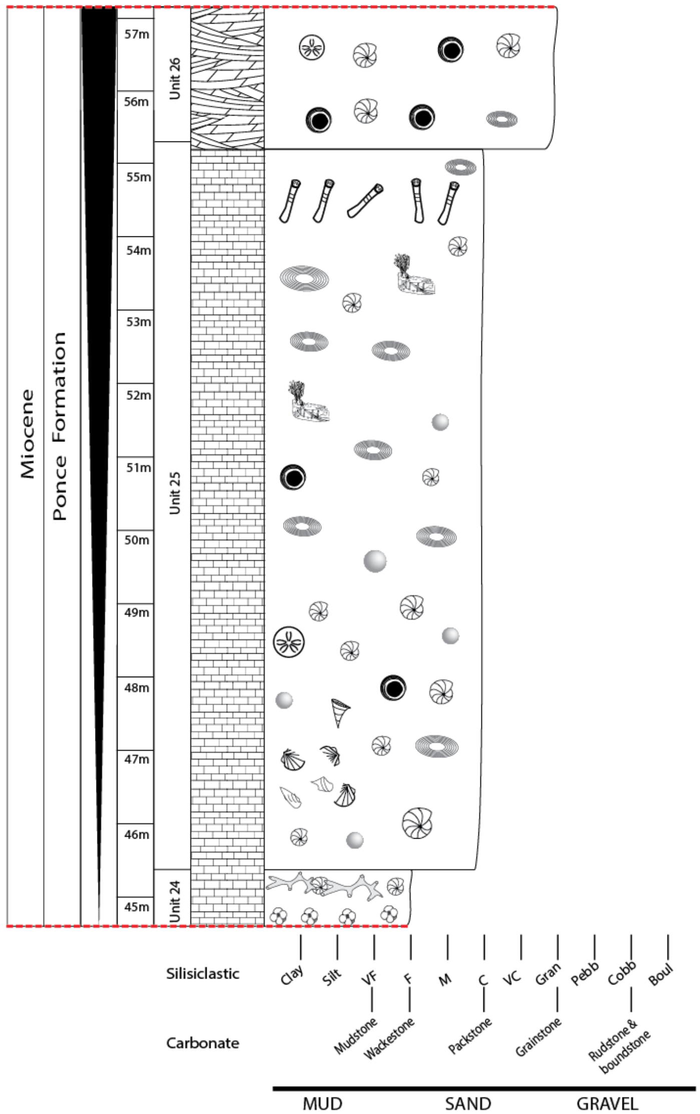

Figure 3.21: Stratigraphic section for Santa Elena III (from units 24 to 26).

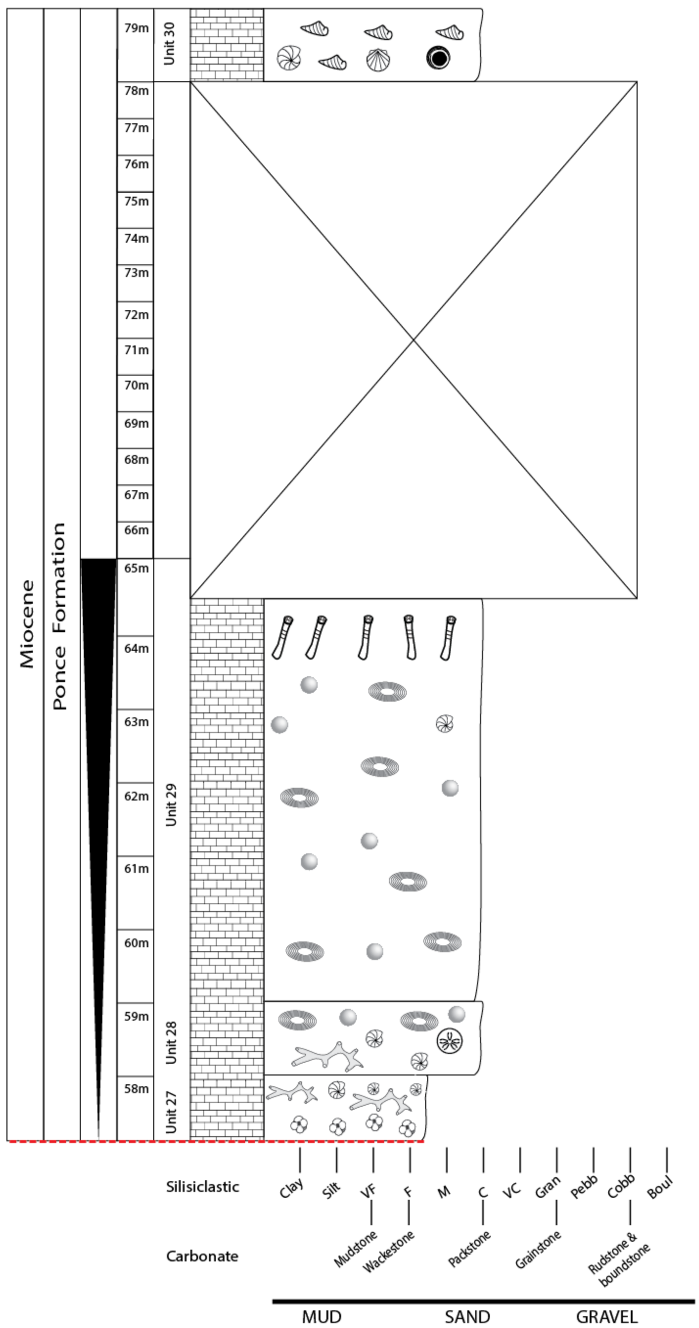

Figure 3.22: Stratigraphic section for Santa Elena III (from units 27 to 30).

3.2.5 Depositional Environment of Santa Elena III

The first parasequence was interpreted to be deposited in a mid-ramp to outer-ramp environment of planktonic foraminifera dominated deposits (Figure 3.23).

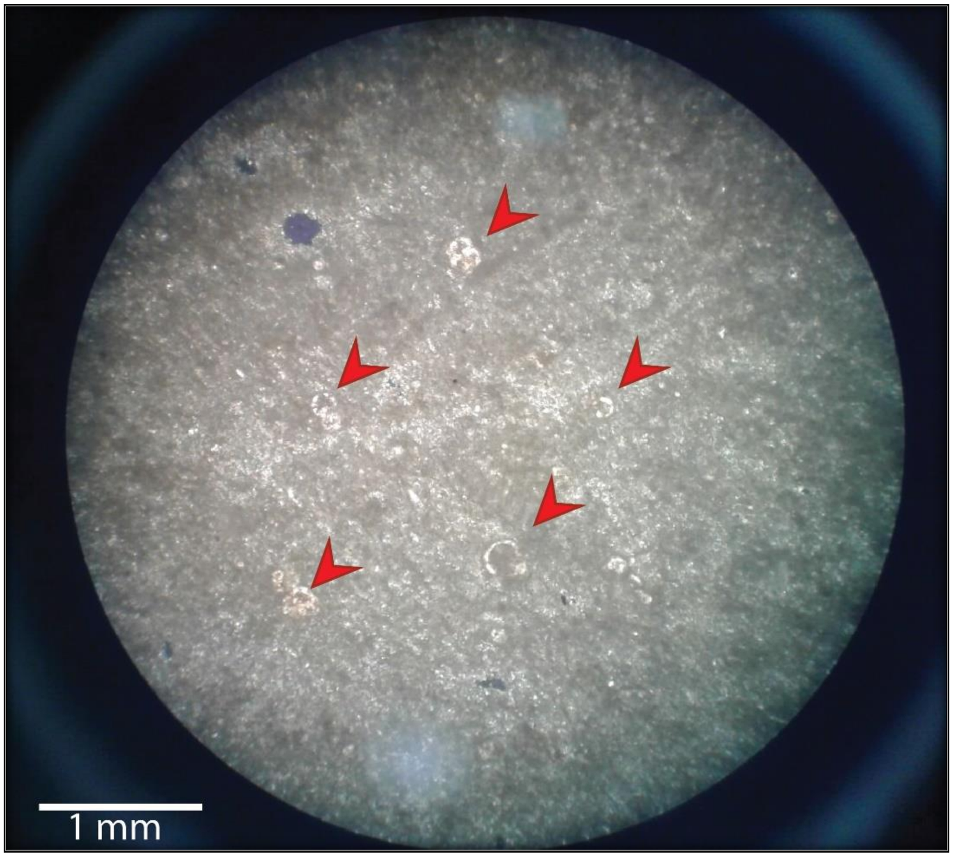

Figure 3.23: Planktonic foraminifers from the first parasequence of Santa Elena III, marked by red arrows.

Parasequences two to seven were interpreted to be deposited in a shallow inner ramp environment represented by soritid wackestone/packestone and cross-bedded grainstone successions with occasional storm deposits of coral rubble.

During the deposition of the last three parasequences, a rapid relative sea level rise extended the depositional environment range from inner to mid-ramp. These include planktonic wackestone facies at the base of each of the soritid wackestone/packestone and cross-bedded grainstone successions.

3.2.6 Sequence Stratigraphy of Santa Elena III

The first unit of the Santa Elena III stratigraphic section is composed of deep water planktonic facies of a transgressive systems tract (TST), on top of these planktonic chalks is an angular unconformity that represents a sequence boundary (SB) (Figure 3.17) with aggrading shallow water TST deposits. No evidence of a highstand systems tract (HST) was found between the two transgressions.

3.3 Facies Types

Below are listed the facies types found at measured stratigraphic sections of Guánica west, Guayanilla II, and Santa Elena III. These facies types were compared to Oligocene facies model of Frost et al. (1983) (Figure 2.3) and the foraminiferal distribution model of Hallock & Charlotte (1986) (Figure 2.4) to establish environmental interpretations.

Massive Coral Framestone. Corals in these facies are predominantly massive and in situ or in growth position. The matrix is usually a muddy packstone of mollusk fragments, encrusting coralline algae, echinoderms and few benthic foraminifers. Massive coral heads can be of up to 60 cm in diameter.

***Lepidocyclina* Packstone/Rudstone.** Packstones and Rudstones where *Lepidocyclina* sp. Is the main component with a muddy matrix. Echinoderm and mollusk fragments and other large benthic foraminifers such as *Amphistegina sp*. and miliolids are common in these facies. Platy corals might be present.

Bioturbated Grainstone. Although pellet abundance may vary in these facies, they always show characteristic thalassinoides type bioturbation. Grainstone constituents include fecal pellets, oysters, *Amphistegina sp*., gastropod fragments, echinoderm fragments, crustose coralline red algae and lithic clasts in some cases. Interparticle porosities are between 15% and 20%. Coralline algae tend to be more abundant towards the top.

Branching Coral Framestone. These facies are composed of *porites sp. and/or Caulastrea portoricencis.* colonies in a wackestone matrix of *Lepidociclyna* sp. fragments, *Amphistegina sp*., bivalve fragments, micritized peloids and coralline algae encrusting porites fingers.

Red Algal Boundtone. These facies occur as white layers of segmented and/or crustose red algae rhodoids.

Abraded Coral Floatstone. Coral rubble facies occur once, below the angular unconformity that separates shallow environment laminated grainstones. The matrix is a packstone with echinoid fragments, miliolids, caliche nodules and and cobble size lithoclasts. Corals are abraded and are on average 10 cm in diameter.

Plannar laminated/Cross bedded Grainstones. Skeletal grainstones are well sorted, often with vug porosity of about 20%.

Lithoclast conglomerate. Conglomerate of siliciclastic fragments, red algae with *Lepidocyclina sp.* Fragments.

Planktonic mudstones/wackestones. Light cream mudstone/wackestones coinsisting of globigerinids such as *globigerin*a *sp.*, *globorotalia sp.*, and *orbulina sp.*

Soritid wackestone to packstone. Foraminiferal wackestone/packstone of *Marginopora sp.* and or *Mioserites sp.* rotalids and Kuphus incrassatus are usually present at the top.

Coral Rubble facies. Coral framestones of abraded alloctonous reefal deposits.

CHAPTER 4 – DISCUSSION

A total of four depositional sequences were found in the west side of Guánica bay, Guayanilla II, Santa Elena, and Santa Elena III stratigraphic sections. This agrees with the results obtained by Ruidíaz (2013) for the east side of Guáncia bay. Ruidíaz (2013) identified four depositional sequences composed of both deep and shallow marine facies. Each one of the depositional sequences is described in the following sections and graphically represented with a fence diagram (Figure 4.1) for the different locations in which the depositional sequences are present.

Depositional Sequence 1

The transgressive systems tract (TST) and highstand system tract (HST) of the first depositional sequence were found at the localities of Guayanilla II and the east and west sides of the Guánica bay. In these three localities the TST is characterized by aggrading parasequences with siliciclastic input, however, because of the paleogeographic differences, the TST building facies vary at the three different locations.

At the stratigraphic sections of MQ Road (MQR) and Mosquito Trail of the east side of Guánica bay and Guayanilla II, the TST is characterized by aggrading parasequences of *Lepidocyclina* packstones/rudstone facies and coral boundstone facies (Ruidíaz, 2013), while at the west side of Guánica bay the parasequences consist of *Lepidocyclina* rudstone facies, coral framestones facies, and bioturbated grainstone facies representing deposition from forereef to back reef lagoonal environment. This suggest that during the marine transgression at Guánica bay, the west side was in a more landward position compared to the east side.

The HST is characterized at the west side of Guánica bay and Guayanilla II localities by prograding cycles of corals in growth position (coral framestone facies) and red algal bindstone facies. At the east and west sides of Guánica bay the HST also contains karst and terra rossa deposits in addition to the coralgal cycles. The HST at each of the three locations is topped by a sequence boundary (SB) is representing a subaerial exposure surface. The surface is identified by the presence of paleosol deposits containing reworked reef clasts and irregular erosional surfaces.

Depositional Sequence 2

The depositional sequence 2 was preserved only at the east side of Guánica bay and Guayanilla II**.** Meaning that it was eroded or wasn't deposited at the west side of Guánica bay because of its landward location.

At the east side of Guánica bay, the TST deposits are present at Upper Mosquito 3 and at Jaboncillo Road as proximal rubble flat deposits (Ruidíaz, 2013). Guayanilla II TST deposits range from fore-reef *Lepidocyclina* rudstone facies to reef-front branching coral framestone facies. Because poor esposure due to vegetation it is difficult to interpret a maximum flooding surface (MFS) or a HST for this depositional sequence.

Depositional Sequence 3

For the third depositional sequence a LST is represented by turbiditic deposits at the east side of Guánica bay on Jaboncillo Trail and Jaboncillo South sections of Ruidíaz (2013). The "New Formation" turbidites found at Santa Elena Section were also deposited during the LST of this depositional sequence in response to the carbonate platform shelf break development after deposition of the first two sequences at the east side of Guánica bay and the Guayanilla II locations.

TST deposits were found present at the lower part of Jaboncillo East section measured by Ruidíaz (2013) on the east side of Guánica bay and at the Santa Elena section of the Guayanilla municipality, measured by Frost (1983). These two sections showed abundant planktonic foraminifera content, which suggest a rapid rise in sea level. The 50-meter stratigraphic section measured by Frost et al. (1983) in Santa Elena represent an extensive deposition of pelagic material derived from a rapid marine transgression. As relative sea level kept rising, only calcareous mudstone deposits (chalks) would deposit on top of the “New Formation” rocks, resulting in what Moussa and Seiglie (1970) called the “Angola Limestone” which was assigned a lower Miocene age by biostratigraphic associations.

Depositional Sequence 4

Using chronostratigraphic Sr isotope analysis Ruidíaz (2013) confirmed that the base of the Ponce Limestone corresponds to a middle Miocene age. This formation represents the fourth (and last) transgression of the area of study. The Base of the Ponce Limestone is characterized by cross-bedded skeletal grainstone facies that are present at the Guánica bay east and west sides, and at the Santa Elena III location.

At the Santa Elena III stratigraphic section, the Ponce Limestone facies are sitting in an angular unconformity on top of a sequence boundary (irregular erosional contact) and an 8-meter unit corresponding to “Angola limestone”. *Globorotalia Kugleri* species from the Lower Miocene were found (Figure 4.2) which confirms the succession of Ponce Limestone.

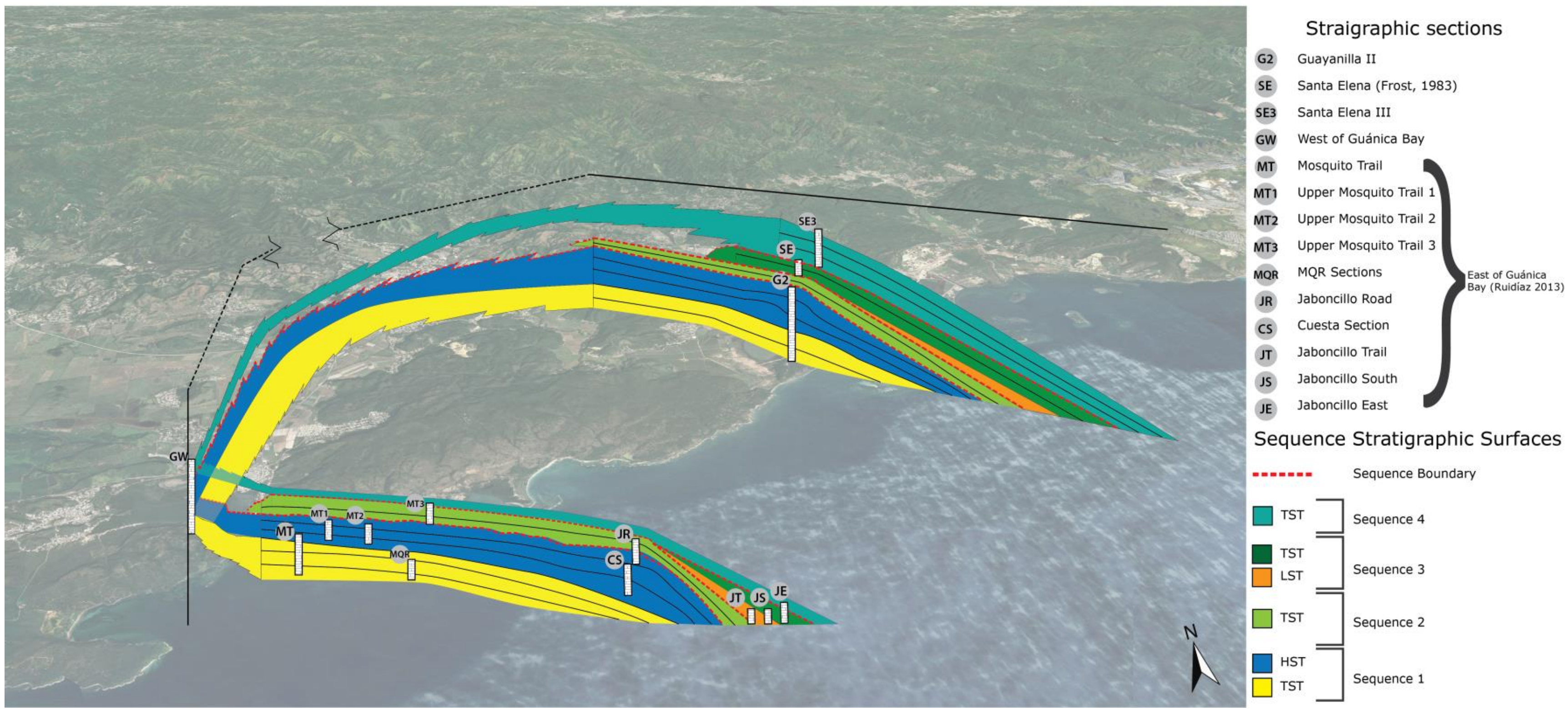

Figure 4.1: Schematic representation of sequence stratigraphic depositional sequences from Guánica bay to Guayanilla, P.R.

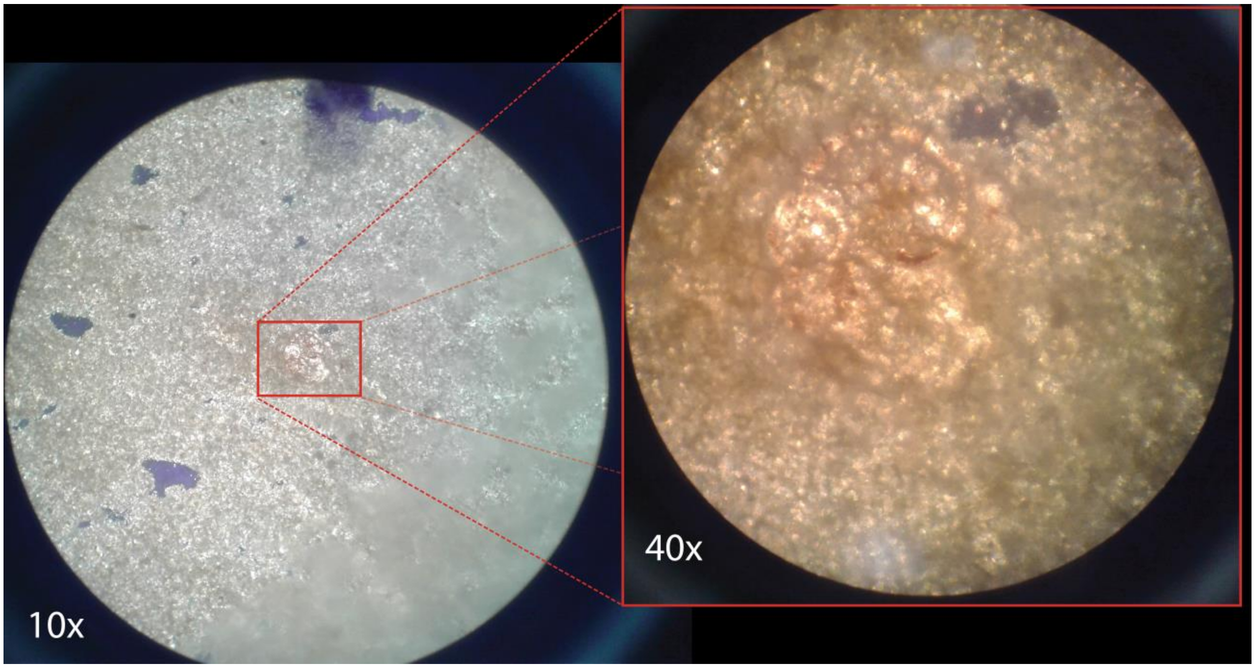

Figure 4.2: Images of planktonic foraminifera *Globorotalia kugleri* with 10x and 40x magnifications.

The Ponce formation was deposited during an ice house period; therefore, the amplitude of sea-level oscillations is larger in comparison to the Juana Díaz formations deposits (Miller et al., 2005) (Figure 4.3). Because of this, nine TST high amplitude aggrading parasequences were deposited at Santa Elena III where the majority of deposits represent shallow inner ramp facies, however, a continuous sea level rise during the marine transgression generated the deposition of deep water facies with every sea level increase in the last three parasequences. This ample transgression reached the more landward localities of Guánica bay east and west. The transgression deposited four parasequences at Guánica west and one at Guánica east.

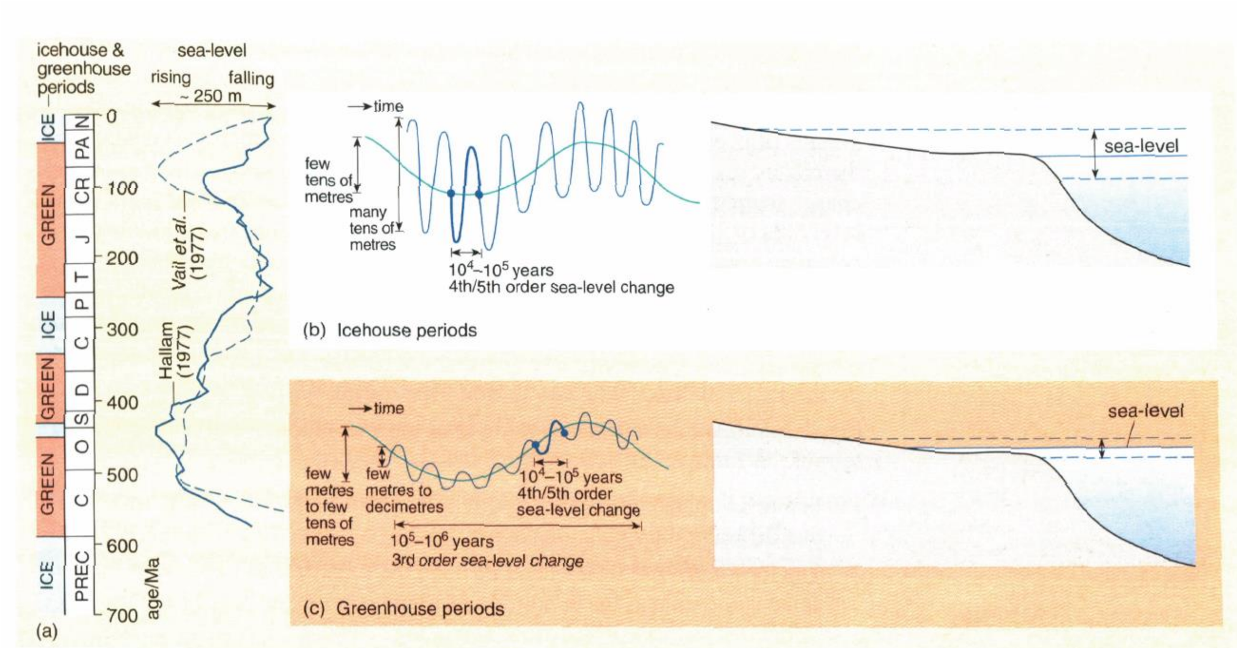

Figure 4.3: Eustatic sea-level amplitude differences between icehouse and greenhouse periods. (a) Greenhouse and icehouse periods throughout the geological time together with eustatic sea-level curve by Hallam and Vail et al. 1977. (b) Sea-level fluctuation amplitudes during icehouse periods (c) Sea-level fluctuations amplitude during greenhouse periods. (From Coe & Church, 2003)

CHAPTER 5 – CONCLUSION

Four depositional sequences and three major sequence boundaries were found from the west side of Guánica bay to the Santa Elena III housing development at Guayanilla, Puerto Rico. The first three depositional sequences belong to the Juana Díaz Formation, and the fourth to the Ponce Formation. The first three depositional sequences were deposited over Eocene volcano-sedimentary rock deposits formed after the termination of volcanism in Puerto Rico (Van Gestel et al. 1999). Therefore, there was siliciclastic input in the Juana Díaz Formation during marine transgressions in proximal areas of the carbonate platform.

Tectonic activity played an important role during the deposition of Juana Díaz and Ponce Limestone Formations at southwestern Puerto Rico, this can be reflected in figure 5.1 where depositional sequence 1 occurs during a major eustatic sea level drop during the Oligocene at around 31 Ma, suggesting that local tectonic influence was exceeding the eustatic fluctuations. Evidence for this mid-Oligocene transgression is the presence of the planktonic foraminifera *Globigerina ampliapertura* (Moussa and Seiglie,1970), and benthic foraminifera *Lepidociclyna undosa*, both characteristic from the mid-late Oligocene and abundant at the base of the Juana Díaz Formation (Banerjeeet al.,2000).

Another major feature caused by tectonic influence is observed at the west side of Guánica bay where the second and third depositional sequences are missing on the west side of the bay but not in the east side which might be caused by a tectonic deformational event during the Oligocene, prior to deposition of the Ponce Limestone. In the south part of the island a major angular unconformity is recognized between Oligocene and mid-Miocene limestone deposits. This angular unconformity is not recognized easily in the limestone formations of the north part of the island which is interpreted as a tectonic quiescence during the Oligocene and lower Miocene on the north of the island (Addarich.,2009). Rapid lateral changes in the south and observed faults within the Oligocene deposits suggest syndepositional events during the Oligocene of south Puerto Rico.

Facies analysis showed that the first three depositional sequences of the Juana Díaz Formation represent a mixed carbonate-siliciclastic platform, which agrees with the interpretations of Ruidíaz (2013) for southwestern Puerto Rico. The fourth depositional sequence of the Ponce formation represents a carbonate ramp. The transition from greenhouse to icehouse that took place from the Oligocene to Miocene is reflected in the systems tracts of the Juana Díaz and Ponce formation, showing more extensive deposition of Mid-Late Miocene deposits of the Ponce formation, compared to the Oligocene Juana Díaz deposits.

A comparison with the eustatic sea-level curve (Haq et al., 1987) was created from planktonic and benthic index fossil ages used in Frost et al. (1983) (Figure 5.1). Of the four proposed depositional sequences, the lower three do not agree with the eustatic sea level curve, while the upper one does agree. This suggest a regional northeastern Caribbean Sea-level curve due to local tectonics. During the Miocene the curve concide meaning that there was more tectonic stability.

Future work should focus on measuring detailed stratigraphic sequences in the municipalities of Peñuelas, Ponce, and Juana Días to expand this model and have a better understanding of the Ponce Formation depositional environments.

Another useful contribution would be obtaining more and better constrained Oligocene chronostratigraphic dates for a more detailed comparison of the Deposited Sequences with the eustatic sea level curve.

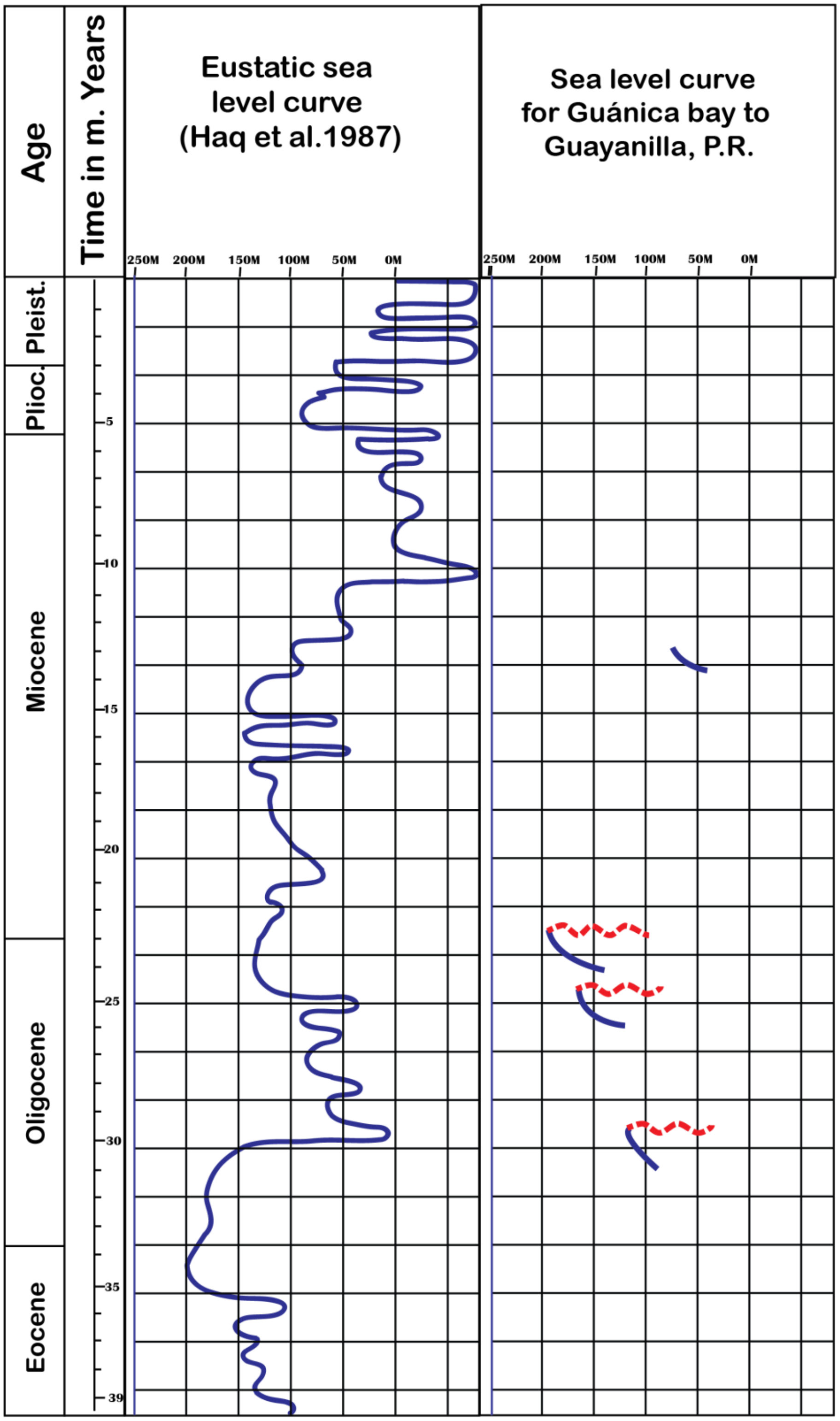

Figure 5.1: Comparison between eustatic sea level curve (Haq et al. 1987) and Guánica bay to Guayanilla P.R. depositional sequences. Estimations for depositional sequence ages were based on Moussa and Seiglie (1970) planktonic fauna correlations and Ruidíaz (2013) chronostratigraphic Sr-isotope analysis.

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APPENDIX I

Detailed Unit Descriptions

Guayanilla II

Unit 1 (4.4m)

Lepidocyclina rudstone with echinoids debris (1), *Amphistegina sp.* (1), bivalves (3) in a wackestone matrix with echinoderm fragments. Skeletal fragments show signs of bioturbation.

Unit 2 (.15m)

Lepidocyclina Wackstone to packstone with *Porites* and mollusk fragments.

Unit 3 (1.45m)

Lepidocyclina rudstone, mollusk (2), Porites and other branching corals mollusk fragments. Siliciclastic fragments are present.

Unit 4 (.5m)

Lepidocyclina packstone with echinoderm fragments. (Poorly consolidated)

Unit 5 (2.6m)

Lepidocyclina grainstone, skeletal grains mostly consisting in rotalids(4), red algae, mollusk and echinoids fragments(1), and platy corals in growth position.

Unit 6 (5.9m)

Coral framestone of branching and massive corals. Fragments of branching corals(2), mollusks and echinoderms(2). Fragments of pebble size siliciclastics are present.

Unit 7 (4.2m)

Boundsone of red algae and coral rubble. Fragments of branching corals(1), *lepidocyclina sp.*(1), mollusks and echinoderms(2) and siliciclastics(2).

Unit 8 (.8m)

Conglomerate of siliciclastics, coral fragments with a red algae bindstone matrix.

Unit 9 (2.5m)

Packstone of branching coral and mollusk fragments. Lithoclasts (2) are more abundant in the lower half of this unit. Rhodoliths and echinoderm fragments and platy corals are common towards the top.

Unit 10 (2.5m)

Coralline algal bindstone. The last meter of this unit has many coral fragments in a bindstone matrix. siliciclasts are present.

Unit 11 (2m)

Branching coral framestone with abundant *Caulastrea portoricoencis* and *Stylocoenia sp.* Most of the corals appear in growth position. Small *Lepidocyclina sp., echinoderm fragments*, and rotalids are common in the packstone matrix.

Unit 12 (1.2m)

Cooralline algal bindstone. Echinoderm fragments and siliciclastics present.

Unit 13 (1.8m)

Coral framestone of *caulastrea portoricoencis* (3) and *Porites sp.* (2).

Acropora sp. (2) is at the top of this unit. Echinoderms are common.

Unit 14 (1m)

Coralline algal bindstone. Small *Lepidocyclina sp.* (2) and Amphistegina (1) in matrix.

Unit 15 (3m)

Branching coral framestone. Massive corals (*Astreopora sp.*) are present at the base of this unit. No siliciclastics visible.

Unit16 (1.6m)

Coralline algal bindstone.

Unit 17 (4.4m)

Massive and branching coral framestone. From meter 40.5 to the top of this unit, rhodoliths, Caulastrea portoricoensis and other branching corals become more abundant. Gastropods are present.

Unit 18 (3.2m)

Rudstone of coral fragments. Fragments are mostly from branching corals although overturned massive coral heads are present.

Unit 19 (4.6)

Coralline algal bindstone. *Porites sp.* fragments (2) are at the base.

Unit 20 (1.5m)

Foraminiferal grainstone consisting of rotalids (3), mollusk fragments encrusting red algae (2), echinoderms (2) small *lepidocyclina sp.*(1), and at the top of this unit, *Kuphus sp.*(4) in growth position. Borrows present also at the top.

Unit 21 (5.7m)

Lepidocyclina rudstone on top of an unconformity. The base of this unit is very weathered. The matrix is clayey and contains red algae (2) and echinoderm fragments (1). At the top of the unit recrystallized Platy (2) and massive (1) corals are found, most of them in an overturned position.

Santa Elena III

Unit 1 (8m)

White to cream argillaceous chalk (calcimudstone) with few and not very sharp stratifications that form an angular uncomformity with unit 2. The great majority of recognizable foraminifers consist of globigerinids such as *globigerin*a *sp.*, *globorotalia sp.,* and *orbulina sp.*

Unit 2 (0.91m)

Wackestone of brecciated corals and bivalve fragments (1) with scattered caliche nodules (2) that become less abundant towards the top. A red thin clay layer is visible on top of this unit.

Unit 3 (1m)

Borrowed Wackestone to packstone of brecciated corals including porites sp, soritids, gastropod, echinoderm, and bivalve fragments. Large Foraminiferal components becomes more abundant (2) gradually towards the top of this unit. moldic porosity is visible on hand samples.

Unit 4 (.61m)

Large blocks of well sorted foraminiferal grainstone within alternating with foraminiferal wackestones. The grainstone sections exhibit fenestral porosity.

Unit 5 (.40m)

Soritid packstone. Skeletal components show an imbricated accommodation.

Unit 6 (3.50m)

Grainstone-packstone alternations with coral rubble (3), soritids (2) gastropods (2), non-in situ kuphus (2), red algae (1) with a 30% interparticle porosity. Laminated grainstone blocks from meter 11.5 to 13.

Unit 7 (.61m)

Soritid Packstone. The majority of skeletal components (soritids) are less then 1.5cm in diameter components are Red **algae** (1).

Unit 8 (3m)

Heavily recrystalized porous packstone coinsisting of mostly benthic organism fragments such as gastropods (2), echinoderms (1), Red algae (2), and large benthic forams (2). This unit has an interparticle porosity of 30-35%.

Unit 9 (0.3m)

Laminated foraminiferal grainstone with fenestral porosity.

Unit 10 (1.3m)

Foraminiferal wackestone of soritids and *Sphaerogyspsina sp. Pecten* fragments are present.

Unit 11 (1.80m)

Laminated foraminiferal grainstone with fenestral porosity.

Unit 12 (4m)

Very recrystalized packstone unit. coinsisting of broken shells of *Sphaerogyspsina sp.* (2), *kuphus incrassatus* (1), Clipeaster sp., soritids. (1), And other bivalves.

Untit 13 (.30m)

Creamy white paleosol with a nodular texture. Nodules range from 1.5 -to 2.5 mm in diameter.

Unit 14 (5.5m)

Massive benthic foraminiferal Packstone containing coral rubble, *Sphaerogyspsina sp.* (2), solitary corals (2), gastropods (2), bivalves (1). Echinoderm and *Flabellum sp*. fragments at its base. At the top of this unit large pieces of non-in situ *Kuphus incrassatus* (2) are present and soritids (3). Becomes more abundant.

Unit 15 (1.8m)

Very fine grained laminated red grainstone. Diagenesis/ grain size makes its components very hard to identify.

Unit 16 (0.30m)

Borrowed foraminiferal wackstone to packstone on an irregular contact with the red grainstone below.

Unit 17 (5.5m)

Foraminiferal packstone of *Gypsina sp. (3), Amphistegina sp. (2) marginopora sp. (1)* With *Kuphus incrassatus* (3) in situ and complete skeletons of *Clipeaster sp. Abundant fecal pellets are visible near the Kuphus incrassatus shells.*

Unit 18 (2.45m)

Foraminiferal Packstone of soritids (4) And *Gypsina sp. (3).*

Unit 19 (1.5m)

Laminated grainstone. Grains are rounded and well sorted.

Unit 20 (0.61m)

Wackestone with abundant globigerinids at the base of the unit. *Thalassionoides* type bioturbation increasing toward the top of the unit. Skeletal components include *Amphistegyna sp. (3)* small bivalve fragments, *Sphaerogypsina sp*. (1).

Unit 21 (1.2m)

Wackestone to packstone of: kuphus3, bivalves 2, clam casts and gastropods 1.

Unit 22 (1.7m)

Foraminiferal packstone of miocerites (3), *Sphaerogyspsina sp.*(2). echinoderm spines present.

Unit 23 (2.13m)

Red stained Laminated grainstone alternating with yellowish grainstone sections.

Unit 24 (1m)

Amphistegina sp. wackestone with abundant globigerinids at the base of the unit. *Thalassionoides* type bioturbation intensifies towards the top of the unit. Skeletal components include *Amphistegyna sp. (3)* small bivalve fragments, *Sphaerogyspsina sp.*, red algae, and dasycladean green algae are present.

Unit 25 (10m)

A.

Packstone of *Amphistegina sp.*(4), bivalve fragments (2), *Gypsina sp.* (2),echinoid fragments (1), Red algae (3), solitary corals (1), *kuphus incrassatus* layers at 1 and 4m with 30% of them in growth position and gastropod casts.

B.

Packstone of *Marginopora sp*. (2), *Sphaeroypsina sp.* (2) and *Amphistegina sp (2). Bryozoans* (2) are present. another kuphus layer occurs at the very top with 65% of them in growth position.

Unit 26 (1.9m)

Laminated grainstone of *amphistegina sp.* and marginopora *sp.* fragmens are recognizable in thin section.

Unit 27 (0.8m)

Ampistegina wackestone with *thalassionoides* type bioturbation. Echinoderm fragments present

Unit 28 (1m)

Foraminiferal Wackestone with *thalassionoides* type bioturbation.

Unit 29 (5.5m)

Packstone of Marginopora sp. (2), Gypsina sp. (2) and amphistegina sp (1).

The layer of *Kuphus inctrassatus* at the top of this unit have the biggest growth position percentage (80%) in the outcrop.

Unit 30 (1 m)

Gastropod dominated packstone with bivalves red, algae, echinoderms. Soritids are present.

Guánica West

Unit 1 (0.7m)

Mudstone to wackestone with *Antiguastrea celulosa* coral heads of 20 to 60 cm in growth position. Crustose algae are abundant at the top of this unit.

Unit 2 (1.7m)

Lepidocyclina sp. rudstone with a marl matrix with graded bedded skeletal grains. Coral heads become present toward the top of the unit, most of them upside down. *Amphistegina sp.*, echinoderm spines, bryozoans, and lithic fragments are present.

Unit 3 (0.7m)

Framestone of coral heads in growth position, big oyster shells are present. A rodolith layer of 0.2 m is at top of the unit.

Unit 4 (4m)

Borrowed packstone with thalassinoides type bioturbation and abundant fecal pellets. Pebble size volcanic clasts are at the base of the unit. Skeletal fragments include gastropods, bivalves, echinoderms, and rhodolits (2). Solitary corals, *Porites sp.* oyster Fragments of are present.

Unit 5 (4m)

Lepidocyclina sp. Rudstone with a marl matrix. *Amphstegina sp.* and echinoderm fragments are common. 85% of skeletal components are broken. Oyster fragments are present at the top.

Unit 6 (1.5m)

Framestone of Massive corals heads in growth position with a poorly consolidated clayey matrix. *Goniopora hilli(3) Porites panamensis*(1) are in growth position.

Unit 7 (4m)

Burrowed peloidal packstone with *Kuphus incrassatus, Lepidocyclina sp.*, oysters (1) and gastropods (2) fragments. Small lithic clasts are present(1).

Unit 8 (1m)

Rudstone of *Lepidocyclina sp., Soritids, Agaricia agaricites platy coral* and small porites fragments. Small lithic clasts are present (1).

Unit 9 (1.5m)

Coral Framestone. “organ pipe coral” *Caulastrea portoricencis* found in growth position in clayey matrix. Red algae abundance of (1)

Unit 10 (.9m)

Porites Rudstone. Porites sp. are in a wackestone matrix of *Amphistegina sp.(1)* and *Lepidocyclina sp*,(2), and micritized peloids(2) are.

Unit 11 (1.5m)

Peloidal grainstone of *Lepidociclyna sp.* (2), *Amphistegina sp.* (1), and red algae (1). Components including porites sp. and echinoderm fragments are broken and present a pink coloration.

Unit 12 (1m)

Porites Rudstone. Porites sp. are in a wackestone matrx. *Lepidocyclina sp,(2) fragments* are present. This unit matrix and skeletal components show a distinctive pink coloration due to subaerial exposure. Red algae are very abundant at the very top of this unit.

Unit 13 (1m)

Heavily recristalized framestone of massive corals, 70% of them in growth position. Porites Fragments present.

Unit 14 (2.1m)

Wackestone to packstone with massive corals, *Caulastrea portoricencis (2), porites sp.* (3) covered by crustose algae. echinoderm spines and Operculinodes foraminifers are present. Very alerted accumulations of pink *porites sp.* at the base of the unit.

Unit 15 (1.3m)

Peloidal packstone of Operculinodes (2) gastropod fragments (2), Red algae (2) and miliolids (2) with sparry calcite cement.

Unit 16 (.4m)

Rodolith bindstone. Echinoderm fragments and gastropods are present.

Unit 17 (1m)

Foraminiferal packstone of Operculinodes (2), miliolids (3) and small lepidocyclinas (1). Red algae and echinoderms are present.

Unit 18 (1m)

Karstified coral famestone of massive and branching porites sp. And other massive corals.

Unit 19 (0.2m)

bindstone of branching crustose coralline red algae.

Unit 20 (1.4m)

Peloidal grainstone. Porosity of 20%

Unit 21 (1.2m)

Coral rubble floatstone in a packstone matrix with echinoid fragments, caliche nodules and miliolids. Corals are abraded and are on average 10 cm in diameter.

Unit 22 (1.7m)

Skeletal Grainstone of red algae (2) *Marginopora sp.* (2). Caliche surface is at the base with rounded coral cobbles, then plannar bedding (at 1.7m), then cross bedded stratification (at 2.8m). large gastropods are present at the top of this unit. Kuphus incrassatus (2)

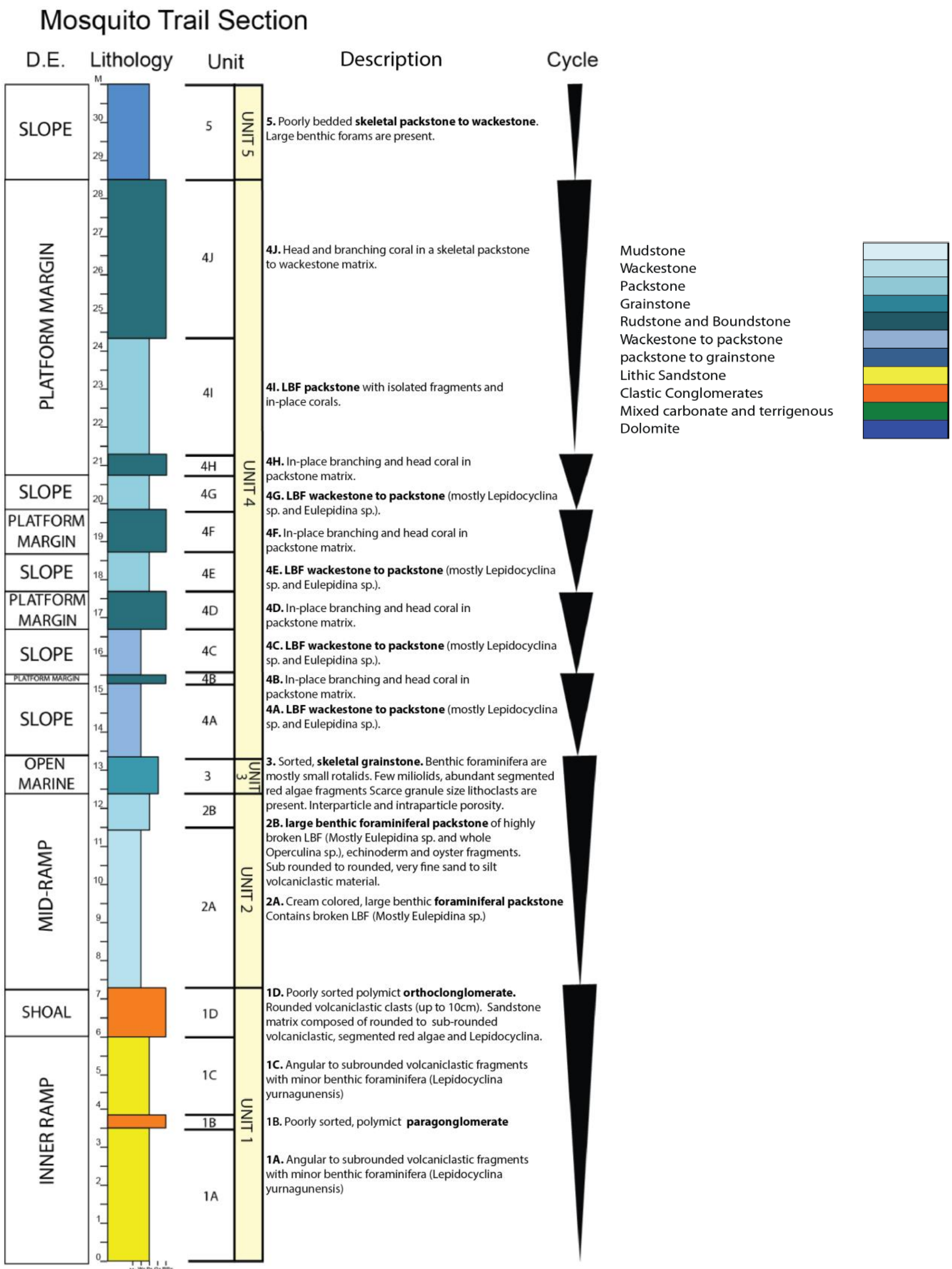
Unit 23 (2.8m)

Skeletal Grainstone with low angle cross beds at the base and plannar laminations at the top with with vuggy porosity, caliche surface at base.

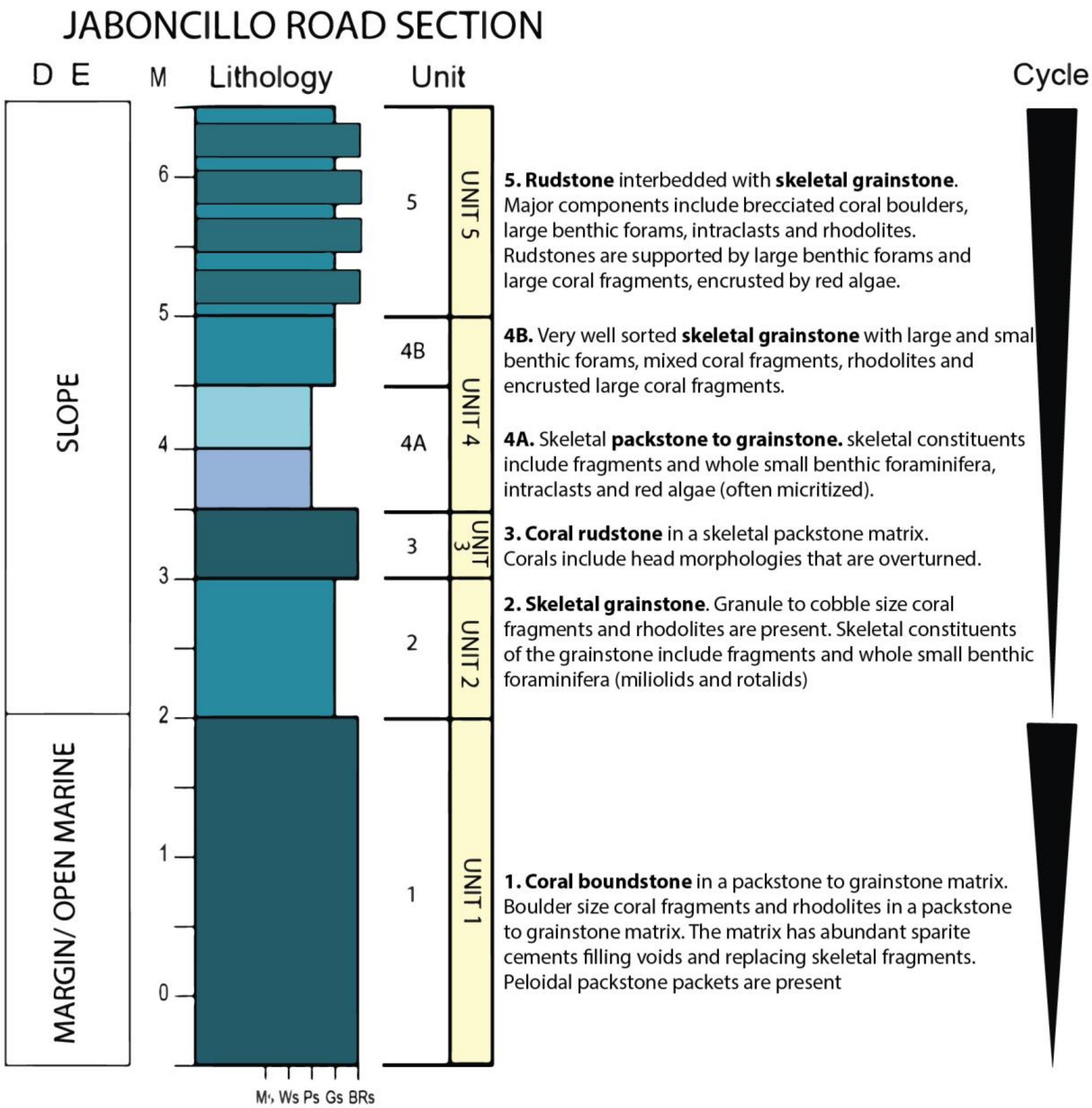
Unit 24 (2m)

with low angle cross beds at the base and plannar laminations at the top with with vuggy porosity, caliche surface at base.

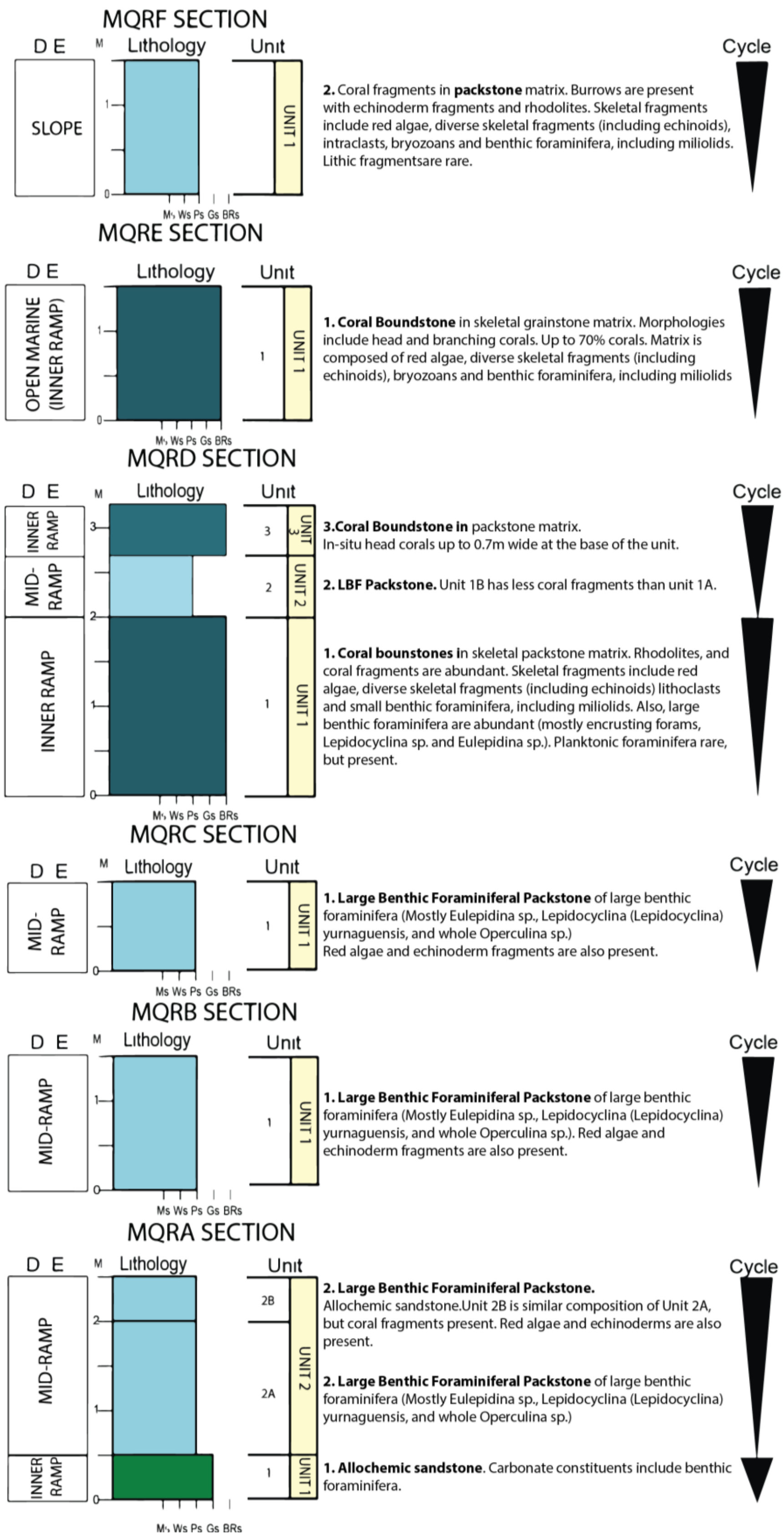
APPENDIX II



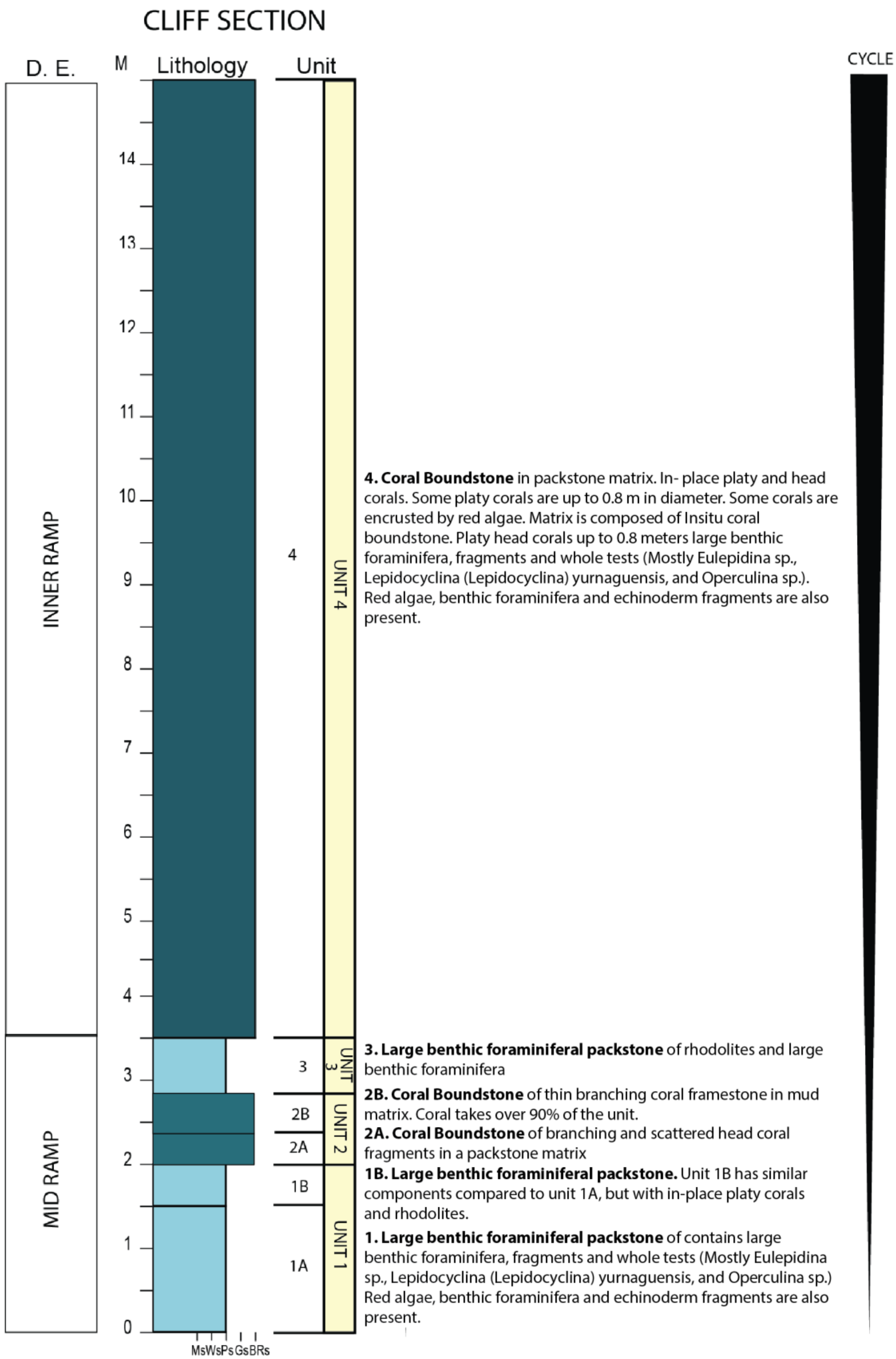
Stratigraphic Section for Lower Mosquito Trail (Modified form Ruidíaz., 2013)



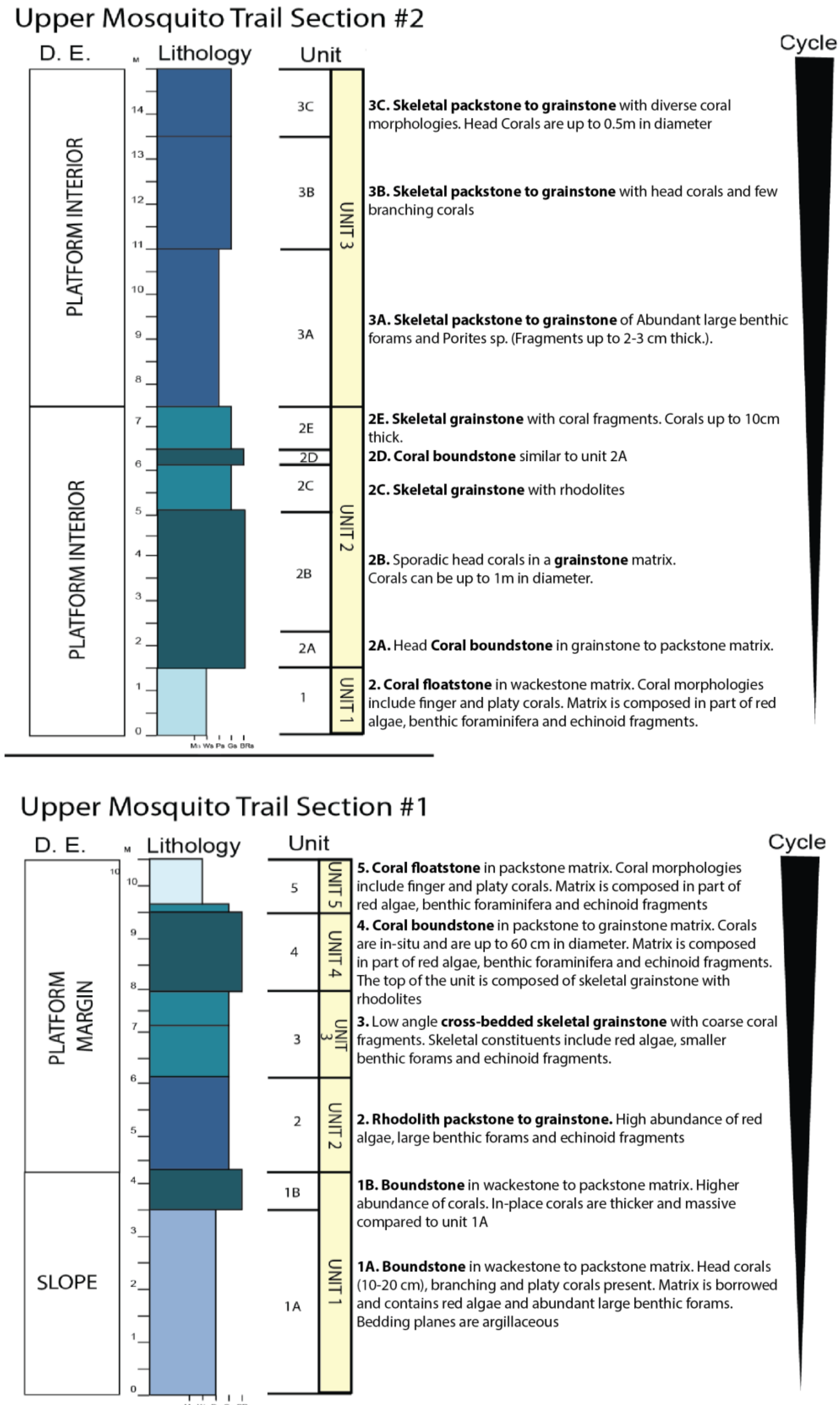
Stratigraphic Section for Jaboncillo Road (Modified form Ruidíaz., 2013)



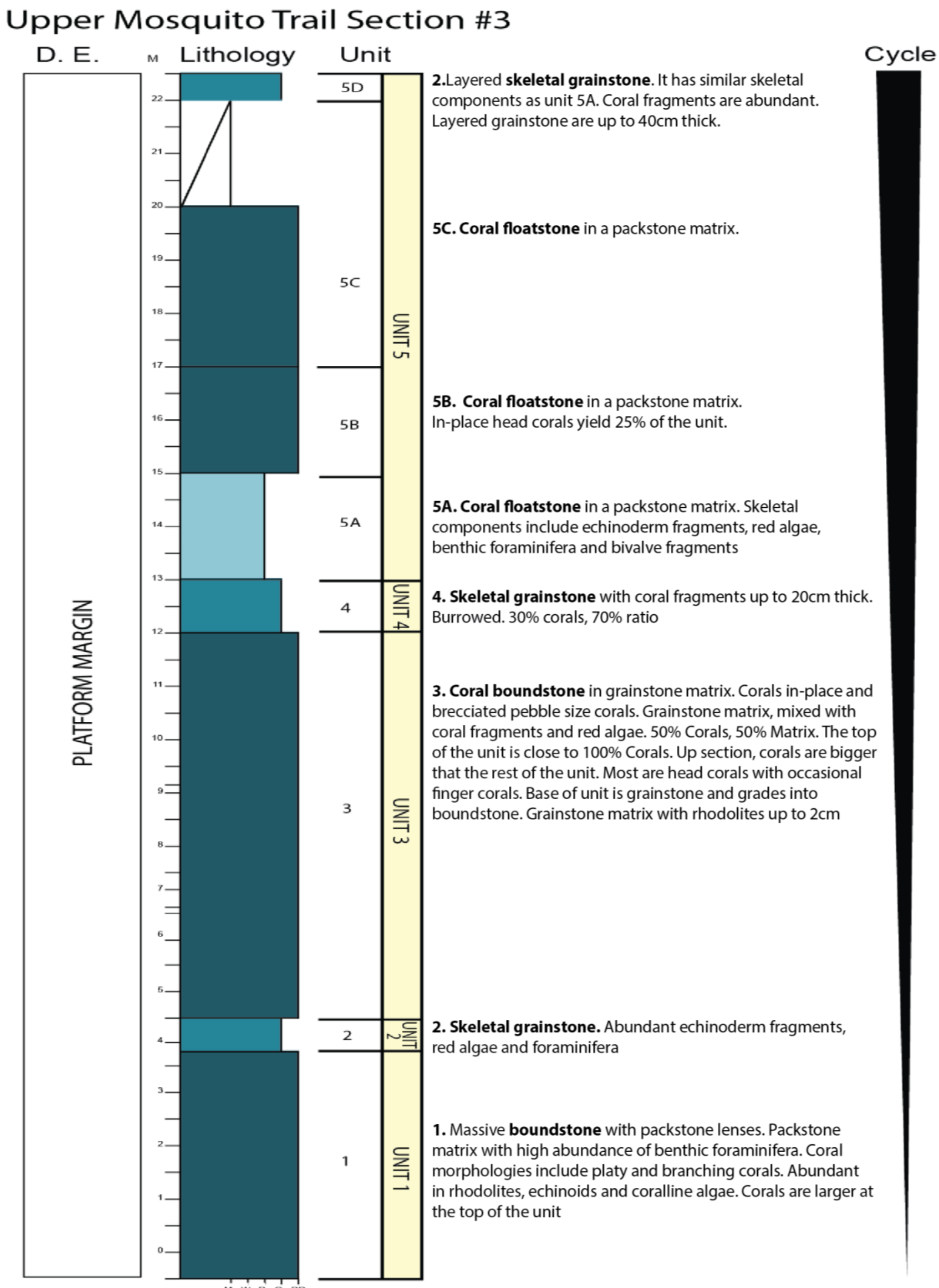
Stratigraphic Sections for MQR A-F (Modified form Ruidíaz., 2013)



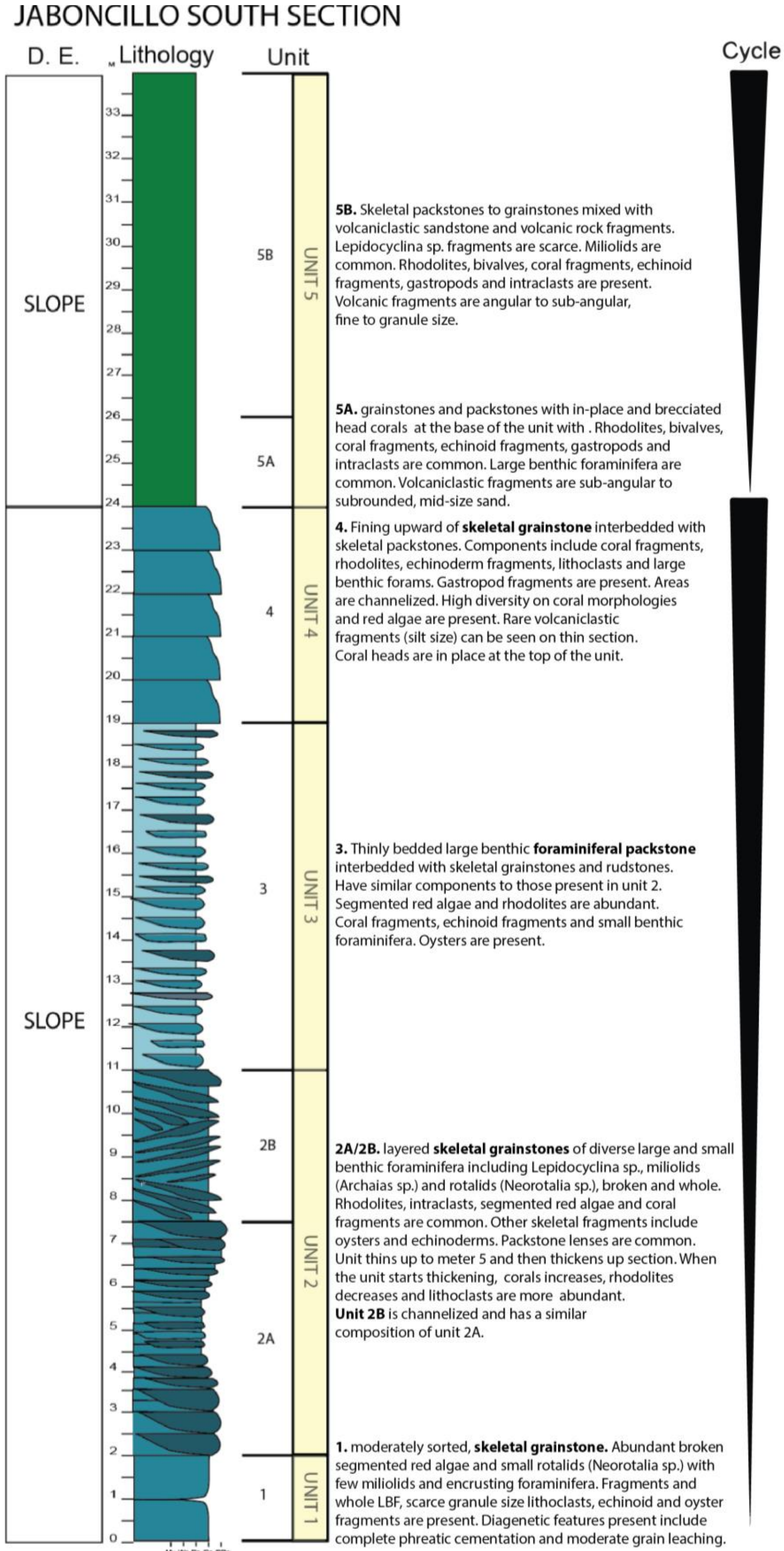
Stratigraphic Section for Cliff Section (Modified form Ruidíaz., 2013)



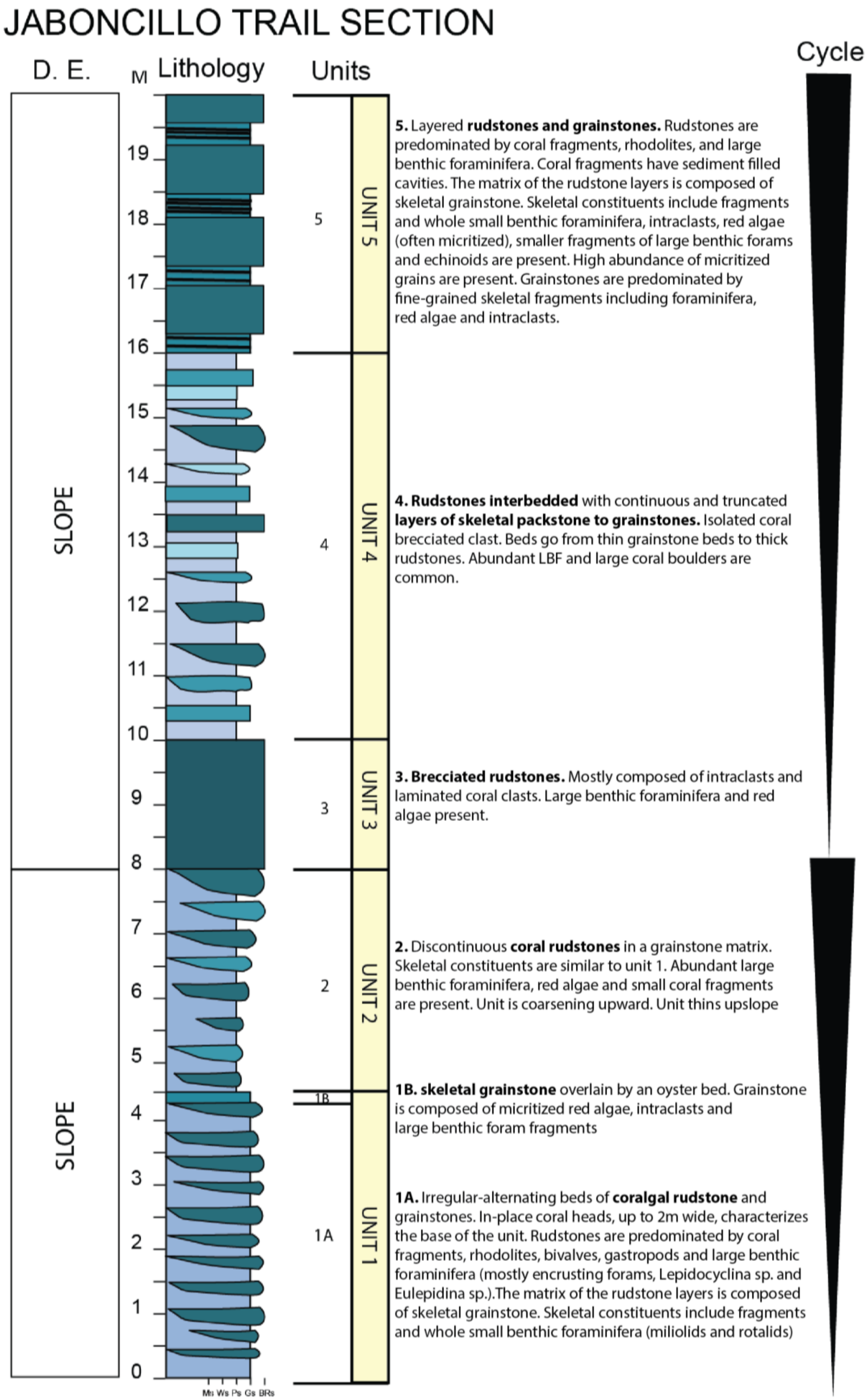
Stratigraphic Sections for Upper Mosquito trail 1 & 2 (Modified form Ruidíaz., 2013)



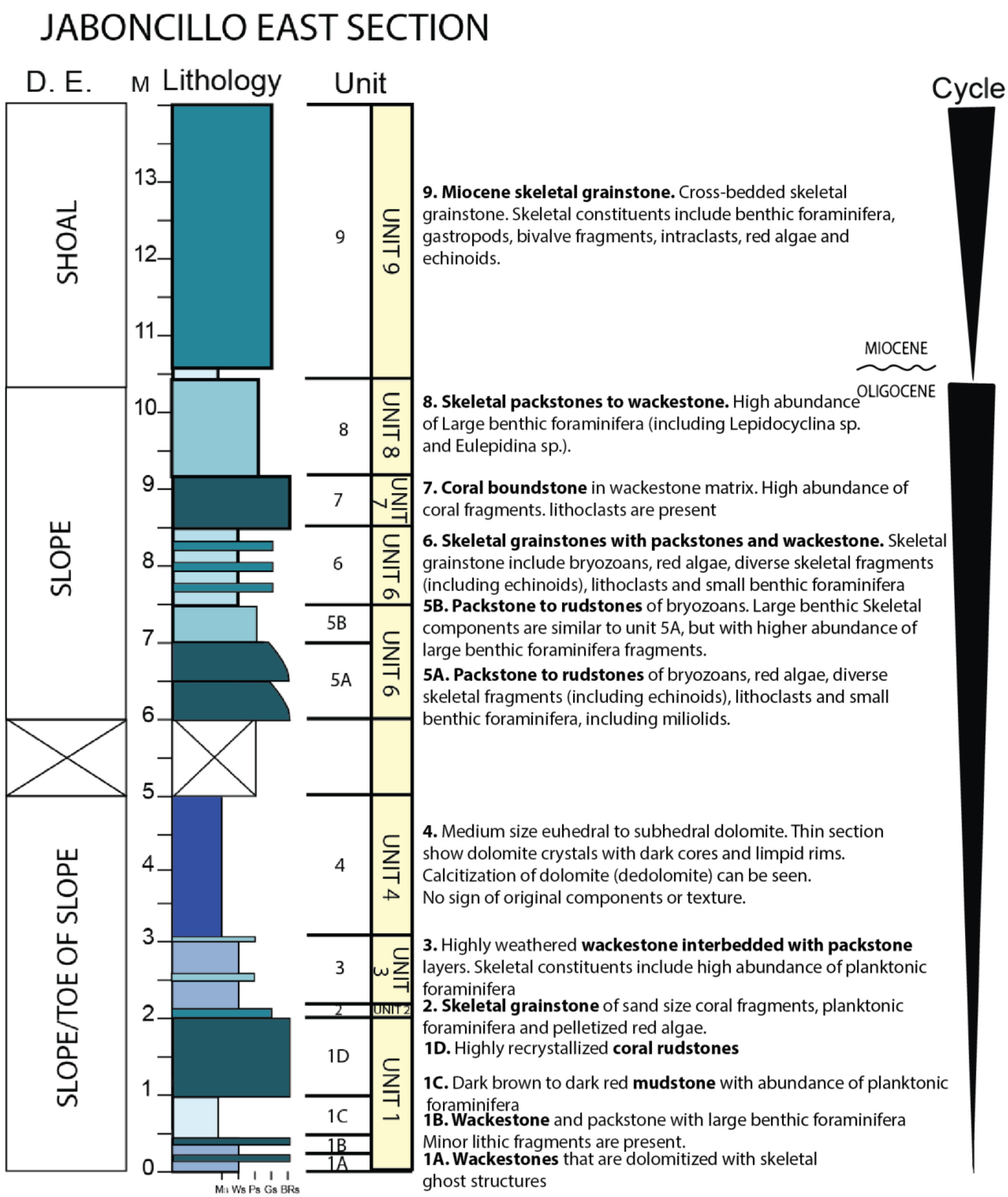
Stratigraphic Section for Upper Mosquito trail 3 (Modified form Ruidíaz., 2013)



Stratigraphic Section for Jaboncillo South (Modified form Ruidíaz., 2013)



Stratigraphic Section for Jaboncillo Trail (Modified form Ruidíaz., 2013)



Stratigraphic Section for Jaboncillo East (Modified form Ruidíaz., 2013)