University of Alberta

Deposition and sea level fluctuations during Miocene times, Grand Cayman, British West Indies

by

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ABSTRACT

The Lower to Middle Miocene Cayman Formation on Grand Cayman, which is part of the Bluff Group, is at least 130 m thick. The mostly dolomitized Cayman Formation is herein divided into a 'limestone member' and 'dolostone member' as limestone is found in the formation in the central part of Grand Cayman. Sediments of the Cayman Formation were deposited in water 10-30 m deep on an isolated open bank with no evidence of reef development. Facies development was controlled primarily by water depth and energy levels. The Cayman Formation is divided into eight facies that range from *Leptoseris*-*Amphistegina* facies to *Amphistegina*-Bivalve facies. Depositional environments range from deep open bank to very shallow open bank. The succession reflects two shallowing-upward sequences that are separated by a transgressive event that saw sea level rise by 20-25 m. Sea level changes were probably related to eustatic changes rather than local tectonic changes.

ACKNOWLEDGEMENTS

Applying to graduate school at the University of Alberta was something that fell into place for me three years ago. I had never visited the UofA campus before, and apart from e-mail correspondence, I had never met Dr. Brian Jones. I was paradropping into the unknown, and what a journey it has been! I have made lifelong friends, went to Grand Cayman for fieldwork, travelled to Burma, Cuba, various States, and Europe. I've gone on a road trip to the west coast, tried ice climbing, witnessed the Discovery Shuttle Launch, and attended numerous department events.

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CHAPTER ONE:
INTRODUCTION

1.1. INTRODUCTION

Grand Cayman, like many islands throughout the Caribbean Sea, has a Tertiary succession that developed on an isolated bank that was surrounded by deep oceanic water. Such banks have long been recognized as optimal study sites to reconstruct the mode of formation and diagenetic evolution of carbonate strata. The Tertiary limestones and dolostones on Grand Cayman belong to the Bluff Group, which is formed of the Brac Formation (Lower Oligocene), the Cayman Formation (Middle Miocene), and the Pedro Castle Formation (Pliocene). Each formation is an unconformity-bounded package of strata, and the sequence of carbonates developed through a succession of deposition-erosion cycles (Jones, 1994).

In this study, the depositional history of the Cayman Formation on the eastern part of Grand Cayman is examined and interpreted. A detailed facies analysis examines the lithology, depositional textures, faunal content and preservation, and facies architecture of this succession in order to establish the depositional paleoenvironments and their response to ever changing sea levels. Such information is then used to determine if the succession developed in response to global eustatic change and/or local tectonic controls.

1.2. GEOLOGIC AND GEOGRAPHIC SETTING

1.2.1. Location

The Cayman Islands are a British Overseas territory located between Jamaica and Cuba in the northwest part of the Caribbean Sea (Fig. 1.1). Grand Cayman (81º15’W, 19º20’N), the largest of the three islands, is located

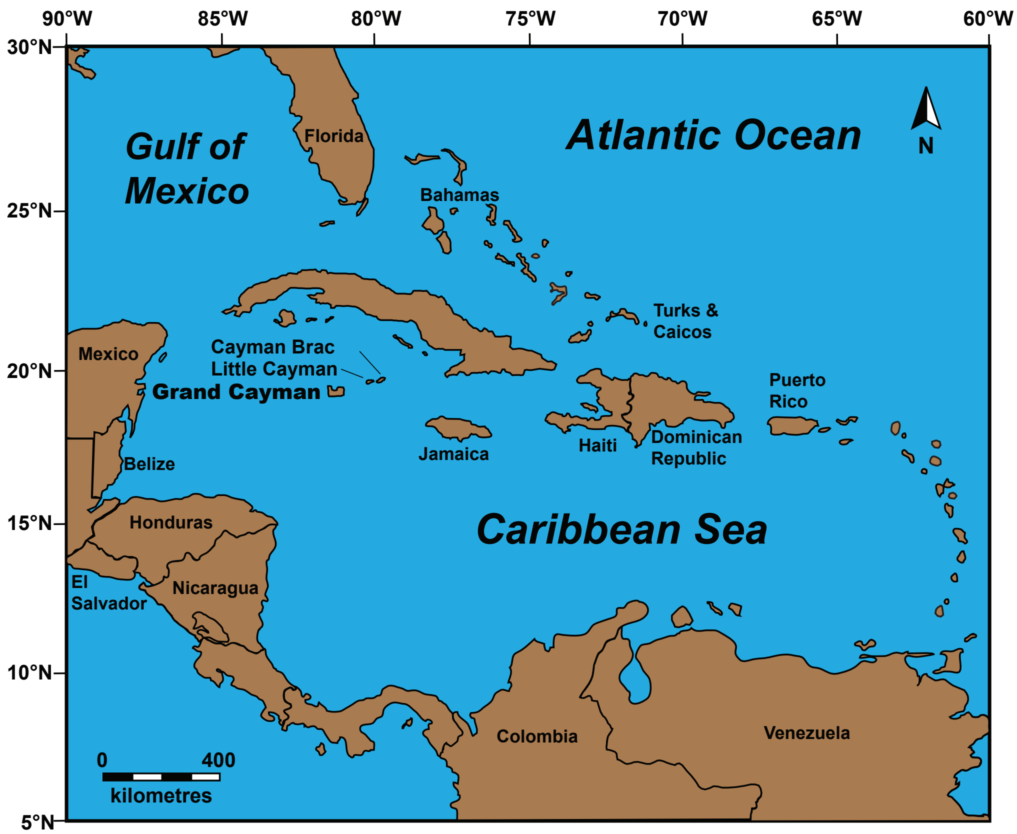

Figure 1.1. Location of the Cayman Islands in the Caribbean Sea. Modified from Uzelman (2009).

approximately 300 km northwest of Jamaica and 300 km south of Cuba. Georgetown, the country's capital, is located on the western shore of Grand Cayman. Cayman Brac and Little Cayman are approximately 130 km northeast of Grand Cayman.

Grand Cayman is approximately 35 km long (east-west), 5-15 km wide (north-south), and encompasses an area of 196 km^2. Topographic relief on Grand Cayman is subdued, as most of it is less than 3 m above sea level (asl). The Mountain, at ~18 m asl defines the highest point on the island. A narrow peripheral ridge (> 6 m asl) borders the north, east, and south coasts along with minor continuations near the Mountain and Pedro Castle (Jones and Hunter, 1994a). The east end of the island is low-lying and mostly covered with dense, tropical bush that makes access to the central outcrops very difficult. There are,

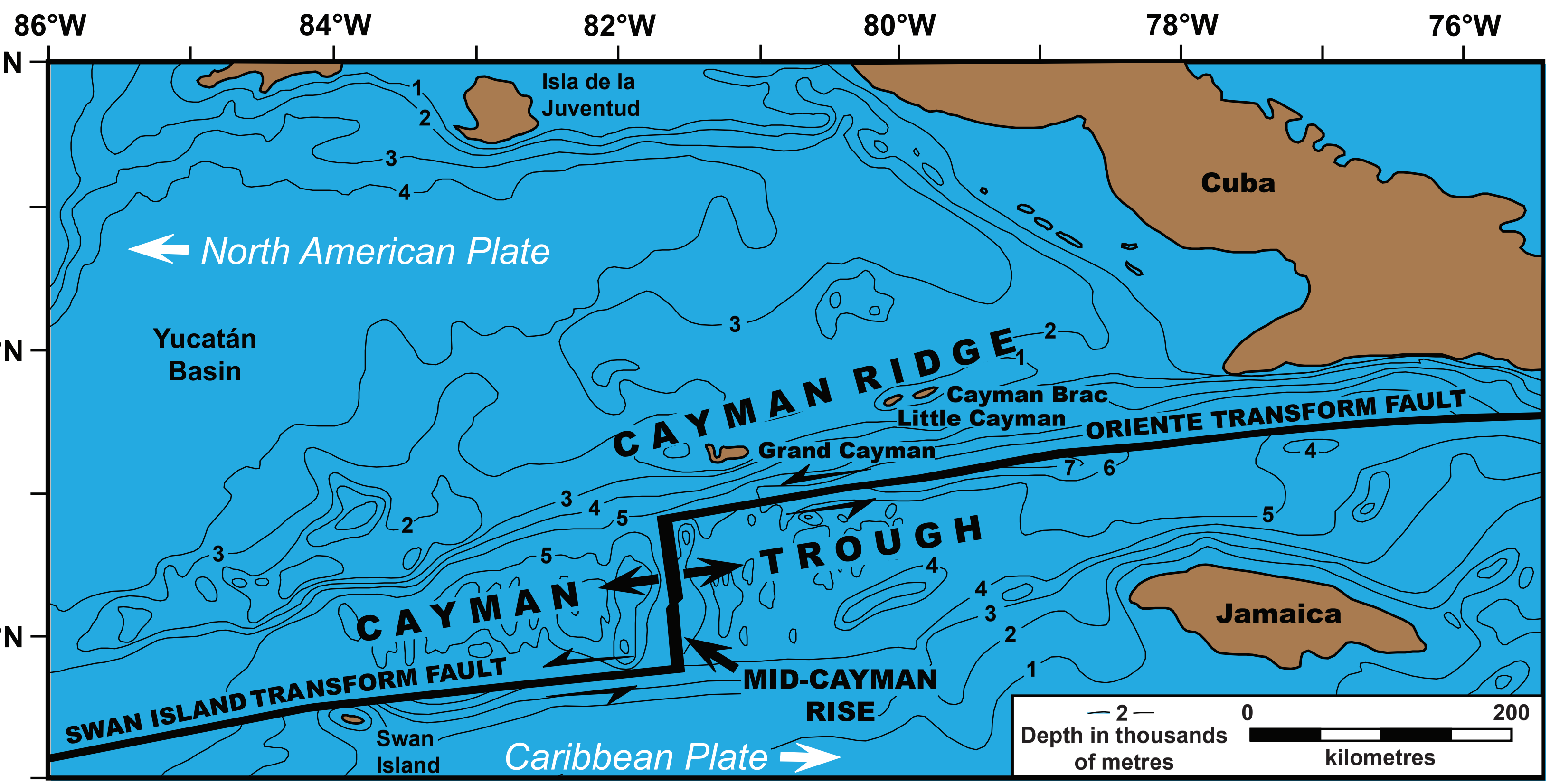

Figure 1.2. Tectonic and bathymetric setting of the Cayman Islands on the Cayman Ridge in the northwestern Caribbean. Modified from Perfit and Heezen (1978) and MacDonald and Holcombe (1978).

however, a limited number of outcrops along some of the roads and along the coastline.

1.2.2. Tectonic Setting

The Cayman Islands are emergent carbonate pinnacles situated on the Cayman Ridge, a submarine rise that extends from the Sierra Maestra of southeast Cuba to the Gulf of Honduras (Fig. 1.2). The Cayman Ridge, which delineates the southern boundary of the North American Plate, is an uplifted fault block (Fahlquist and Davies, 1971) that formed in a Late Mesozoic to Early Cenozoic island-arc setting (Holcombe *et al.*, 1990). Information gathered from dredge samples indicate that the Cayman Ridge is composed of a granodiorite foundation that is overlain by volcanics and capped by carbonate rocks (Perfit and Heezen, 1978; Holcombe *et al.*, 1990). Independent tectonic movement experienced by each of the Cayman Islands implies that each island is situated on independent fault blocks that are elevated above the general level of the Cayman Ridge (Matley, 1926; Horsfield, 1975). Although the total thickness of the carbonate succession on Grand Cayman is unknown, drilling indicates that it is at least 401 m thick (Emery and Milliman, 1980). In 1956, two exploratory wells were drilled to test the oil potential of the island. These wells were drilled to 159 m and 401 m, with the latter well being the deepest well drilled on Grand Cayman to date. No samples from these wells are known and attempts to find these samples have failed. The only known information from these two wells, located along Frank Sound Road, is the depths and very vague descriptions of the rock types as provided by Emery and Milliman (1980).

The Cayman Trough is a 100 km wide and 1200 km long slow-spreading ocean basin bounded by the Cayman Ridge to the north and the Nicaraguan Plateau to the south (Fig. 1.2). This trench marks the present day strike-slip boundary between the Caribbean Plate and the North American plate. With depths in excess of 6800 m, it is the deepest feature in the Caribbean Sea, (Ladd *et al.*, 1990). The Mid-Cayman Rise, a 100 km long, active north-south spreading center, bisects the Cayman Trough southwest of Grand Cayman at 82ºW. Left-lateral strike slip motion of the North American Plate relative to the Caribbean Plate is accommodated by two transform faults: the Oriente Transform Fault to the east of the Mid-Cayman Rise and the Swan Island Transform Fault to the west (MacDonald and Holcombe, 1978). Global Positioning System (GPS) measurements record a plate movement rate of 20 mm/yr in a direction 070º (Dixon *et al.*, 1998). Since the opening of the Mid-Cayman Rise, which may have begun during the Eocene (Perfit and Heezen, 1978), the Caribbean Plate has been displaced 190 km relative to the North American Plate (Leroy *et al.*, 1996). This area is still tectonically active, as earthquakes have been felt on Grand Cayman recently. The most recent tectonic activity felt on the island was just after the January 12, 2010 7.0 magnitude earthquake in Port-au-Prince, Haiti (USGS).

1.3. DEVELOPMENT OF STRATIGRAPHIC NOMENCLATURE

The geology of the Cayman Islands was first documented by Matley (1924a) and has undergone considerable revision since the original reconnaissance survey for the British government. Based on his investigation, Matley (1924a, b, 1925a, b, 1926) appropriately named the buff coloured, massive, semi-crystalline carbonates he encountered in sheer cliffs along the coasts of Cayman Brac as the "Bluff Limestones". Samples of *Lepidocyclina* (a benthic foraminifer) were used to assign a Middle Oligocene (Rupelian) age to the strata. Subsequent geological investigations (Rigby and Roberts, 1976; Jones, 1989; Jones and Hunter, 1989; Pleydell *et al.*, 1990) revealed that most of the Bluff Limestone consisted largely of dolostones. Jones and Hunter (1989) proposed that the succession be called the Bluff Formation in order to remove the lithological connotation. A type section was designated at Pedro Castle Quarry on Grand Cayman, and the Bluff Formation was divided into the Cayman Member and Pedro Castle Member (Jones and Hunter, 1989).

The stratigraphy of the Cayman Islands was further revised in 1994 as a result of extensive outcrop analysis on Cayman Brac (Jones *et al.*, 1994a). A third stratigraphic division, the Brac Formation, was established with the type section designated at the basal 33 m of the succession exposed on the cliff at the east end of the island. The Bluff Formation was promoted to group status with three constituent formations including the Brac Formation, Cayman Formation, and the Pedro Castle Formation (Jones *et al.*, 1994b). Lithological variations and age gaps between the three unconformity-bound packages of strata of the Bluff Group justified their elevation to formational status.

The Tertiary Bluff Group is onlapped and overlain by the Pleistocene Ironshore Formation (Jones, 1994). The term 'ironshore' was first coined by Matley (1924a) and is derived from a local term used for the rocky limestone shoreline that forms a low coastal terrace on the periphery of each island.

1.4. STRATIGRAPHIC OVERVIEW

Strata at the surface and in the shallow subsurface on the Cayman Islands belong to the Brac Formation, Cayman Formation, Pedro Castle Formation, and Ironshore Formation (Fig. 1.3). The Brac Formation, Cayman Formation, and Pedro Castle Formation, which comprise the Bluff Group, are Tertiary in age (Jones *et al.*, 1994a) whereas the Ironshore Formation is Pleistocene in age (Woodroffe *et al.*, 1983; Vézina *et al*., 1999).

Overall, the succession represents periods of deposition during eustatic sea

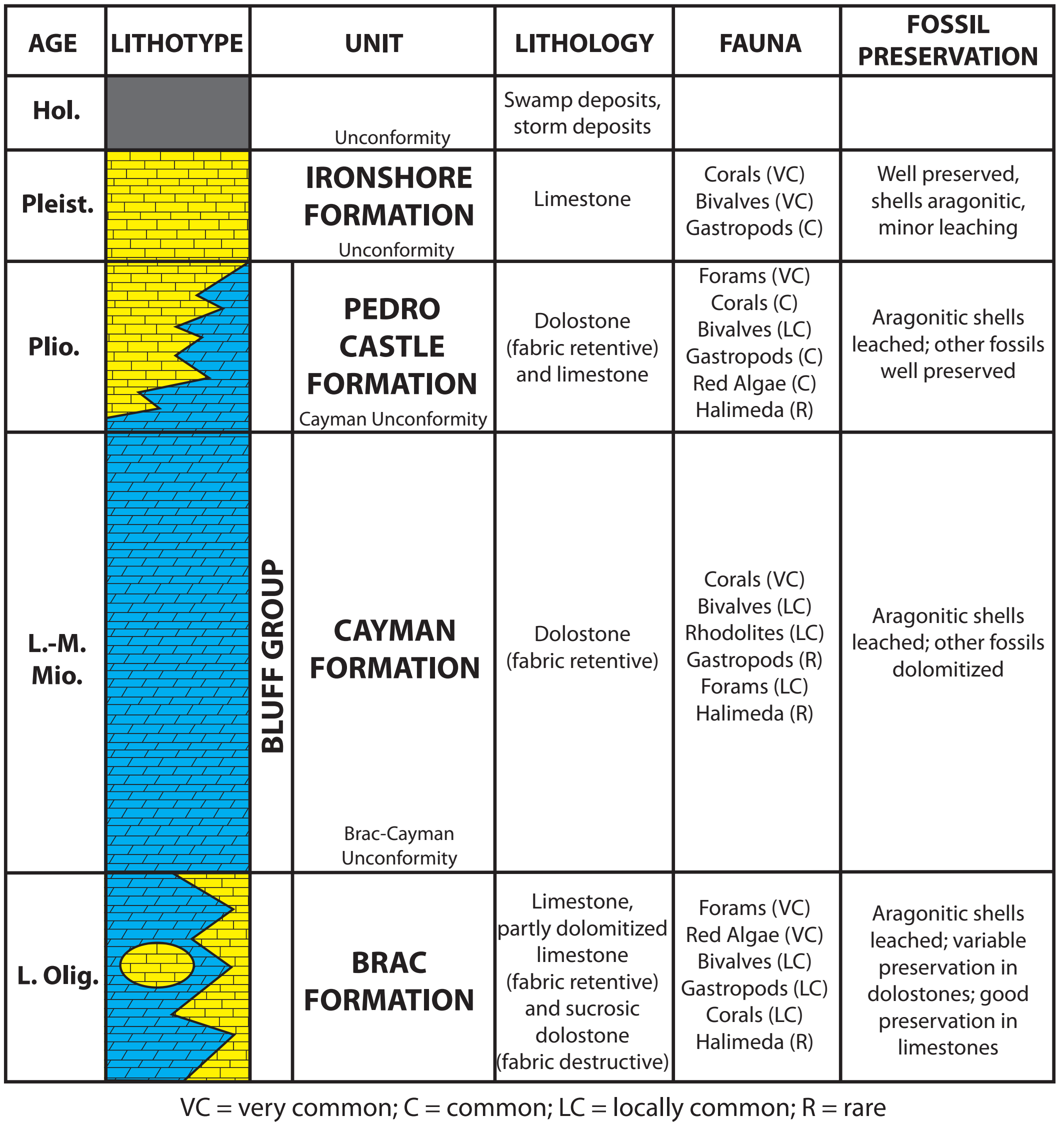

Figure 1.3. Stratigraphic column for the Cayman Islands showing key features of each depositional unit. Modified from Jones (1994).

level highstands followed by episodes of erosion and karst development during eustatic sea level lowstands (Jones *et al.*, 1994a). Erosional unconformities bounding the individual formations of the Bluff Group represent sequence boundaries that developed during such lowstands. The Brac Unconformity delineates the contact between the Brac Formation and Cayman Formation (Jones and Hunter, 1994a). The Cayman Unconformity separates the Cayman Formation and Pedro Castle Formation. The Pedro Castle Unconformity defines the boundary between the Pedro Castle Formation and Ironshore Formation.

On Grand Cayman, the Cayman Formation, Pedro Castle Formation, and Ironshore Formation are found in the subsurface and surface exposures. The distribution of each formation varies laterally and vertically. The Ironshore Formation is found at the surface over most of the western part of the island. The Cayman Formation is found at the surface over most of the east end of the island. Surface exposures of the Pedro Castle Formation are restricted to the area around Pedro Castle (Fig. 1.4). The Brac Formation is not present in surface exposures on Grand Cayman and is only present in the subsurface in the deep wells in Lower Valley (Jones and Luth, 2003) and NSC#1/2/3.

The Tertiary strata can also be correlated with carbonate successions on neighboring Caribbean Islands. The Cayman Formation, which is the focus of this study, can be correlated with the Paso Real Formation of Cuba, the Los Puertos and Aymamom limestones of Puerto Rico, and the Buff Bay Formation of north-central Jamaica (Jones *et al.*, 1994a).

1.5. STUDY AREA

The study area is located on the eastern part of Grand Cayman (Fig. 1.4A). It extends southwest to northeast, from Lower Valley to Roger's Wreck Point and the eastern coastline. The study area is bound to the north by the north coast and to the south by the south coast. The twelve wells examined (Fig. 1.4B) in this study were chosen on the basis of their depth, location, type of data available, and if previous studies have been conducted. LV#2, QHW#1, and RWP#2 have been previously documented (Jones and Luth, 2003; Willson, 1998) and this study incorporates and expands on these previous studies.

This study includes data from the deepest well, for which samples are available on the island at 245 m (Fig. 1.4B). Previous studies have only examined

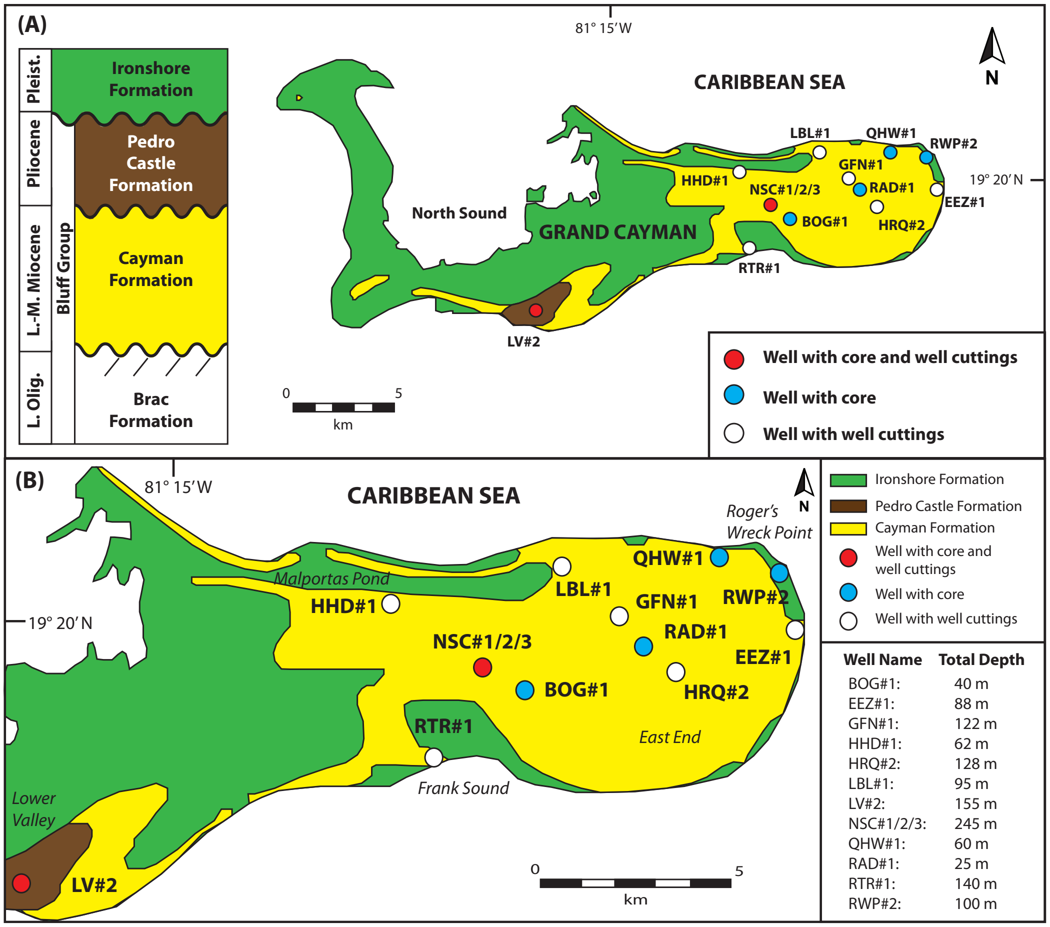

Figure 1.4. (A) Stratigraphic column and geological map of Grand Cayman showing location of wells from which core and well cuttings were obtained. (Modified from *Jones et al.*, 1994a). (B) Detailed map of study area on Grand Cayman including well depths. Well numbers indicate how many wells have been drilled in the same location.

wells to depths of 155 m drilled on the perimeter of the island. The 12 wells included in this study vary in depth from 25 m to 245 m. Drilling issues largely controls depths to which wells are drilled.

The study area in the east end is relatively flat-lying (< 3 m), and minimal surface exposures are present. Much of the surface of the interior of the island is heavily vegetated whereas the coastline is dominated by the rugged karsted surface of the Cayman Formation (Fig. 1.5). The Pedro Castle Formation occurs poorly at the surface in a sinkhole at Roger's Wreck Point (Willson, 1998). Apart

Figure 1.5. Rugged karsted surface of the Cayman Formation along the south coast.

from this, the Cayman Formation, both in the subsurface and surface, is the most common formation on the eastern part of the island.

The coastline in the Lower Valley area contains the only surface exposures of the Pedro Castle Formation on Grand Cayman. Pedro Castle Quarry, also in the Lower Valley area, is an old quarry that exposes 8 m of the succession. The Cayman Formation is present in the bottom 5.5 m, and the Cayman Unconformity separates the Pedro Castle Formation at the top of the exposed section. This locality is the type section for the Cayman Formation and Pedro Castle Formation because the contact is clearly exposed (Jones and Hunter, 1989).

1.6. PREVIOUS WORK

Since Matley's original investigation (1924a), the geology of the Cayman

Islands has been meticulously studied and expanded significantly (Rigby and Roberts, 1976; Jones, 1989; Jones and Hunter, 1989; Jones, 1994). Research has focused on refinement of the stratigraphic framework (Jones and Hunter, 1989; Jones, 1994; Jones *et al.*, 1994a,b), establishing the age of the strata (Jones, 1994), determining the paleoecology of the original biota (Willson, 1998; Hills and Jones, 2000), and modern biota (Li and Jones, 1997; Corlett and Jones, 2005). Detailed examinations of post-depositional diagenetic processes, which have significantly modified these rocks, have included consideration of porosity and permeability (Ng *et al*., 1992), caves (Jones and Motyka, 1987; Lips, 1993), cave sediments (Jones, 2009), karst surface unconformities (Jones, 1994; Coyne *et al.*, 2007), and dolomitization (Jones and Luth, 2002; MacNeil and Jones, 2003; Jones, 2004, 2005, 2007). This research has included virtually every exposure on Grand Cayman and Cayman Brac (Jones, 1994) as well as samples from numerous wells that have been drilled on the islands.

1.7. OBJECTIVES

The objective of this study is to describe and characterize the sedimentological and stratigraphic features of the Cayman Formation on the eastern part of Grand Cayman. Core and well cuttings data have been analyzed to meet the following goals:

1. To describe the sedimentology of the Cayman Formation, with emphasis on the lithology and paleontology, in order to define the depositional facies and facies architecture.
2. To elucidate depositional realms based on the depositional fabrics of the rocks and the paleoecology of fossils.
3. To develop a model of sedimentation for an open carbonate bank. This will allow determination of the response of sedimentation to the ever-

changing sea levels that controlled the deposition and exposure cycles.

4. To investigate how the depositional regimes changed with time, determine if there is evidence for deepening and/or shallowing of the bank, and to attempt to tie these sea level changes to Miocene eustatic sea-level changes and/or tectonic activity.

1.8. METHODS

Numerous wells to depths of 245 m have been drilled on Grand Cayman. These wells are from a mixture of (1) The Cayman drilling program, which was initiated in 1991 by Dr. Brian Jones and his graduate students, (2) wells that Dr. Jones has hired Industrial Services Ltd. to drill, and (3) wells that were drilled by other organizations such as the Cayman Water Authority. Mechanical limitations of the drilling equipment as well as variability in competency of the rock determine the maximum depth to which wells are drilled. Drilling fluids are unnecessary as compressed air is pumped down the drill stem to where the bit is, and water is forced up the hole by the compressed air to lubricate the drill. Core retrieval was conducted when possible, but it is expensive and often difficult due to the friability of the rock. Instead, well cuttings were generally collected on mesh gathering screens over 2.5 to 3 foot intervals (~ 0.75 to 0.9 m). Core and well cuttings were packaged and shipped to the University of Alberta for logging and petrographic analysis.

1.8.1. Core and Well Cutting Logging and Thin Section Petrography

Core and well cuttings were logged by identifying the biota present and the textural relationships in the rock. Particular attention was paid to the nature of dissolution features and how they relate to the original deposition material. The texture of the matrices is described using Dunham's (1962) Classification scheme as modified by Embry and Klovan (1971). A more detailed study of the core and well cuttings, to examine the smaller allochems and the biota content of the matrices, was made possible using thin section petrography. A polarizing light microscope (25-500x magnification) was used to examine standard thin sections (2.5 x 5 cm and 5 x 7.5 cm) sampled from regular intervals. Most thin sections from wells were stained with Alizarin Red S to facilitate differentiation between calcite and dolomite, and blue stain was added to the epoxy to emphasize original porosity. Scholle and Ulmer-Scholle (2003) was used as a petrographic guide to identify grains.

1.8.2. Scanning Electron Microscopy

Scanning electron microscopy (SEM) was utilized to obtain high resolution images (1) for the identification of benthic foraminifera from well RTR#1, and (2) for the dolomite crystals in the Cayman Formation. Samples were prepared and analyzed at the University of Alberta using a Jeol SM-6301 FXV SEM. Samples were mounted on a stub using conductive glue and sputter coated with a thin layer of gold.

1.8.3. X-ray Diffraction

X-ray diffraction was utilized in order to determine the mineralogical composition of the carbonate samples. Samples were ground and sent for XRD analysis at the University of Alberta. The peak-fitting X-ray diffraction (PF-XRD) technique of Jones *et al.* (2001) was employed to determine the percent of calcite and dolomite in the samples. This XRD information was provided by Dr. Brian Jones and served as a method to back-check lithological observations made from core, well cutting, and thin section analysis.

1.8.4. Outcrop Analysis

Core, well cuttings, thin sections and SEM analysis were integrated with data and observations made from outcrop analysis conducted on Grand Cayman in August 2010. Outcrop exposures (meters to 10 meters) provided a better sense of the scale of observations, as many allochems are larger than what is often retrieved from wells. When naming and classifying facies it was important to be aware that drill core and well cuttings restrict observations to areas that are < 3.5 cm wide whereas outcrops permit meter scale observations.

CHAPTER TWO:

STRATIGRAPHY

2.1. STRATIGRAPHIC FRAMEWORK OF THE CAYMAN ISLANDS

The Tertiary carbonate succession on the Cayman Islands includes the Lower Oligocene Brac Formation, the Lower to Middle Miocene Cayman Formation, and the Pliocene Pedro Castle Formation, which collectively comprise the Bluff Group. The Bluff Group is unconformably onlapped by the Late Pleistocene Ironshore Formation (Fig. 2.1). These formations are separated from each other by regional unconformities that developed during sea level lowstands (Jones and Hunter, 1994a). The distribution of outcrops of the Tertiary and Pleistocene strata on the Cayman Islands is variable. The Ironshore Formation and Cayman Formation outcrop on all three islands, whereas exposures of the Pedro Castle Formation are limited to Grand Cayman and Cayman Brac. Exposures of the Brac Formation are found only in the vertical to overhanging sea cliffs at the east end of Cayman Brac.

2.1.1. Brac Formation

The Brac Formation is named after its type locality on the northeast end of Cayman Brac. Although the total thickness of this formation is unknown because the lower boundary is not exposed and has never been reached during drilled; it is at least 33 m thick (Jones, 1994; Uzelman, 2009). The lithology of the Brac Formation varies with location. Bioclastic limestones (wackestones to grainstones) with numerous *Lepidocyclina* and lesser numbers of other foraminifera, red algae, and echinoid plates are found on the northeast coast. On the south coast, however, the formation is composed largely of coarse, sucrosic dolostones (euhedral rhombs up to 1.5 mm long) that encase scattered lenses of bioclastic limestone. Corals are rare in this formation apart from scattered *Porites* fragments in the upper 2 m of the formation (Jones, 1994). The incomplete dolomitization of this formation results in a lateral lithological transition over a distance of ~ 2 km. Although the Brac Formation does not crop out on Grand Cayman, it has been found in some wells at depths of 122 to 155 m below sea level (Jones and Luth, 2003).

The Brac Formation is considered to be upper Lower Oligocene in age based on foraminifera biostratigraphy (Vaughan, 1926) and $^{87}Sr/^{86}Sr$ isotope ratios (average = 0.70808, corresponding to 28 million years) from the constituent limestones (Jones, 1994). The uneven topography on the Brac-Cayman unconformity (dipping from 0.5 to 2° southwest, with a relief of at least 25 m) indicates that subaerial exposure, lithification, and erosion of the Brac Formation predated deposition of the overlying Cayman Formation (Jones, 1994).

2.1.2. Cayman Formation

The Cayman Formation, which unconformably overlies the Brac Formation, is widely exposed on each of the Cayman Islands. On Cayman Brac, the formation is at least 100 m thick (Jones, 1994; Zhao and Jones, 2012), whereas on Grand Cayman it is at least 130 m thick (Jones and Luth, 2003). The Cayman Formation, as originally defined, is composed entirely of fabric-retentive microcrystalline dolostones (euhedral crystals 5-100 μm long, average 15-30 μm long). Despite pervasive dolomitization and extensive diagenetic modification, many of the original depositional textures have been preserved. The biota of the Cayman Formation, which is more diverse than that in the Brac Formation, includes corals (domal, platy, branching, free living), bivalves, gastropods, red algae, foraminifera, echinoids, rhodolites, and *Halimeda* (Jones, 1994). *Lepidocyclina*, which are prevalent in the Brac Formation, have not been found above the Brac Unconformity. Instead, *Amphistegina* dominate the foraminiferal fauna in the Cayman Formation. Although corals are common throughout this formation, there is no evidence of reef development (Jones and Hunter, 1994a). $^{87}Sr/^{86}Sr$ isotope ratios have been reset by dolomitization (Pleydell *et al.*, 1990) and age diagnostic fossils are not yet recognized. A foraminifera fauna corresponding to established Caribbean associations implies a Lower to Middle Miocene age for the formation (Jones, 1994).

The Cayman Unconformity, which separates the Cayman Formation from the overlying Pedro Castle Formation, developed during the Messinian (terminal Miocene), 5-6.7 Ma ago (Jones and Hunter, 1994b). During that time, sea level reached a lowstand that resulted in the 'Messinian Salinity Crisis (MSC)" that led to the deposition of thick evaporite successions in the Mediterranean (Hsü *et al.*, 1977). This eustatic drop in sea level led to subaerial exposure of many isolated oceanic islands, including Grand Cayman. The Cayman Unconformity is marked by locally variable relief of up to 40 m that formed as a result of exposure during the Messinian lowstand event, when sea level was > 40 m lower than present day sea level (Jones and Hunter, 1994b). The well-developed karst topography and irregular surface on the Cayman Unconformity indicates that subaerial exposure and dissolution occurred prior to the deposition of the Pedro Castle Formation (Jones, 1994). Faunal borings on this erosional surface also developed during the initial phases of the Pliocene transgression.

2.1.3. Pedro Castle Formation

The Pedro Castle Formation, the uppermost stratigraphic unit in the Bluff Group, ranges in composition from limestone (mudstone to packstone) to dolomitic limestone to dolostone (MacNeil and Jones, 2003). Differential erosion, significant paleorelief on the underlying Cayman Unconformity, and deposition of the Pedro Castle Formation on irregular topography has produced a unit that ranges from 6 to 10 m thick on Cayman Brac and up to 20 m thick on Grand Cayman. The biota, similar to that of the Cayman Formation, includes free-living and branching corals, foraminifera (dominantly *Amphistegina*), bivalves, gastropods, red algae, rhodolites, *Halimeda*, and echinoids (Jones, 1994; MacNeil and Jones, 2003). Corals are less abundant than in the Cayman Formation and are dominantly free-living (Jones, 1994). There are also fewer large hemispherical corals in the Pedro Castle Formation than the Cayman Formation. The distribution of dolostone in this formation varies laterally and vertically, and the style of dolomitization varies from fabric retentive but non-mimetic to fabric destructive replacive dolomite (Jones *et al*., 1994b; MacNeil and Jones, 2003). The Pedro Castle Formation is Pliocene in age, based on coral biostratigraphy and $^{87}Sr/^{86}Sr$ isotope ratios determined from the limestones (Jones *et al*., 1994b). The Pedro Castle Unconformity, which separates the Pedro Castle Formation from the Ironshore Formation, is exposed in a few outcrops but is mainly identified in wells by a change in core recovery controlled by the lithology of the strata (Jones *et al*., 1994b). The maximum relief on the Pedro Castle Unconformity on Grand Cayman is 8 m (Jones *et al*., 1997).

2.1.4. Ironshore Formation

The Pleistocene Ironshore Formation unconformably overlies the Tertiary Bluff Group and covers much of the western half of Grand Cayman. It forms a narrow coastal platform around the Bluff Group on Cayman Brac (Uzelman, 2009). Although generally less than 9 m thick, it reaches a thickness of 19 m on the northeast coast of Grand Cayman (Vézina *et al*., 1999). The Ironshore Formation is composed of friable limestones and to date, no dolomite has not been found in this unit (Jones *et al*., 1997). A diverse assemblage of corals and molluscs characterize this formation (Jones and Hunter, 1994a; Cerridwen, 1989). Faunal assemblages also include foraminifera, *Halimeda*, and well preserved trace fossils (Pemberton and Jones, 1988; Vézina, 1997). The range of textures preserved in this unit includes mudstones, oolitic grainstones, and coral framestones. These textures represent diverse depositional environments. This formation is divided into six unconformity-bounded units (A through F) that represent highstands from the last interglacial periods at >400 ka, ~346 ka, ~229ka, ~125 ka, ~104 ka, and ~84 ka, respectively (Vézina *et al*., 1999; Coyne *et al*., 2007). The upper boundary of the Ironshore Formation is formed by the present day erosional surface on Grand Cayman.

2.2. STRATIGRAPHY OF THE STUDY AREA

2.2.1. Limestone–Dolostone Issue

The succession exposed at Pedro Castle Quarry on Grand Cayman (Fig. 2.1) was designated the type section for the Cayman Formation and Pedro Castle Formation because the well exposed sequence includes the Cayman Unconformity (Jones and Hunter, 1989). Based on that succession and samples from wells that had been drilled up to 1988, Jones and Hunter (1989) defined the Cayman Formation as a dolostone unit and the Pedro Castle Formation as a limestone to dolomitic limestone to dolostone unit. This lithological division between the Cayman Formation and Pedro Castle Formation held true in all exposures and in the 90 wells drilled on Grand Cayman before 1999; no limestone was found in the Cayman Formation.

Surface exposures along the south, east, and north coasts on the east end of the island are formed of dolostones that belong to the Cayman Formation. The interior of the east end of Grand Cayman was largely inaccessible due to lack of roads, dense tropical vegetation, and widely scattered outcrops in the interior.

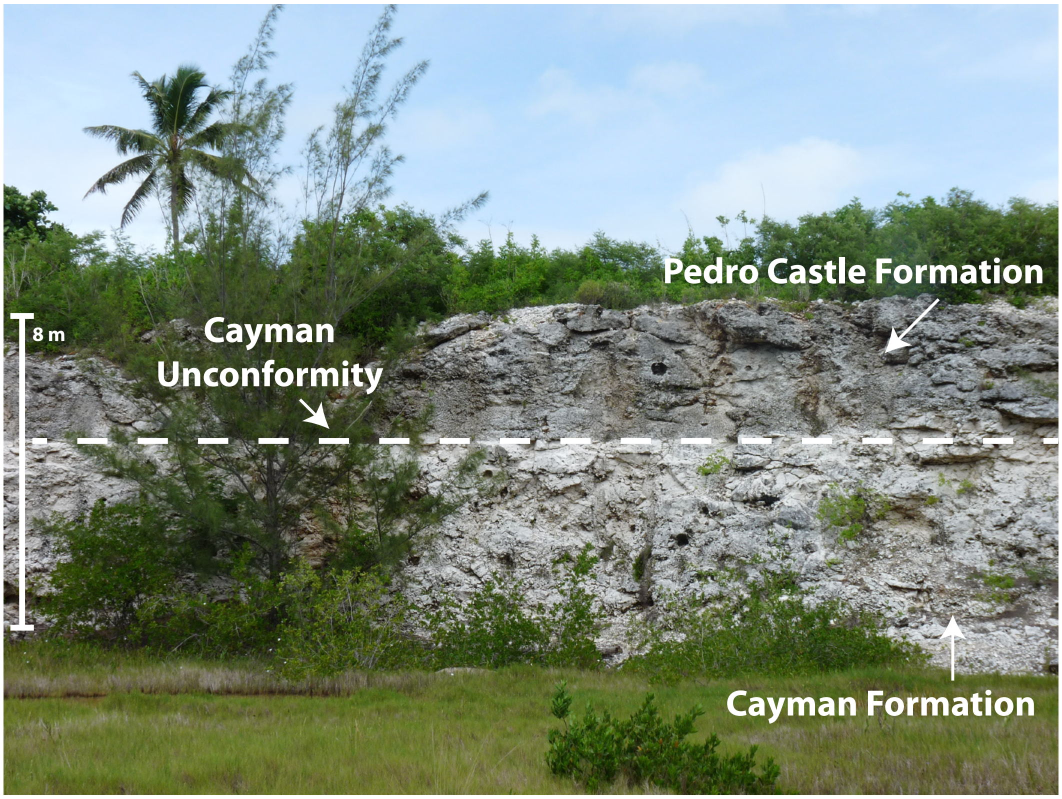

Figure 2.1. Field photograph of Pedro Castle Quarry showing the Cayman Unconformity between the Cayman Formation and the overlying Pedro Castle Formation.

Only with increased access to the central part of the island over the last 10 years has it been possible to examine some of these outcrops and to drill wells. Such drilling has shown that there are thick successions of limestone and variously dolomitized limestones in the central part of the island (Fig. 2.2 and 2.3). These successions do not include obvious unconformities and thus, questions arise regarding the stratigraphic affinity of these limestones.

An examination of a cross section that incorporates the deep wells on the east end of the island is key to understanding the affinity of these limestones (Fig. 2.4A). This cross section shows that RTR#1 is formed entirely of dolostone to a depth of 138 m. In contrast, the succession in NSC#1-2 comprises limestone from 0 to 60 m, dolomitic limestone from 60 to 120 m, and dolostone from 120 to 140 m (Fig. 2.4B). The succession in RWP#2, located on the north coast, is similar to

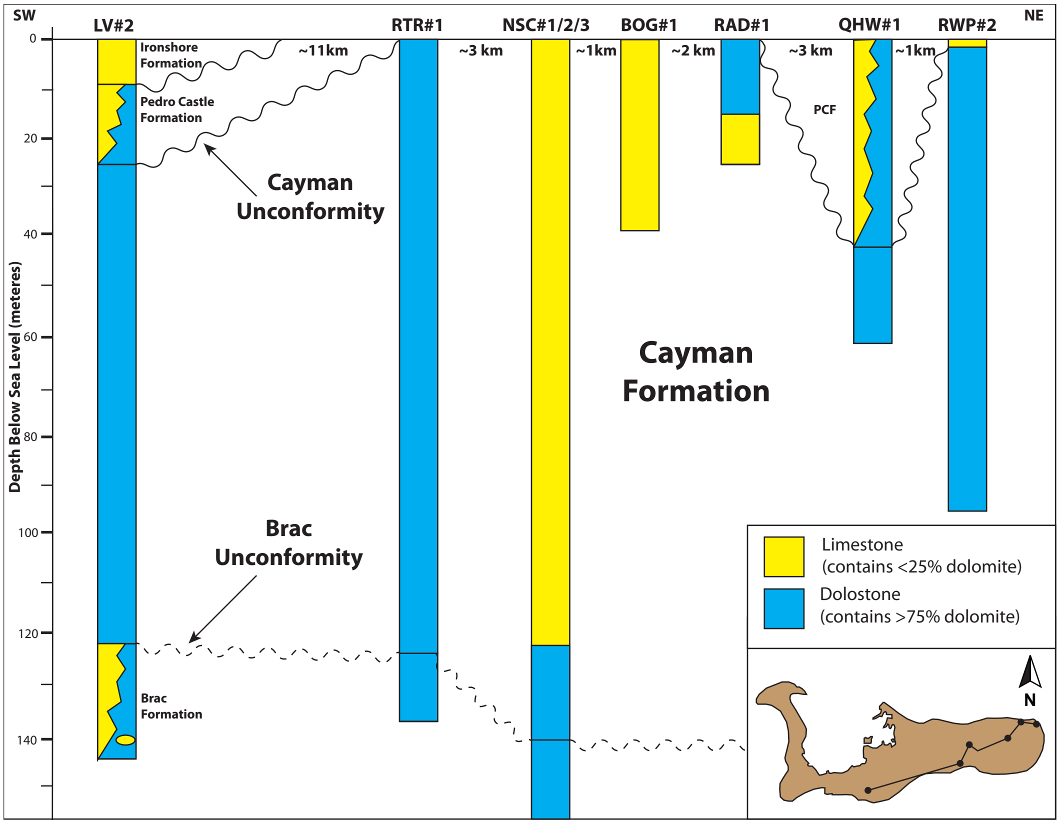

Figure 2.2. Lithology of stratigraphic units found in wells LV#2, RTR#1, NSC#1/2/3, BOG#1, RAD#1, QHW#1, and RWP#2 on Grand Cayman.

that in RTR#1, being formed entirely of dolostone to a depth of 95 m. It is clear from this cross section that wells on the coast are dolomitized whereas a lens of limestone and dolomitic limestone is present in the central part of the island. This pattern of dolostones in the peripheral regions of the island and variously dolomitized limestones and limestones in the interior of the island is maintained in all of the other wells drilled on the eastern part of the island.

By definition, the Cayman Formation is formed entirely of dolostone (Jones and Hunter, 1989; Jones, 1994). There is the possibility that the limestones and dolomitic limestones found in the central part of the island belong to the Pedro Castle Formation. This possibility, however, is deemed unlikely because examination of air photos, stratigraphic maps, and surface exposures reveal no evidence of faults or structural offset in the region, and no evidence of folding.

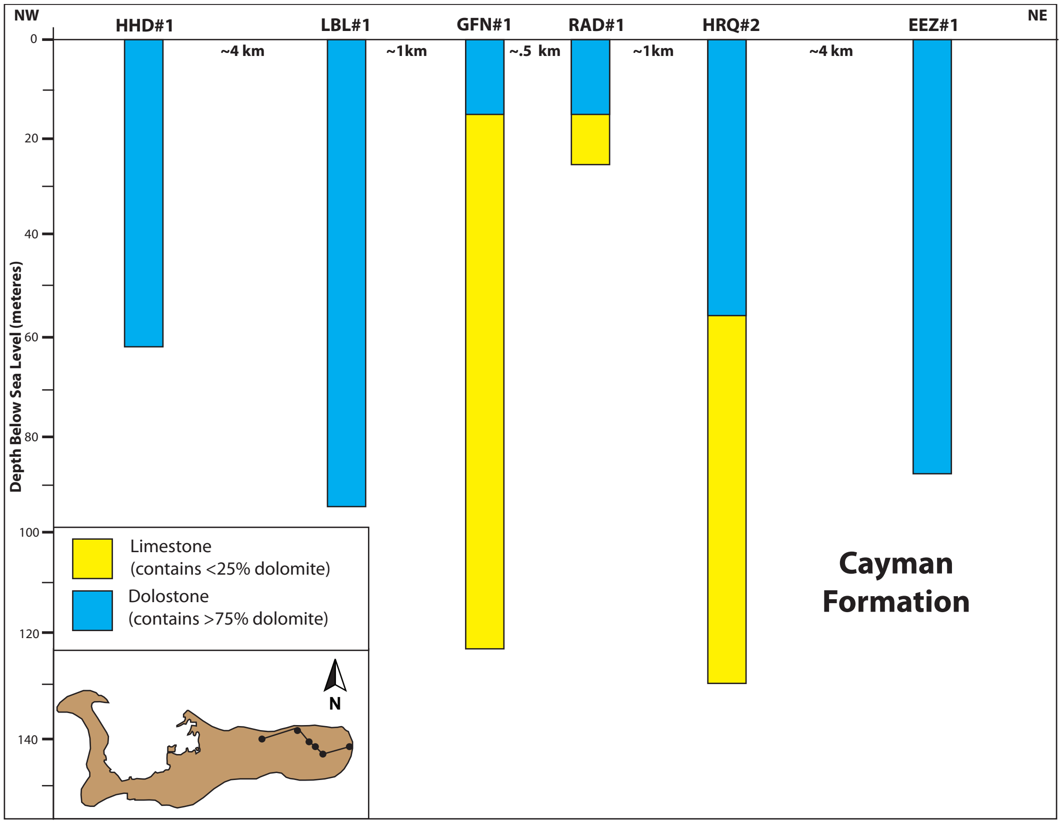

Figure 2.3. Lithology of the Cayman Formation in wells HHD#1, LBL#1, GFN#1, RAD#1, HRQ#2, and EEZ#1.

Furthermore, all other successions in the wells in the region fit the definition of the Cayman Formation. It appears, therefore, that the contrast between the coastal dolostones and interior limestones reflects diagenetic facies change within the Cayman Formation.

2.2.2. Revised Stratigraphy

The Cayman Formation is herein divided into two informal members: a 'dolostone member' and a 'limestone member'. The dolostone member contains an overall average of >75% dolostone, and the limestone member contains an average of <25% dolostone. The dolostone member of the Cayman Formation is found around the perimeter of the island, whereas the limestone member of the Cayman Formation is present in the central part of the east end of the island (Fig.

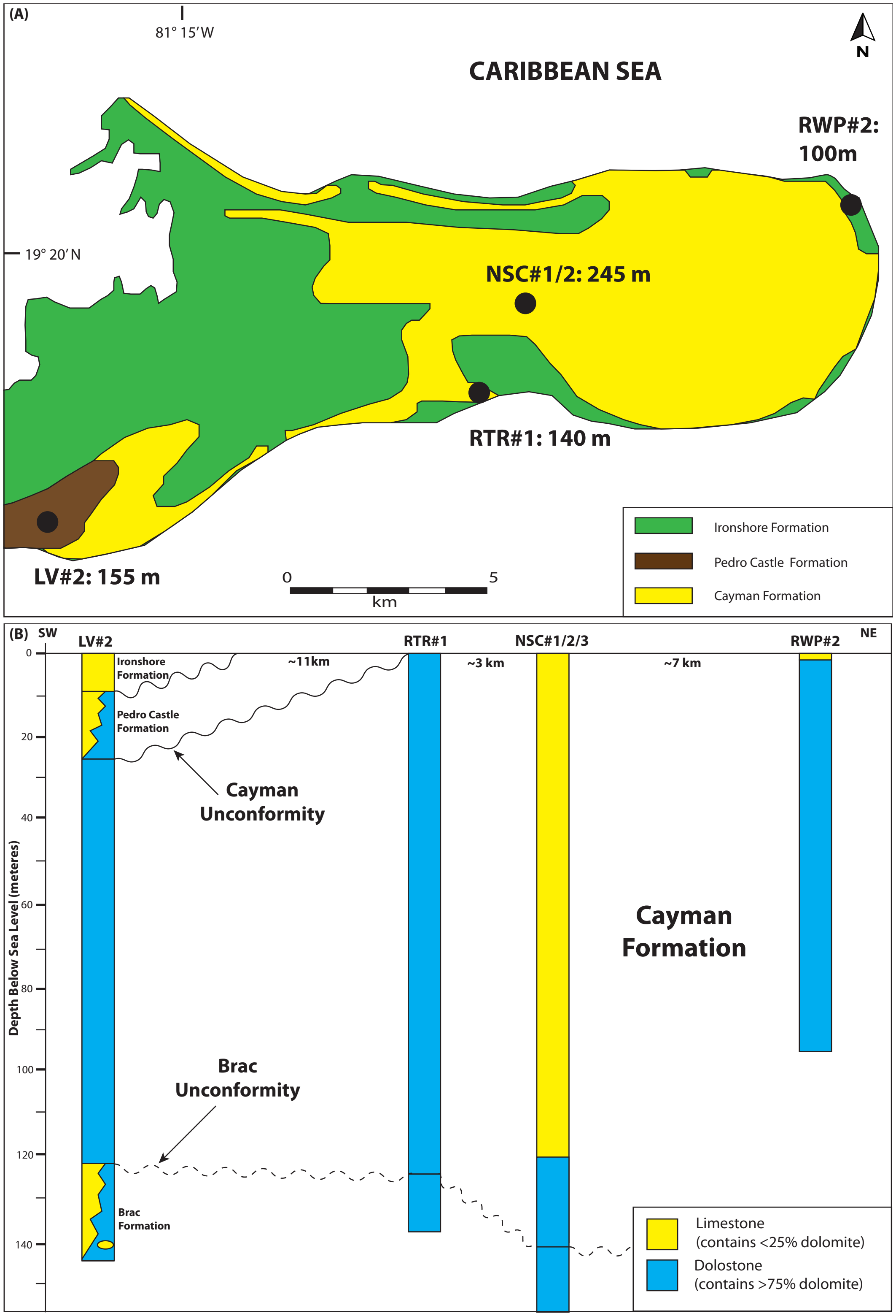

Figure 2.4. (A) Location of deep wells on the east end of Grand Cayman. (B) Lithological cross section showing that limestone is present in the Cayman Formation in the central part of the island. Wells on the perimeter of the island contain dolostone in the Cayman Formation.

2.4B).

The limestone and dolomitic limestone down to depth of 120 m in NSC#1-2 belongs to the limestone member of the Cayman Formation. This unit is not the Pedro Castle Formation because local geology indicates that there is no Pedro Castle Formation in the area. There is also no clear evidence of the Cayman Unconformity in the well as drilling is consistent, facies are consistent, the lithologies are the same, and there is no evidence of any unconformities.

2.2.3. Definition of Boundaries

The division of the Cayman Formation to include a dolostone member and a limestone member raises the problem of how to define the boundary between formations in the Bluff Group. The inclusion of a limestone member in the Cayman Formation makes the distinction between these three formations difficult based on lithological differences.

Although unconformities are apparent in some outcrops, it is extremely difficult to recognize the boundaries in well samples. This is possibly due to poor recovery, and/or insufficient data presently. Unless lithological differences or an obvious karst erosional surface can be observed, boundaries between formations in the Bluff Group are unclear. With the information that is available to date, this problem cannot be solved, and it is beyond the scope of this research.

2.3 SYNOPSIS

To date, the stratigraphic framework of Grand Cayman consists of four unconformity-bounded units: the Brac Formation, Cayman Formation, Pedro Castle Formation, and Ironshore Formation. The Cayman Formation is divided into two informal members: a 'dolostone member' and a 'limestone member'. The division of the Cayman Formation to include a limestone member renders defining the boundaries between the formations a challenge.

CHAPTER THREE:
FACIES AND FACIES ARCHITECTURE OF THE CAYMAN FORMATION

3.1. INTRODUCTION

3.1.1. Definitions

Facies in the Cayman Formation have commonly been described using a two-fold method with the megafossils (allochems > 2 cm) being described separately from the surrounding matrix (Jones and Hunter, 1994a; Wignall, 1995; Willson, 1998; Arts, 2000). This method is used because the data comes from large exposures (meters to 10 meters), drill core (3.5 cm diameter), and well cuttings (mostly < 1 cm long). Drill core and well cuttings restrict observations to areas that are < 3.5 cm wide whereas outcrops permit meter scale observations. Although megafossils, including corals that are commonly >10 cm long, are common in outcrops on Grand Cayman, there is a high probability that the 3.5 cm drill hole will cut through the intervening matrix and thus miss the large fossils. Thus, a facies that would be classified as a floatstone in an outcrop may appear as a mudstone in core. Similar issues of scale exist between the well cuttings and full-diameter core. Another complication arises due to the fact that many of the large allochems (e.g., corals) are leached and thus represented by cavities that are not evident in cuttings and not readily apparent in core.

3.1.2. Allochems and Preservation

Dolostones and limestones in the Cayman Formation contain a wide variety of allochems. Megafossils are dominated by branching corals (*Porites* and *Stylophora*) with lesser numbers of domal and platy corals (*Montastrea*, *Leptoseris*). Other common allochems include rhodolites, solitary corals, and bivalves. Although the finer-grained matrices include numerous benthic foraminifera (*Amphistegina*, *Sphareogypsina*, miliolinids, *Homotrema*), *Amphistegina* is the dominant benthic species throughout the formation. Coralline red algae, *Halimeda*, bivalves, gastropods, rhodolites, echinoids, and planktonic foraminifera are also found in varying numbers.

The variable preservation of allochems is fundamentally related to the original skeletal mineralogy. Corals, bivalves, and gastropods that had aragonite skeletons are now represented by molds. *Stylophora*, *Montastrea, Leptoseris*, and solitary corals are invariably leached and are identifiable only from internal and/or external molds. The leaching commonly reveals corallite imprints or filled calices as well as mud filled sponge borings in the coral (*Entobia* – cf. Pleydell and Jones, 1988). *Halimeda*, bivalves, and gastropods are commonly leached and preserved as distinct hollow or mud filled molds. The benthic foraminifera (*Amphistegina*, *Sphareogypsina*, miliolinids, *Homotrema*), originally formed of low magnesium calcite, are variably preserved. Some have been replaced by fabric retentive dolomite (Fig. 3.1A) whereas others are leached to varying degrees (Fig. 3.1B).

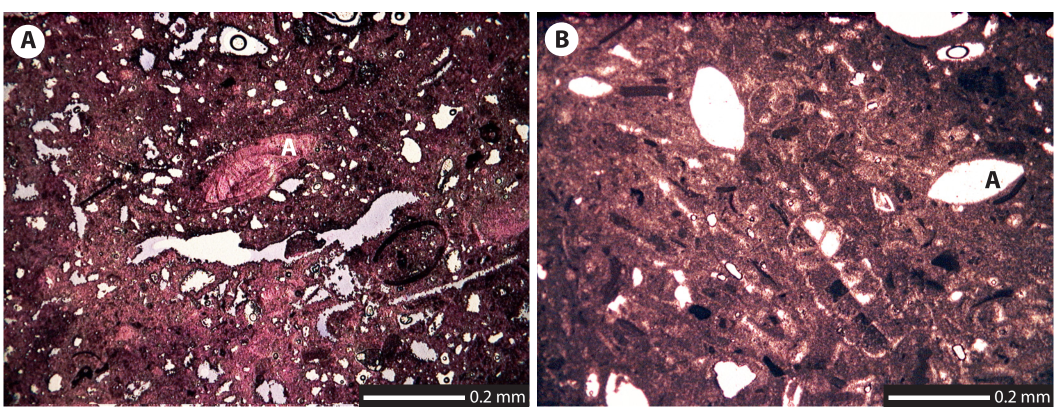

Figure 3.1. Variable preservation in the Cayman Formation. A = *Amphistegina*. (A) *Amphistegina* replaced by fabric-retentive dolomite (NSC#1) 148 m. (B) Leached *Amphistegina* (RWP#2) 78 m.

Coralline red algae and planktonic foraminifera are generally preserved by fabric retentive dolomites. Rhodolites are recognizable by cortical coatings surrounding coral nuclei that are commonly leached. Echinoderms are commonly replaced by dolomite and are distinct in thin sections as uniaxial crystals that are commonly surrounded by syntaxial overgrowths.

3.2. FACIES OF THE CAYMAN FORMATION

The Cayman Formation in the study area is divided into eight facies (Fig. 3.2) that are defined by the fossil content. Facies are named according to the most abundant allochems present with the allochems being listed in order of decreasing abundance. Matrices are named according to Embry and Klovan's (1971) modifications to Dunham's (1962) classification scheme.

3.2.1. *Leptoseris-Amphistegina* facies

Numerous *Leptoseris*, which dominate this facies, occur as fragmented pieces up to 5 x 5 cm (Fig. 3.3A). Scattered fragments of *Montastrea* (3 x 2 cm), *Porites* (2 x 2 cm), *Stylophora* (2 x 1 cm), and solitary corals (2 x 1 cm) are also present. The wackestone matrix contains numerous benthic (mainly *Amphistegina)* and planktonic foraminifera along with scattered bivalves, gastropods, *Halimeda*, red algae, and echinoids.

3.2.2. Branching and Platy Coral-*Amphistegina*-Red Algae facies

This facies contains numerous *Porites* and *Stylophora*. *Porites* fragments are up to 4 x 3 cm whereas *Stylophora* occurs as thick (5 x 3 cm) to thin (2 x 1 cm) branches. Fragments of *Leptoseris*, up to 5 x 5 cm, are also common along with scattered rhodolites (2 cm diameter) and solitary corals (2 x 1 cm). The wackestone matrix is dominated by *Amphistegina* and red algae. Other allochems present in the matrix include fragments of Halimeda, bivalves, gastropods, and echinoids.

FACIES	TEXTURE	MAJOR ALLOCHEMS AND MATRIX COMPONENTS	MINOR ALLOCHEMS AND MATRIX COMPONENTS
Amphistegina Bivalve	Wacke-graintstone	**MATRIX** *Amphistegina*, Bivalves, Large Benthic Foraminifera, Gastropods, *Halimeda*	**MEGAFOSSILS** *Stylophora, Porites,* Rhodolites **MATRIX** Red Algae
Rhodolite Coral *Amphistegina*	Floatstone with a wacke-packstone matrix	**MEGAFOSSILS** Rhodolites, *Porites, Stylophora, Montastrea* **MATRIX** *Amphistegina*	**MEGAFOSSILS** *Leptoseris* **MATRIX** Red Algae, *Halimeda*, Bivalves, Gastropods, Echinoids
Rhodolite Branching Coral *Amphistegina*	Floatstone with a wacke-packstone matrix	**MEGAFOSSILS** Rhodolites, *Porites, Stylophora* **MATRIX** *Amphistegina*	**MEGAFOSSILS** *Montastrea* **MATRIX** Red Algae, *Halimeda*, Bivalves, Gastropods
Porites Amphistegina	Floatstone with a mud-packstone matrix	**MEGAFOSSILS** *Porites* **MATRIX** *Amphistegina*	**MEGAFOSSILS** *Stylophora,* Bivalves, Solitary Corals **MATRIX** Red Algae, *Halimeda*
Branching Coral Benthic Foraminifera	Floatstone with a wacke-packstone matrix	**MEGAFOSSILS** *Porites, Stylophora* **MATRIX** *Amphistegina, Sphaeogypsina*	**MEGAFOSSILS** *Montastrea, Leptoseris,* Solitary Corals **MATRIX** Red Algae, *Halimeda*, Bivalves, Gastropods, Echinoids
Branching and Domal Coral *Amphistegina*	Floatstone with a wacke-packstone matrix	**MEGAFOSSILS** *Porites, Stylophora, Montastrea, Leptoseris* **MATRIX** *Amphistegina*	**MEGAFOSSILS** Rhodolites **MATRIX** Bivalves, Red Algae, *Halimeda*
Branching and Platy Coral *Amphistegina* Red Algae	Floatstone with a wackestone matrix	**MEGAFOSSILS** *Porites, Stylophora, Leptoseris* **MATRIX** *Amphistegina,* Red Algae	**MEGAFOSSILS** Rhodolites, Solitary Corals **MATRIX** *Halimeda,* Bivalves, Gastropods, Echinoids
Leptoseris Amphistegina	Floatstone with a wackestone matrix	**MEGAFOSSILS** Leptoseris **MATRIX** *Amphistegina*	**MEGAFOSSILS** *Montastrea, Porites, Stylophora,* Solitary Corals **MATRIX** Bivalves, Gastropods, *Halimeda*, Planktonic Foraminifera, Red Algae, Echinoids

Figure 3.2. Facies in the Cayman Formation.

3.2.3. Branching and Domal Coral-*Amphistegina* facies

The presence of *Montastrea* differentiates this facies from the Branching and Platy Coral-*Amphistegina*-Red Algae facies (Fig. 3.3B). This facies also contains numerous *Porites* fragments (3 x 1 cm), thick branches of *Stylophora* (5 x 3 cm), and *Leptoseris* (5 x 5 cm). *Leptoseris* is less abundant than the other corals. *Montastrea* occurs either intact or as fragmented pieces up to 10 x 5 cm. Scattered rhodolites (< 2 cm diameter) are also present. The wackestone to packstone matrix is dominated by *Amphistegina* and fragments of bivalves, red algae, and *Halimeda*.

3.2.4. Branching Coral-Benthic Foraminifera facies

Numerous *Porites* and *Stylophora* dominate this facies. *Porites* occurs as fragments up to 4 x 3 cm (Fig. 3.4). *Stylophora* occurs as thick (5 x 3 cm) to thin (2 x 1 cm) branches (Fig. 3.5). Other less abundant corals in this facies include fragments of *Montastrea* (5 x 4 cm), *Leptoseris* (5 x 3 cm), and solitary corals (2 x 1 cm). The wackestone to packstone matrix is dominated by *Amphistegina* and *Sphaerogypsina* along with fewer fragments of red algae, *Halimeda*, bivalves, gastropods, and echinoids.

3.2.5. *Porites-Amphistegina* facies

This facies is dominated by numerous *Porites* (up to 2 x 1 cm) that are held in a *Amphistegina* dominated mudstone to wackestone matrix (Fig. 3.6A). Scattered *Stylophora* (2 x 1 cm), solitary corals (2 x 1 cm), and bivalves (2 x 1 cm) are also present in this facies, but they are less abundant than *Porites*. Other allochems present in the matrix include red algae and *Halimeda* fragments.

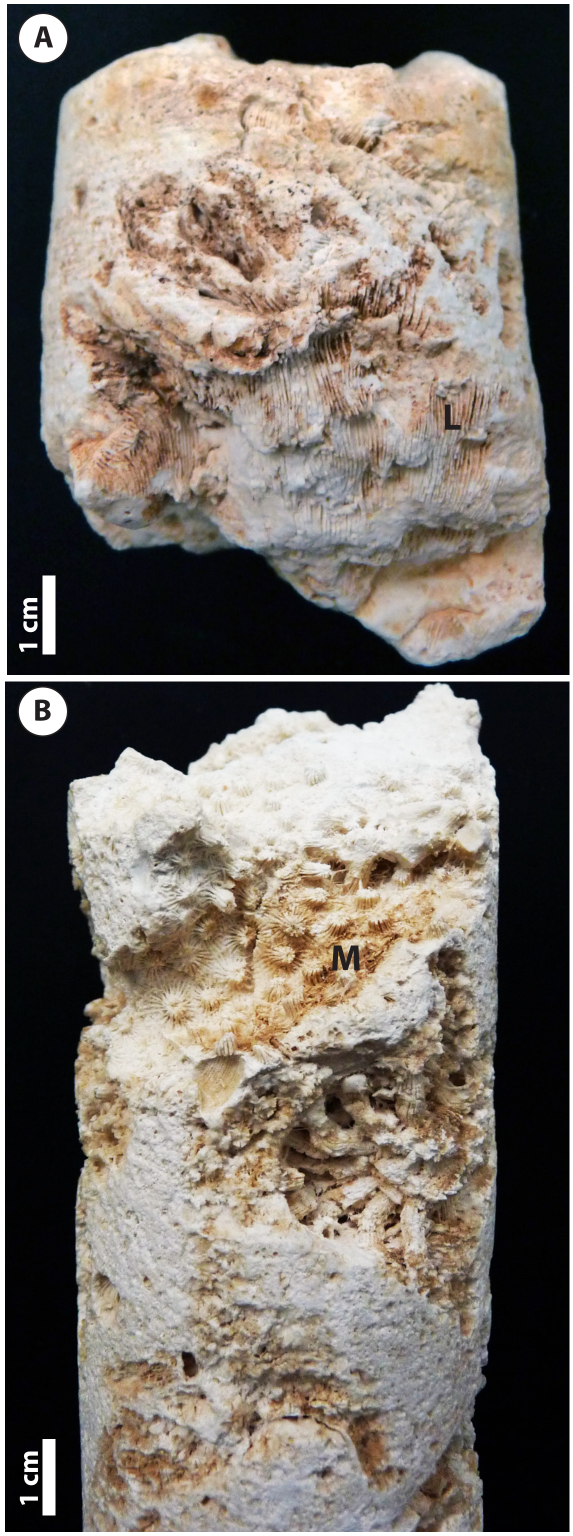

Figure 3.3. L = *Leptoseris*; M = *Montastrea*.
(A) *Leptoseris-Amphistegina* Facies (NSC#2: C-19). Dolostone; 68 m.
(B) Branching and Domal Coral-*Amphistegina* Facies (NSC#2: C-15). Limestone; 50 m.

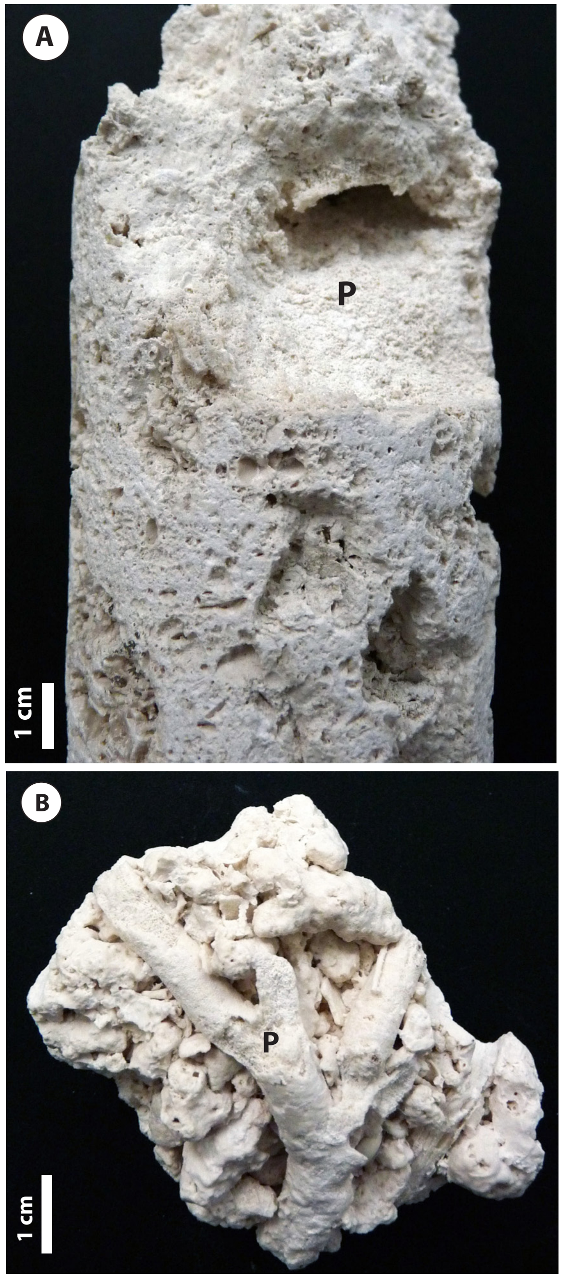

Figure 3.4. Branching Coral-Benthic Foraminifera Facies. P = *Porites*.
(A) Leached mold of *Porites* (NSC#2: C9-1). Limestone; 18 m.
(B) Mold of small diameter branch of *Porites* (HHD#1:30). Dolostone; 23 m.

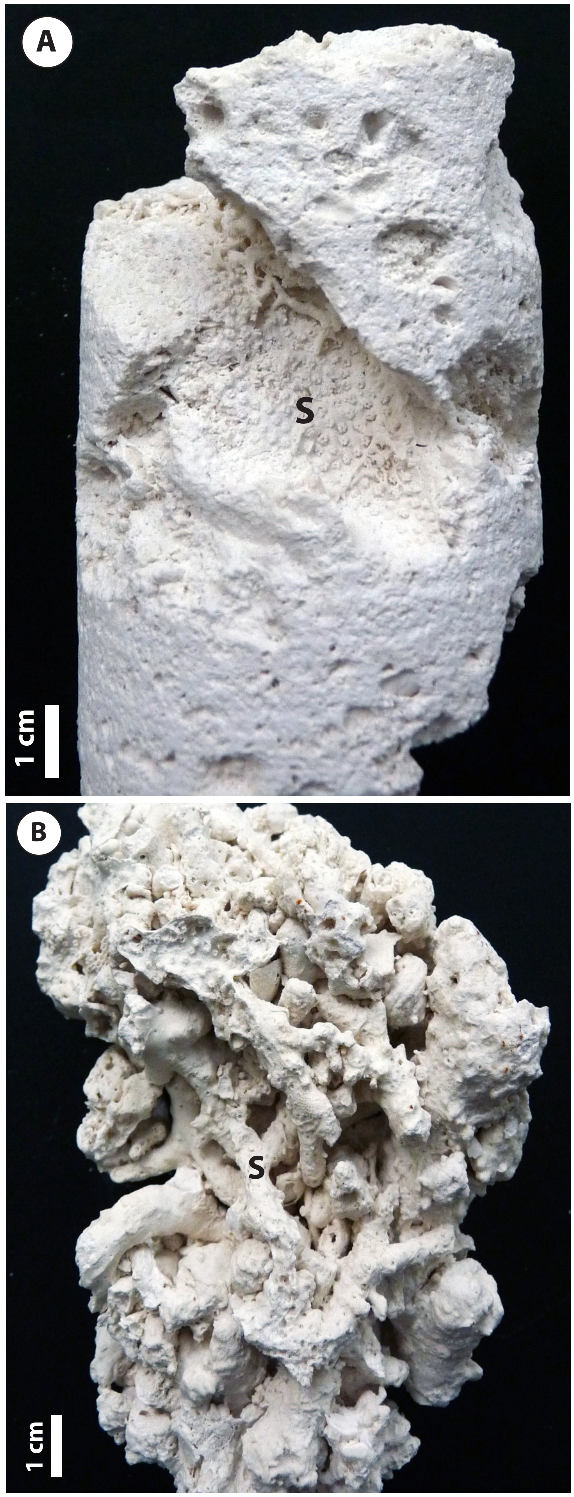

Figure 3.5. Branching Coral-Benthic Foraminifera Facies. S = *Stylophora*.
(A) Leached mold of *Stylophora* (NSC#2: C8-2). Limestone; 20 m.
(B) Mold of small diameter branches of *Stylophora* (HHD#1:30). Dolostone; 23 m.

3.2.6. Rhodolite-Branching Coral-*Amphistegina* facies

Numerous *Porites* (2 x 1 cm) and *Stylophora* (5 x 1 cm) and rhodolites with *Porites* and *Stylophora* nuclei (1-3 cm diameter) dominate this facies (Fig. 3.6B). Rhodolites are generally spherical due to the shape of the spherical nucleus, which is a fragment of a delicately branching *Porites* or *Stylophora*. Other corals present in this facies include fragments of *Montastrea* (5 x 4 cm). *Amphistegina* dominates the wackestone to packstone matrix that also contains scattered red algae, *Halimeda*, bivalves, and gastropod fragments.

3.2.7. Rhodolite-Coral-*Amphistegina* facies

This facies contains a diverse coral assemblage and numerous rhodolites. Thick (5 x 4 cm) to thin (2 x 1 cm) branches of *Porites*, thick (5 x 3cm) to thin (2 x 1 cm) branches of *Stylophora*, and fragmentary *Montastrea* (10 x 5 cm) with scattered fragments of *Leptoseris* (5 x 5 cm) are found in this facies. Numerous rhodolites range from 5 x 4 cm to 1 x 1 cm in size according to the size and shape of their nuclei (Fig. 3.7A). Larger, more irregularly shaped rhodolites encrust thick branches of *Porites* or *Montastrea* fragments whereas smaller, rounder rhodolites encrust thinly branching *Porites* or *Stylophora* (Fig. 3.7B). *Amphistegina* dominates the wackestone to packstone matrix of the floatstone. Scattered red algae, *Halimeda*, bivalves, gastropods, and echinoid fragments are also present in the matrix.

3.2.8. *Amphistegina*-Bivalve facies

This facies is distinct because it contains a diverse biota that is dominated by benthic foraminifera and bivalves rather than corals. Texture ranges from wackestones to grainstones. Wackestones contain numerous *Amphistegina* (< 1 mm long), bivalves (1-2 cm), gastropods (0.5-2 cm), and *Halimeda* plates (1 cm

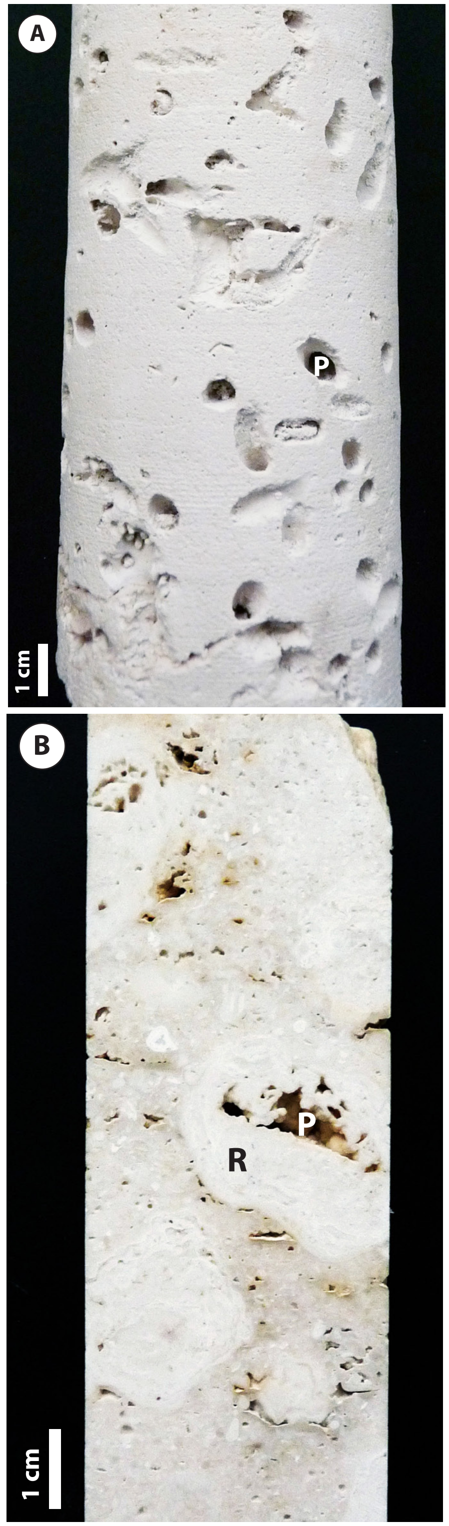

Figure 3.6. (A) *Porites-Amphistegina* Facies. P = *Porites*. (RAD#1: 6-13). Dolostone; 10 m.
(B) Rhodolite-Branching Coral-*Amphistegina* Facies. R = Rhodolite. (RWP#2: 21-6). Dolostone; 7 m.

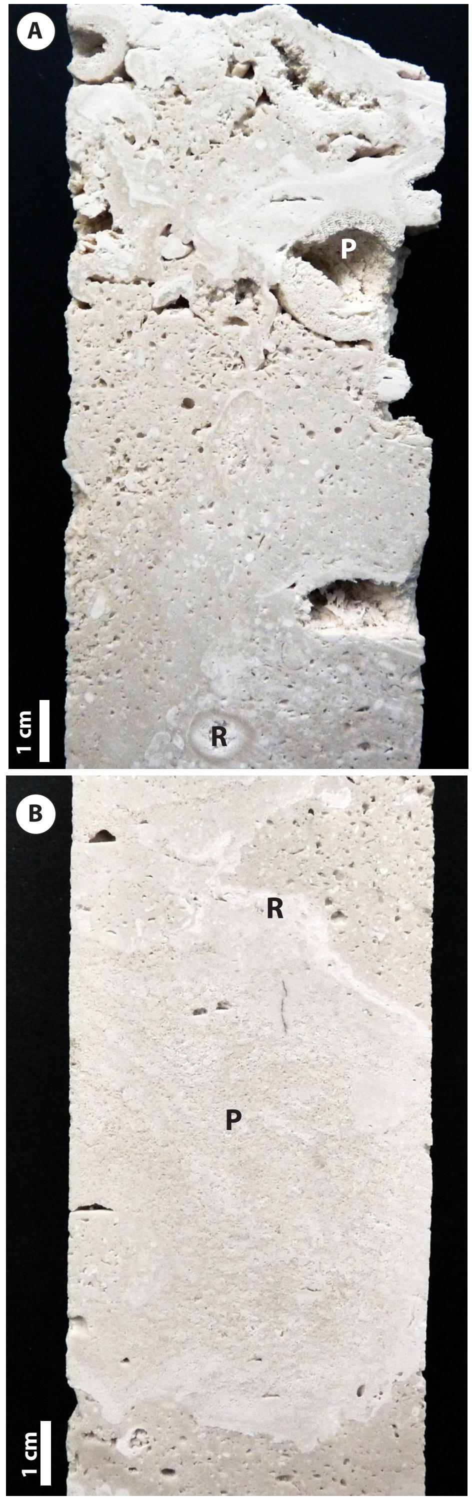

Figure 3.7. Rhodolite-Coral-*Amphistegina* Facies. P = *Porites*; R = Rhodolite.
(A) Small rhodolite encrusting *Porites* (LV#2: 1-3B). Dolostone; 25 m.
(B) Large rhodolite encrusting *Porites* (LV#2: 3-3a). Dolostone; 35 m.

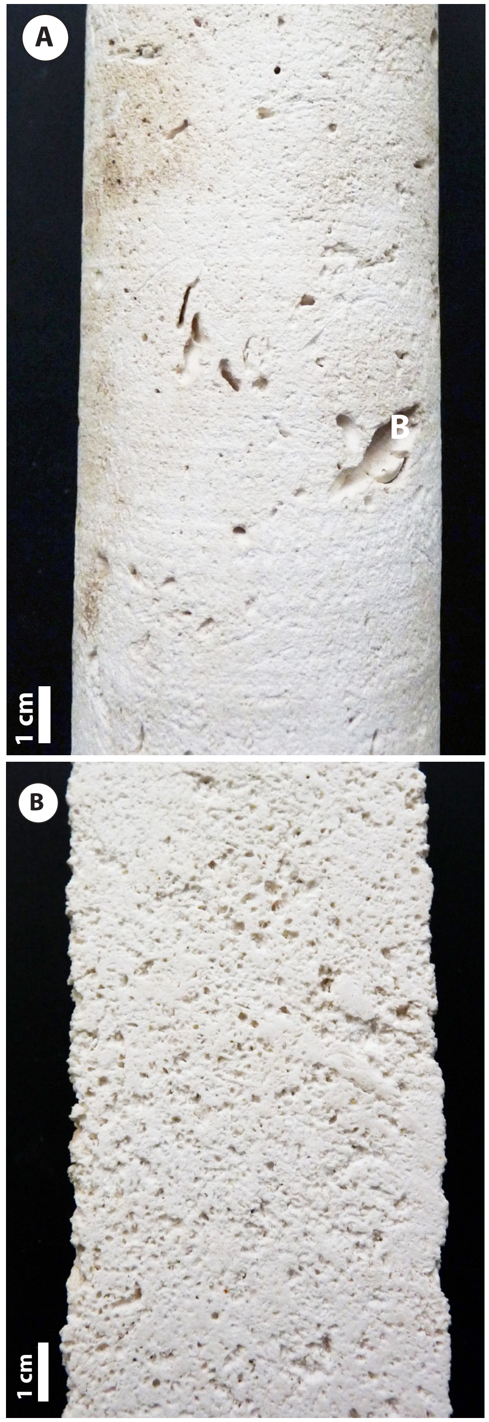

Figure 3.8. *Amphistegina*-Bivalve Facies. B = Bivalve mold.
(A) Leached bivalve molds (RAD#1: 8-21). Dolostone; 15 m.
(B) Leached *Amphistegina* molds (LV#2: 19-5b). Dolostone; 114 m.

length) (Fig. 3.8A). Some *Amphistegina* and *Discocyclina* up to 2 cm in diameter are also present. These large benthic foraminifera are found only in this facies. Scattered rhodolites (2 cm diameter), *Stylophora* (2 x 1 cm), and *Porites* (2 x 1 cm) are also present. Grainstones are dominated by *Amphistegina* (1 mm) and *Halimeda* plates (1 cm length) (Fig. 3.8B). Scattered red algae fragments are present in both wackestones and grainstones.

3.3. COMPARISON OF FACIES WITH OTHER STUDIES

Hunter (1994) examined the diverse coral biota in the Cayman Formation and Pedro Castle Formation. The coral fauna was divided into seven associations that were named after the dominant taxa. Willson (1998) examined the Cayman Formation found in the succession in RWP#2 and named five facies. Many of the facies defined during this study can be correlated with those defined by Hunter (1994) and Willson (1998) (Fig. 3.9).

3.4. FACIES ARCHITECTURE

A ~22 km southwest to northeast stratigraphic cross section, from Lower Valley to Roger's Wreck Point, herein called Transect 1 (Fig. 3.10) and a ~11 km northwest to east cross section, from Malportas Pond to East End, herein called Transect 2 (Fig. 3.11), provide an extensive view of the lateral and vertical facies variations. In the following discussion of the facies architecture, the depths of the facies are expressed in meters below sea level (mbsl) to the top of the facies.

3.4.1. Transect 1

Examination of Transect 1 reveals the following important points.

1. The Branching and Domal Coral-*Amphistegina* facies, which is 10-25 m thick, can be traced across the entire 22 km cross section from west to east

THIS STUDY	HUNTER 1994	WILLSON 1998
Amphistegina-Bivalve	————	————
Rhodolite-Branching Coral-*Amphistegina*	————	Rhodolite Finger Coral Floatstone to Rudstone Facies
Rhodolite-Coral-*Amphistegina*	————	Rhodolite Coral Fragment Rudstone to Grainstone Facies
Porites-Amphistegina	*Porites baracoaensis* Association	————
Branching Coral-Benthic Foraminifera	*Stylophora-Porites* Association, *Stylophora* Association	*Stylophora* Floatstone Facies
Branching and Domal Coral-*Amphistegina*	*Montastrea limbata* Association	*Porites Leptoseris Montastrea Stylophora* Floatstone Facies
Branching and Platy Coral-*Amphistegina*-Red Algae	*Leptoseris* Association, *Stylophora-Porites* Association	————
Leptoseris-Amphistegina	*Leptoseris* Association	*Leptoseris Montastrea* Floatstone Facies

Figure 3.9. Comparison of facies identified in this study with coral associations of Hunter (1994) and facies of Willson (1998).

at a depth of 30-40 mbsl.

2. The *Leptoseris-Amphistegina* facies is found at two stratigraphic levels with the lower one being laterally restricted and the upper one laterally widespread. The lower level is only found in well NSC#1-3 at 122 mbsl. To the west, the facies is deposited on the inferred irregular surface of the Brac Unconformity and is not present in wells LV#2 and RTR#1. To the east of this well core data is unavailable beyond 90 m from wells in Transect 1 (Fig. 3.10). The upper level of this facies (5-20 m thick), 60-70 mbsl, is found in every well except for RWP#2 (Fig. 3.10).
3. The *Amphistegina*-Bivalve facies is found at three stratigraphic levels. At 80-110 mbsl, this facies (10-30 m thick) is traceable for ~16 km between LV#2, RTR#1, and NSC#1-3. The middle level of this facies (~ 20 m thick), at 20 mbsl, can be traced for 2 km between wells BOG#1 and RAD#1. To the east of RAD#1, well QHW#1 contains a sinkhole (Willson, 1998), which cuts down through the upper part of the Cayman Formation. The upper level (10 m thick), found at a depth of 0 mbsl is restricted to well NSC#1-3.
4. The *Amphistegina*-Bivalve facies is also found in the bottom 135 m in NSC#3; however, this is not included on Transect 1 (Fig. 3.10). This well is much deeper than surrounding wells in the cross section and presently, correlations are not possible.
5. Several facies are laterally restricted along Transect 1 including the Rhodolite-Coral-*Amphistegina* facies, the Rhodolite-Branching Coral-*Amphistegina* facies, the *Porites-Amphistegina* facies, and the Branching Coral-Benthic Foraminifera facies. The Rhodolite-Coral-*Amphistegina* facies and Rhodolite-Branching Coral-*Amphistegina* facies, which are each 10-25 m thick, are found only in wells LV#2, RTR#1, and RWP#2.

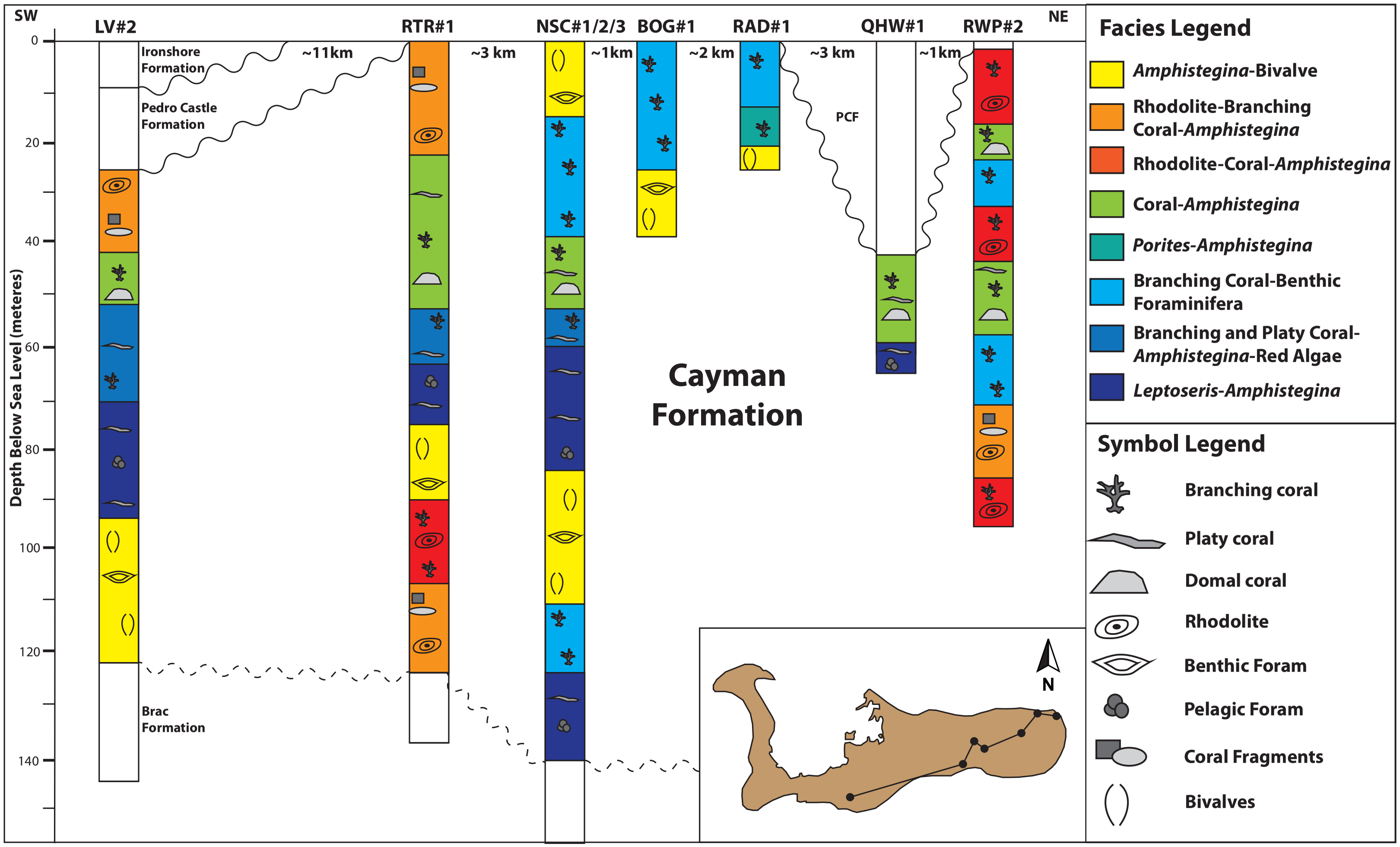

Figure 3.10. Transect 1. Distribution of facies in the Cayman Formation. Well cuttings analyzed from well RTR#1. Core examined from other wells.

Although the rhodolite-dominated facies is laterally restricted, it is found at several stratigraphic levels (Fig. 3.10). The Branching Coral-Benthic Foraminifera facies are also laterally restricted, as it is found locally in wells NSC#1-3, BOG#1, RAD#1, and RWP#2. This facies occurs vertically numerous times in well RWP#2, but it is laterally restricted. At a depth of 0-15 mbsl this facies is locally common and correlates laterally 3 km across wells NSC#1-3, BOG#1, and RAD#1 at a thickness of 10-20 m (Fig. 3.10).

3.4.2. Transect 2

Examination of Transect 2 reveals the following important points.

1. The Branching and Domal Coral-*Amphistegina* facies (10-25 m thick) is laterally continuous and can be traced 11 km from west to east at a depth of 50-68 mbsl (Fig. 3.11).
2. The *Leptoseris*-*Amphistegina* facies (5-25 m thick) is also laterally continuous and can be traced 11km from west to east at a depth of 32-58 mbsl (Fig. 3.11).
3. The *Amphistegina*-Bivalve facies is found at numerous stratigraphic levels. At 75 mbsl a ~40 m thick interval of this facies occurs in HRQ#2. At 0-45 mbsl, this facies (5-30 m thick) is laterally traceable for 7 km (Fig. 3.11).
4. Several facies are laterally restricted along Transect 2 including the Rhodolite-Branching Coral-*Amphistegina* facies and the *Porites*-*Amphistegina* facies. The Rhodolite-Branching Coral-*Amphistegina* facies (5 m thick) is found only in well LBL#1 at 88 mbsl. The *Porites*-*Amphistegina* facies (5 m thick) is only present in wells RAD#1 and GFN#1 at 15 mbsl (Fig. 3.11).

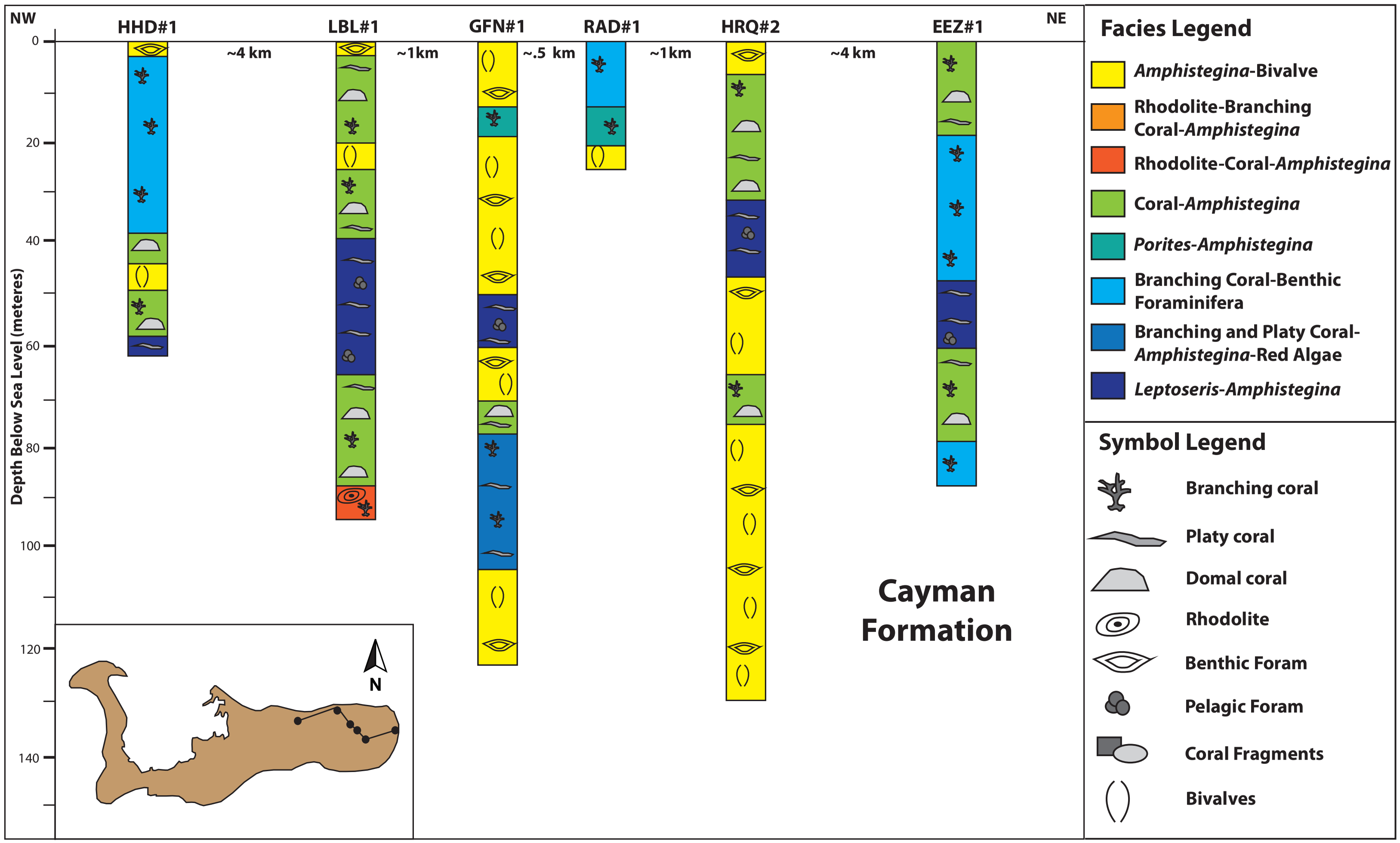

Figure 3.11. Transect 2. Distribution of facies in the Cayman Formation. Core analyzed from RAD#1. Well cuttings examined from other wells.

Analysis of the facies evident along Transect 1 and Transect 2 shows that (1) some facies are widespread and can be traced along the entire cross section, (2) some facies are laterally restricted to particular wells, and (3) the succession can be divided into two sequences (Fig. 3.10, 3.11).

3.4.3. Sequences in the Cayman Formation

The Cayman Formation can, on the basis of its constituent facies, be divided into the lower and upper sequences, herein called S1 and S2. The lower sequence S1, typically ~40 m thick, is overlain by the upper sequence S2 that is typically ~70 m thick. The boundary between the two sequences, usually at a depth of 70-90 mbsl, is placed at the base of the laterally continuous stratigraphic level of the *Leptoseris*-*Amphistegina* facies. The depth of the boundary varies for 20 m due to lateral variation in the thickness of the *Leptoseris*-*Amphistegina* facies across the bank.

Generally in S1, platy coral dominated facies assemblages grade into branching and domal coral dominated coral assemblages. At the top of this coral succession is the *Amphistegina*-Bivalve facies (Fig. 3.11, 3.12). The boundary between S1 and S2 is defined by a repeat of this succession whereby platy coral dominated facies overly the *Amphistegina*-Bivalve facies at the top of S1. The facies succession in S2 is essentially a repeat of the facies succession in S1.

3.5 SYNOPSIS

There are eight facies in the Cayman Formation on the eastern half of Grand Cayman. Facies delineation is on the basis of biota content, matrix composition, and texture. The distribution of these units varies laterally and vertically and also in terms of stratigraphic thickness; however, each contains characteristics that make them distinct and easily recognizable. The succession can be divided into two sequences, S1 and S2, based on the repetition of facies in each sequence.

CHAPTER FOUR:
FACIES INTERPRETATION

4.1. FACIES ANALYSIS AND PALEOENVIRONMENT

Carbonate depositional systems commonly contain a diverse array of organisms that are very sensitive to local environmental conditions (Wells, 1967; Hallock and Glenn, 1986; Bosence, 1983; Jones and Hunter, 1994a). Factors such as energy levels, salinity, temperature, light conditions, nutrient levels, and substrate can control the distribution of many organisms, as most tend to live in specific marine conditions. Facies analysis of a rock succession can provide insight into the depositional regime if the ecological factors controlling the distribution of the organisms are known.

Plants and animals used in this study to interpret paleoenvironmental conditions include red algae, green algae, benthic foraminifera, planktonic foraminifera, corals, echinoids, bivalves, and gastropods. There are inherent problems when using these organisms to interpret the original environment of deposition. Although the presence of a particular organism may indicate a specific environment, it may have actually lived in a different environment due to adaptation. There is also the issue of transportation. Shells and remains of an organism might have been moved from their original setting by storms. Another major problem is the identification of the taxa in terms of extant taxa. It is important to consider the overall fossil assemblage and abundance, rather than the presence of a particular organism in order to gain a better interpretation of what the original environment of deposition was.

4.2. ENVIRONMENTAL IMPLICATIONS OF ALLOCHEMS

4.2.1. Foraminifera

Foraminifera are sarcodine protistans, which includes a large and diverse number of living and fossil species that occur abundantly in modern and ancient marine environments. Fossil foraminifera are excellent tools for paleoenvironmental interpretations because most of them lived in well-defined and well-understood ecological niches. They have been studied for many years, and quantitative studies on their distribution and ecology are numerous (Phleger, 1964; Funnell, 1967; Hallock and Glenn, 1986; van der Zwaan *et al*., 1990; Boltovskoy *et al*., 1991; Li and Jones, 1997; Armynot du Chalet, 2009).

Water depth and temperature are the main controls on the distribution of foraminifera. Distinctive foraminifera faunas characterize marine marshes, lagoons, barrier islands, continental shelves continental slopes, and the deep sea (Phleger, 1964). Benthic foraminifera are abundant in a range of environments but are most common on the continental shelf. Encrusting foraminifera commonly coat sea grasses in the back reef/lagoonal setting and are characterized by a flat ventral side (Hallock and Glen, 1986). Planktonic foraminifera tend to occur in large numbers offshore to deep-sea environments (Funnell, 1967).

Amphistegina

Amphistegina, a common Caribbean reefal taxon, is the most abundant benthic foraminifera found in the Cayman Formation. This benthic genus has a widespread distribution and cannot be considered diagnostic of any one particular environment (Cushman *et al*., 1954). *Amphistegina* inhabits reef, near reef, and carbonate bank environments in water depths less than 100 m (Cushman *et al*., 1954; Crouch and Poag, 1979). These foraminifera live primarily as epibionts on sea grasses and hard substrates and may also live in or on soft sediments (Crouch and Poag, 1979; Hottinger and Dreher, 1975; Li and Jones, 1997). Although the influence of depth is difficult to separate from the effects of other ecological parameters, some morphologic variations have been linked to variations in depth (Hallock and Glenn, 1986; Boltovskoy, 1991). The presence of thinner walled tests and a flatter, more lenticular shape, for example, has been attributed to lower light levels and quieter waters. In contrast, more robust and spherical forms characterize shallow (generally <10 m), high-energy environments (Hallock and Glen, 1986).

Large Benthic Foraminifera

Large Benthic Foraminifera (LBF), common in the Cayman Formation, are characterized by their centimeters-size as well as complex internal morphologies that are related to algal symbiosis. Algal symbiosis in LBF is comparable to that found in hermatypic corals in terms of growth stimulation and carbonate fixation (Ross, 1972; Hallock and Glenn, 1986). Thus, most living foraminifera are restricted to relatively shallow, well-lit waters. Modern and fossil foraminifera are associated with shallow water tropical-subtropical carbonate sediments and are generally indicative of depths much less than 100 m (Chaproniere, 1975; Hallock and Glenn, 1986). LBF are important paleoenvironmental indicators and have been studied for many years (Frost and Langenheim, 1974; Chaproniere, 1975; Hallock and Glenn, 1986; Boltovskoy, 1991; Bensing *et al*., 2008). These studies provide a better understanding of basic ecologic trends in larger foraminifera and show that, like benthic foraminifera, different morphologies characterize different energy and light conditions related to their depth distribution.

Planktonic Foraminifera

Planktonic foraminifera are rare in the Cayman Formation, but their presence can be very useful for paleoenvironment interpretations. Planktonic foraminifera are microscopic stenohaline organisms that inhabit offshore to deep basin water masses (Phleger, 1964). Living and fossil planktonic foraminifera are easily identifiable by their microscopic size and chambered shell and are well studied for their ability to characterize bodies of oceanic water for paleoenvironment and paleotemperature research (Smith, 1955; Phleger, 1964; Funnell, 1967; Hallock and Glenn, 1986; van der Zwaan *et al*., 1990; Field *et al*., 2006). The presence of planktonic foraminifera in the succession on Grand Cayman indicates that the bank was open to circulation from deeper ocean waters.

4.2.2. Calcareous Algae

Calcareous algae are calcified aquatic plants that produce their own food using photosynthetic energy and lack the vascular tissue of higher plants (Scoffin, 1987). As light dependent organisms, they are useful fossils for paleoenvironment interpretations.

Green Algae

Green algae are important constituents of lagoonal/ back reef environments. Utilizing a strong root system, green algae colonize reefs, flat bottom plains of sand, rubble, and hard substrates. *Halimeda*, a common form of green algae in the Cayman Formation, is a major contributor to present day carbonate sediments in the tropics (Kooistra *et al*., 2002). Other green algae taxons, such as *Penicillus*, are not identified in the Cayman Formation because they probably disintegrated into mud-size particles. *Halimeda* may live down to depths of 70 m but are most productive in depths < 15 m in quiet water settings

(Hine *et al*., 1988; Liddell *et al*., 1988; Kooistra *et al*., 2002). Most species of *Halimeda* prefer hard substrates but may live in sandy sediments (Goreau, 1963).

Red Algae

There are two distinct groups of coralline red algae: (1) articulated corallines in which uncalcified zones divide calcified segments, and (2) crustose corallines that either encrust hard substrates or occur as free-living structures called rhodolites (Bosence, 1983). Attributes of coralline algae morphology (shape, internal structure) and biology (biota, growth form) have been related to ecologic parameters including light, temperature, salinity, energy, and substrate (Bosellini and Ginsburg, 1971; Adey and MacIntyre, 1973; Bosence, 1983; Martindale, 1992; Steller and Foster, 1995). Coralline algae communities occur at depths ranging from the intertidal zone to over 200 m (Littler *et al*., 1991).

Articulated coralline red algae are branching plants that commonly grow in small clumps and dominate shallow subtidal settings (Konar and Foster, 1992). These free-living algae are more delicate than the crustose varieties and are also common in shaded, sheltered settings (Humann, 1993). Konar and Foster (1992) studied temperate water geniculate corallines from Stillwater Cove in Carmel Bay, California, and determined that the distribution and abundance of corallines varied with substratum type and depth. Density and growth of crusts and fronds tended to be greater at shallower depths and decreased with increasing depth. Different species are more successful at different depths and substratum; however, they are most abundant at depths < 15 m (Konar and Foster, 1992; Goldberg and Foster, 2002; Kundal and Mude, 2009). Upon death, articulated corallines disintegrate into sand sized particles (Gill and Hubbard, 1985). Broken pieces of coralline algae are common in the Cayman Formation on Grand Cayman.

Crustose forms of red algae are commonly preserved in rhodolites.

Rhodolites, as defined by Bosellini and Ginsburg (1971), are free-living structures composed mostly (>50%) of non-articulated coralline algae that belong to the Corallinaceae family as well as encrusting foraminifera and worms. Rhodolites come in a variety of sizes, shapes, and species. They can be composed entirely of non-articulated coralline algae (sometimes more than one species) or have a core of different material such as coral fragments. Hill and Jones (2000) described rhodolites from the Ironshore Formation on Grand Cayman composed of *Peyssonnelia rubra* growing around fragments of coral. Other species of red algae that commonly contribute to the formation of rhodolites include *Lithothamnium*, *Neogoniolithon*, *Porolithon*, *Archeolithothamnium*, *Lithophyllum,* and *Phymatolithon* (Adey and MacIntyre, 1973).

Rhodolite beds have been found from the low intertidal zone to depths of 150 m. Light and temperature primarily control the distribution of rhodolites (Adey and MacIntyre, 1973), as they can be found in shallow areas as well as deeper water from 50 to 268 m depth in clear tropical waters (Littler *et al*., 1991). Beyond the controls of light and temperature, the distribution as well as morphology of rhodolites is controlled by water motion (Marrack, 1999).

Rhodolites develop when the level of hydraulic energy is within a specific ‘window’. Too much energy causes the algae to abrade whereas too little energy does not allow the red algae to encrust the nucleus on all sides (Foster, 2001). The morphology of rhodolites depends on the size and shape of the nucleus, but morphology has also been used to indicate hydraulic energy. Spherical and ellipsoidal forms imply more frequent turning in higher energy environments (Stellar and Foster, 1995; Marrack, 1999). Irregular forms indicate infrequent movement in quiet water settings (Bosellini and Ginsberg, 1971). Rhodolite growth form as an indicator of environment is controversial (Reid and MacIntyre, 1988), as they have been found actively growing in deep water settings of up to

90 m (Adey and MacIntyre, 1973; Reid and MacIntyre, 1988; Littler *et al*., 1991). Rhodolites are largely associated with shallow, high-energy, tropical waters, but they are not uniquely characteristic of such environments (Adey and MacIntyre, 1973; Hills, 1998; Marrack, 1999).

4.2.3. Corals

Hermatypic scleractinian corals are useful for paleoenvironment interpretations because they are generally limited by the requirements of their photosynthetic symbiotic zoozanthellae to well-lit, normal marine waters of the tropics. The key-limiting factor of these organisms is light conditions, and they flourish in the photic zone down to depths of 100 m (Wells, 1967; James and Wood, 2010).

Variations in environmental factors can influence coral skeletal shape. Light intensity, rate of sedimentation, and water energy are the main influences on the growth pattern of an individual coral colony. External coral shape and internal growth banding geometry of a fossil colony can be used to interpret water turbulence and relative sedimentation rates (James and Wood, 2010). Where wave energy is moderate, thick robust branching and massive domal corals are common. Thin delicately branching corals and laminar platy corals are better suited to low water energy environments (Schuster and Wielandt, 1999). Branching growth forms are also able to resist burial under conditions of high sedimentation whereas domal and platy growth forms are better suited to environments with low sedimentation rates (James and Wood, 2010).

Modern coral shape is also largely dependent on light conditions. Domal and branching forms are generally better suited to relatively shallow water environments where light is refracted and comes from all directions. In contrast, platy growth forms are well adapted to deeper water environments. A thin subhorizontal plate skeleton maximizes surface area relative to size in order to maximize lower light levels wherein all intercepted light is vertical (James and Wood, 2010).

There are limitations to the application of these concepts directly to fossil corals. The relationship between coral morphology and environment is one of the oldest and most controversial topics in biology and paleontology (James and Wood, 2010). No general patterns are applicable to all fossil corals. Variations in coral morphology may be due to genetic differentiation instead of environmental parameters (Todd, 2008).

Coral morphology in the rock record can be useful in making some generalizations. Corals exhibit a depth zonation because of decreasing wave energy and light intensity (Graus and Macintyre, 1989). The following discussion will provide information regarding specific coral taxa that are found in the Cayman Formation and their depth implications.

Leptoseris

Leptoseris is a laminar to encrusting coral that is usually found in areas of low light. *Leptoseris cucullata* is found on modern reefs around Grand Cayman on the sides of shallow spurs and in deeper water on the deep terrace fore-reef (Hunter, 1994). Its thin platy skeletal shape gives this coral a competitive advantage in these low light conditions. During the Tertiary, *Leptoseris* was abundant throughout the Caribbean Sea; however, in modern oceans *Leptoseris* is more prolific in the Indo-Pacific (Vaughan, 1919; Frost and Langenheim, 1974; Veron, 2010a). Today, this coral is typically found in deep water with low water turbulence on lower reef slopes, under overhangs, on vertical walls or on the ocean floor between reefs (Veron, 2010a). Based on these observations, Hunter (1994) estimated that *Leptoseris* probably grew in water 10-30 m deep.

Stylophora

Stylophora is a sub-massive to branching coral that became extinct in the Caribbean Sea at the end of the Pliocene (Wineberg, 1994). In modern oceans, *Stylophora* has a higher diversity in the western Indian Ocean and Red Sea than in the central Indo-Pacific (Veron, 2010b). Different species of *Stylophora* exhibit a wide range of environment-correlated growth-forms. Generally, *Stylophora* with small and large diameter branches grow in sheltered lagoons to shallow reef environments with some wave action. Encrusting forms occur on vertical surfaces in deeper water or on the mid-lower slope (Veron, 2010b). *Stylophora* is one of the most abundant corals present in the Cayman Formation. Hunter (1994) suggested that the *Stylophora* Association in the Cayman Formation on Grand Cayman probably grew in water 15-20 m deep.

Porites

Porites, which includes many different species, has a wide geographic range and occurs as laminar, encrusting, massive domal, and branching growth forms. Branching to massive growth forms of *Porites* are common in the Cayman Formation. The branching species is probably *Porites baracoaensis*, a common Tertiary coral in the Caribbean Sea (Vaughan, 1919; Foster, 1986). Modern day *Porites* grow in a wide range of environments, but *Porites porites*, a common branching coral in the present day Caribbean, prefers shallow protected reef environments. Other species of branching *Porites* also occur in similar environments (Veron, 2010c).

Montastrea

Montastrea is a diverse coral genus that occurs over a wide geographic range. Colonies of this coral are massive, domal, platy, or columnar. In the

Cayman Formation, massive to domal growth forms of *Montastrea* are abundant. Hunter (1994) identified the species as *Montastrea limbata*, as the specimens from the Cayman Islands agree with other descriptions of this coral elsewhere from the Caribbean (Vaughan, 1919; Vaughan and Hoffmeister, 1926; Frost and Langenheim, 1974; Budd, 1991). *Montastrea limbata* was common in the Caribbean from the Early Miocene to late Pliocene when it became extinct (Budd, 1991). *Montastrea limbata* is closely related to *Montastrea annularis*, which is common in the present day Caribbean (Vaughan, 1919). *M. annularis* is abundant in all reef environments with a bathymetric range of 0.3-82.0 m (Hunter, 1994). It is particularly abundant in lagoons and upper reef slopes in water less than 30 m (Goreau and Wells, 1967; Reed, 1985; Veron, 2010d). de Buisonjé (1974) described *M. limbata* from the Seroe Domi Formation on Curaçao and Bonaire and suggested that these corals grew in moderate water depths, probably 20-30 m.

Trachyphyllia

Trachyphyllia is a solitary, free-living coral that is present on Caribbean and Indo-Pacific reefs starting in the Miocene and extending to the present in the Indo-Pacific and the Pliocene in the Caribbean (Veron, 1986). *Trachyphyllia geoffroyi* is the only modern species of this genus (Veron, 2010e). *Trachyphyllia bilobata,* however*,* has been described from Tertiary strata at a number of localities in the Caribbean (Behrens, 1976; Saunders *et al*., 1980; Meeder, 1987). This coral lives in a range of environments including lagoon, inter-reef, and on soft substrates in water 30-40 m deep (Hunter, 1994; Veron, 2010e). Its cup shape suggests that this coral was immobile and grew upwards in response to siltation (Hunter, 1994). *Trachyphyllia* is locally common in the Cayman Formation; however, it is more abundant in the Pedro Castle Formation (Hunter, 1994).

4.2.4. Echinoids

Echinoids are exclusively marine organisms and are common constituents of the benthic fauna in tropical and temperate environments. They are found in all zones of the ocean in a wide array of habitats (Nebelsick, 1992; Kroh and Nebelsick, 2003). Organic material of the echinoderm decays upon death and individual plates, spines, and ossicles disarticulate. Upon burial, calcite cement precipitates as syntaxial rims in optical continuity with the single calcite crystals of the echinoid plate. Although rare in the Cayman Formation, echinoid spines are present in a number of horizons in the succession.

4.2.5. Bivalves and Gastropods

Epifaunal and infaunal varieties of bivalves are diverse organisms that are found in abundance at all latitudes (Dame, 2011). The shells of these creatures are relatively resistant to fragmentation, and generally, thicker shelled varieties live in areas of higher water turbulence (Cerridwen and Jones, 1989, 1991). Bivalves of varying size are common in several horizons of the Cayman Formation. Boring bivalves, such a *Lithophaga*, are evident in many corals in the Cayman Formation.

Gastropods have a widespread distribution in fresh and saltwater environments at all latitudes. The dense skeletal structure of these organisms generally inhibits fragmentation. Marine gastropods are smaller in size than their fresh water counterparts. Thinner shelled varieties are more common in colder, deeper waters, whereas thicker shelled varieties are tolerant of higher water turbulence (Cerridwen and Jones, 1989, 1991). Gastropods generally occur in similar horizons as bivalves in the Cayman Formation.

4.3. FACIES PALEOENVIRONMENT INTERPRETATIONS

During the Tertiary, deposition on Grand Cayman occurred on an open bank, as there is no evidence of reef development in the succession (Jones and Hunter, 1994a). The mains controls on deposition were therefore water depth and energy levels.

Eight facies have been identified in the Cayman Formation on the eastern part of Grand Cayman (Fig. 4.1). The facies can be divided into cross-bank facies and local facies based on their lateral distribution across the bank. An energy window between 0-20 m water depth controlled the distribution of cross-bank facies. At shallower depths within the energy window, the bank was subject to constant energy, and finer sediment was swept off the bank. Storm events also influenced sediment within the energy window. Below the energy window in deeper water environments, there was periodic energy and less off-bank sediment movement.

All of the local facies, that are restricted in aerial extent, are indicative of shallow water conditions. The distribution of these facies is therefore controlled primarily by energy levels. The edge of the bank is an environment subject to higher energy levels and storm events. Facies that contain rhodolites are only present in areas located on the present day perimeter of the island. This could have been the edge of the bank during Miocene times. The center of the bank is an environment that can be subject to lower energy conditions. Facies that contain coral thickets are generally more abundant in areas located on the present day center of the island. This implies that the center of the bank could have been a protected, low energy setting during Miocene times.

Cross-Bank Facies	Depositional Setting	Energy	Sedimentation Rate	Relative Water Depth
Amphistegina Bivalve	**Very Shallow Open Bank**	Low-High	High	Very Shallow
Branching and Domal Coral *Amphistegina*	**Shallow Open Bank**	Moderate	Moderate	Shallow
Branching and Platy Coral *Amphistegina* Red Algae	**Intermediate Open Bank**	Low-Moderate	Moderate	Intermediate
Leptoseris Amphistegina	**Deep Open Bank**	Low	Low	Deep
Local Facies	**Depositional Setting**	**Energy**	**Sedimentation Rate**	**Relative Water Depth**
Rhodolite Coral *Amphistegina*	**Shallow Bank Edge**	Moderate-High	Moderate	Shallow
Rhodolite Branching Coral *Amphistegina*	**Coral Thickets Bank Edge**	Low-High	Moderate-High	Shallow
Porites Amphistegina	**Low Energy Coral Thickets**	Low	Moderate-High	Shallow
Branching Coral Benthic Foraminifera	**Shallow Coral Thickets**	Low-Moderate	Moderate-High	Shallow

Fig 4.1. Interpretation of depositional environments based on facies.

4.3.1. Cross Bank Facies

The Leptoseris-Amphistegina facies

The *Leptoseris-Amphistegina* facies is laterally continuous across the bank and occurs at 122 mbsl, 60-70 mbsl, and 32-58 mbsl (Fig. 4.2, 4.3). The following features indicate a deep, quiet water setting for this facies (1) platy corals that suggest conditions of low light and low sedimentation rates, (2) the occurrence of planktonic foraminifera in the matrix (Fig. 4.4A) implies open circulation and access to deeper ocean water (Phleger, 1964), and (3) the

Amphistegina dominated wackestone matrix implies low energy conditions. The *Leptoseris-Amphistegina* facies was probably deposited in a **deep water, open bank** setting. This facies is similar to Hunter's (1994) *Leptoseris* Association that he considered of water 10-30 m deep; however, water depth was probably at the deeper end of that range considering the dominance of *Leptoseris*.

The Branching and Platy Coral Amphistegina-Red Algae facies

This facies is laterally traceable across the bank and occurs at ~50 mbsl (Fig. 4.2). Branching and platy corals dominate this facies suggesting a depositional environment with low illumination and/or reduced water energy. The *Amphistegina* and red algae wackestone matrix indicates a depositional environment with lower energy conditions; however, the abundance of *Stylophora* and *Porites* suggests energy conditions were at least moderate (Veron, 2010b, c). Sedimentation rates for this facies are moderate indicated by the abundance of branching and platy growth forms.

This facies contains fossils that indicate low to moderate light, moderate sedimentation rates, and low to moderate energy conditions. The Branching and Platy Coral-*Amphistegina*-Red Algae facies was probably deposited in an **intermediate water depth in an open bank** setting. This facies is intermediate between Hunter's (1994) *Leptoseris* Association and *Stylophora*-*Porites* Association, and he interpreted a water depth of 10-30 m deep.

The Branching and Domal Coral-Amphistegina Facies

This facies is laterally traceable across the bank and occurs at 50-68 mbsl, 30-40 mbsl, and 0-40 mbsl (Fig. 4.2, 4.3). The diverse coral assemblage in this facies suggests a depositional environment that was suitable for many different corals. The abundance of *Stylophora*, *Porites*, and *Montastrea* indicates a shallow

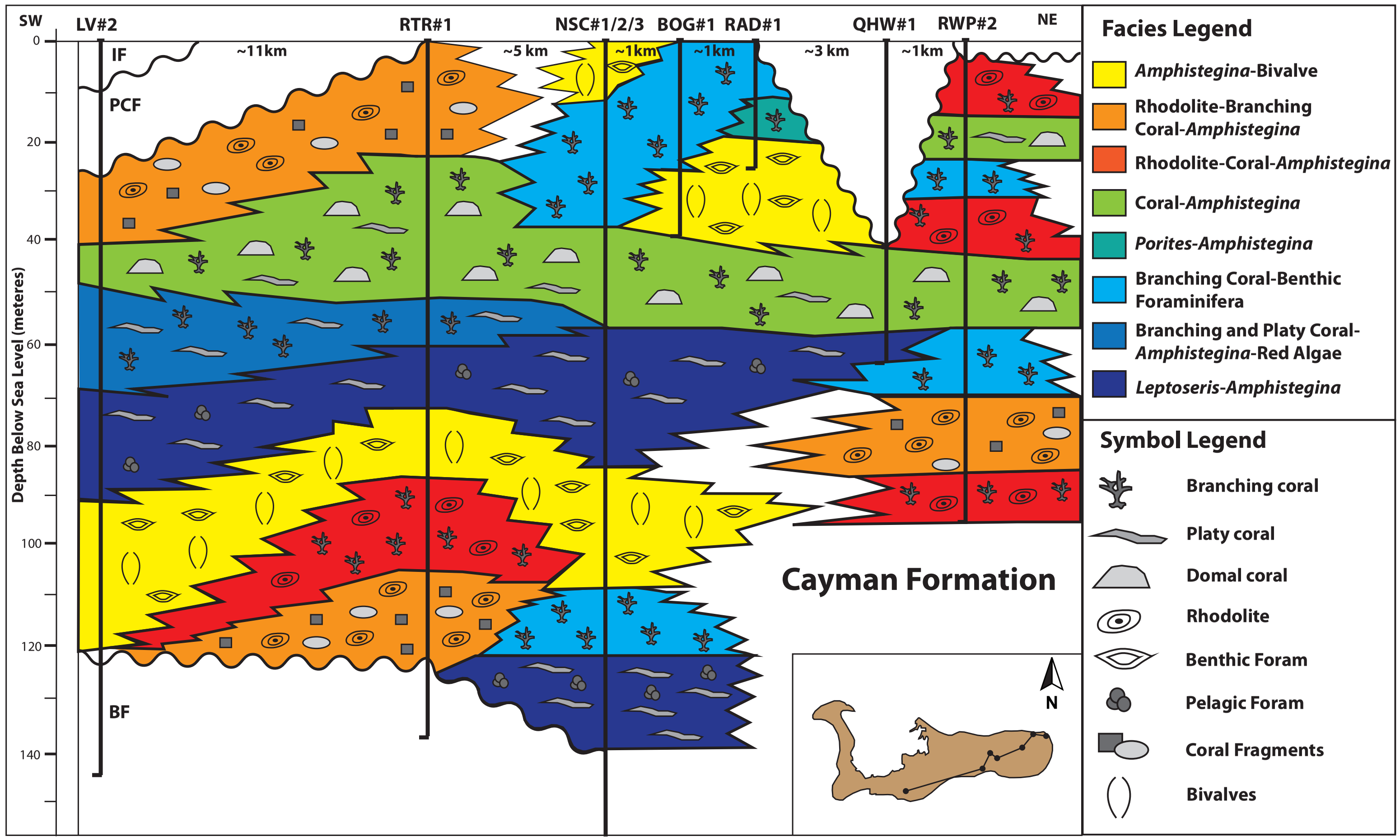

Figure 4.2. Correlation of facies for Transect 1.

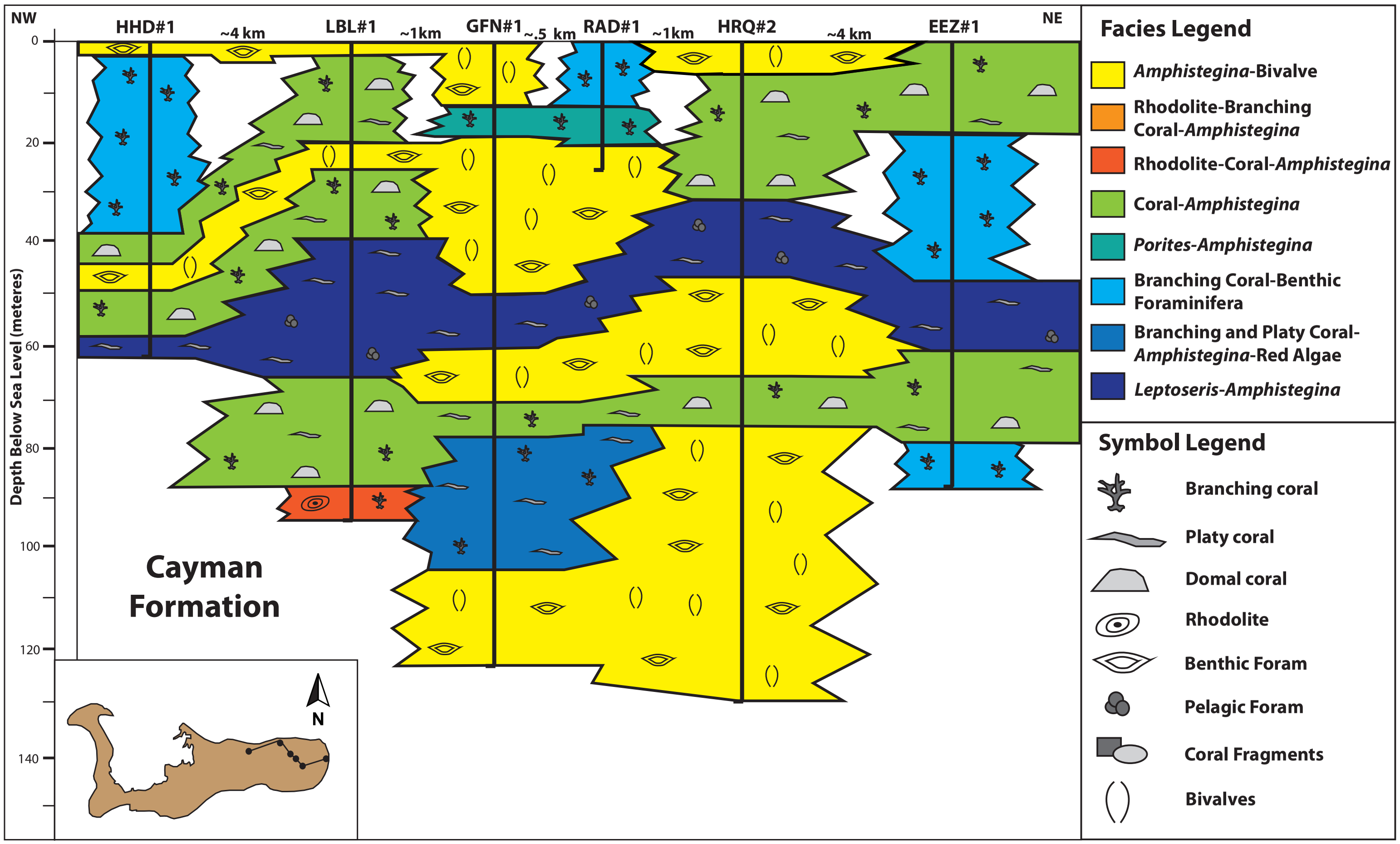

Figure 4.3. Correlation of facies for Transect 2.

water depth with moderate energy levels. The *Amphistegina* wacke-packstone matrix further indicates that energy conditions were moderate. Branching coral growth forms dominate this facies indicating higher sedimentation rates. The domal coral *Montastrea* is also abundant in this facies and like platy growth forms, they are sensitive to rapid deposition. Sedimentation rates were therefore moderate.

This facies contains organisms that indicate shallow water, low to moderate sedimentation rates, and moderate energy conditions. The Branching and Domal Coral-*Amphistegina* facies was probably deposited in a **shallow water, open bank** setting, similar to Hunter's (1994) *Montastrea limbata* Association and Willson's (1998) *Porites Leptoseris Montastrea Stylophora* Floatstone facies. Hunter (1994) suggested a bathymetry of 20-30 m; however, water depth was probably at the shallower end of that range considering the depth implications of *Amphistegina, Halimeda*, and red algae (Crouch and Poag, 1979; Hottinger and Dreher, 1975; Li and Jones, 1997).

The Amphistegina-Bivalve facies

The *Amphistegina*-Bivalve facies is laterally continuous across the bank and occurs at 80-110 mbsl, 75 mbsl, and 0-45 mbsl (Fig. 4.2, 4.3). This facies is unlike the other coral dominated facies because benthic foraminifera and molluscs dominate. The abundance of large benthic foraminifera implies very shallow, well-lit waters. Foraminifera sand composed primarily of *Amphistegina* are locally common (Fig. 4.4C, 4.4D, 4.4E, 4.4F). The range from wackestone to grainstone indicates that energy levels varied considerably from low energy to high energy. Local foraminifera grainstones are possibly storm deposits. Sedimentation rates were probably high as indicated by the local grainstones in this facies.

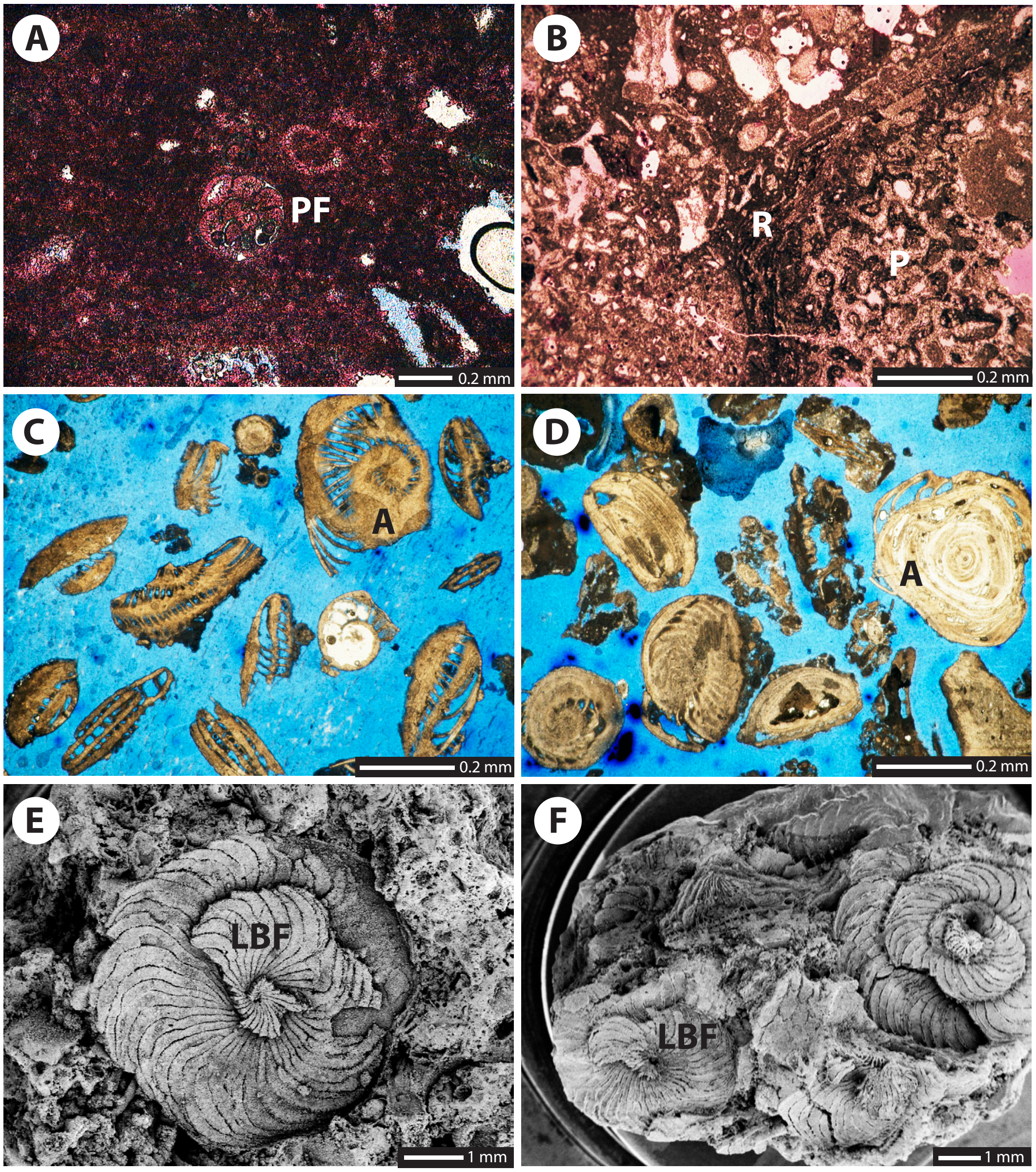

Figure 4.4. PF = Planktonic Foraminifera; R = Rhodolite; P = *Porites*; A = *Amphistegina*; LBF = Large Benthic Foraminifera.
(A) *Leptoseris-Amphistegina* Facies. Wackestone matrix with planktonic foraminifera (NSC#1) 130 m.
(B) Rhodolite-Coral-*Amphistegina* Facies. Packstone matrix and rhodolite with *Porites* nucleus (RTR#1) 25 m.
(C) *Amphistegina*-Bivalve Facies. Unconsolidated benthic foraminifera sand (HRQ#2) 98 m.
(D) *Amphistegina*-Bivalve Facies. Unconsolidated benthic foraminifera sand (HRQ#2) 98 m.
(E) *Amphistegina*-Bivalve Facies. SEM image (RTR#1) 80 m.
(F) *Amphistegina*-Bivalve Facies. SEM image (RTR#1) 72 m.

This facies contains a fossil assemblage that indicates very shallow water, high sedimentation rates, and low to high energy levels. The *Amphistegina*-Bivalve facies was probably deposited in a **very shallow water, open bank** setting. During low energy periods, benthic foraminifera, large benthic foraminifera, bivalves, and gastropods flourished in the shallow, muddy, open bank. During higher energy periods, benthic foraminifera sands developed and mud was winnowed out by the higher energy conditions. No previous work has described a facies similar to this one. A water depth of less than 10 m is indicated by the large benthic foraminifera and foraminifera grainstones.

4.3.2. Local Facies

The Branching Coral-Benthic Foraminifera facies

This facies is locally abundant in the center of the bank and occurs at 0-15 mbsl and 0-20 mbsl (Fig. 4.2, 4.3). The branching *Porites* and *Stylophora* that dominate this facies point to a protected shallow water environment. The abundance of red algae and *Halimeda* in this facies also indicates shallow water conditions. The matrix of this facies ranges from wackestone to packstone indicating a range in energy levels from low to moderate. *Stylophora* also occurs as both small and large diameter branches indicating low to moderate energy conditions. Sedimentation rates were moderate to high indicated by the dominance of branching corals.

The Branching Coral-Benthic Foraminifera facies represents **coral thickets** that grew in **shallow water**. This facies is similar to Hunter's (1994) *Stylophora*-*Porites* Association and *Stylophora* Association, and Willson's (1998) *Stylophora* Thicket facies. Hunter (1994) described the presence of the *Stylophora-Porites* Association as small patch reefs; however, the word 'reef' is misleading. Hunter (1994) described the *Stylophora* Association as forming coral thickets or coppices. Branching corals act as baffles that trap sediment and mud. Hunter (1994) suggested a bathymetry of 10-30 m, which also seems to be a reasonable water depth range for this facies.

The Porites-Amphistegina facies

This facies only occurs in the center of the bank at a depth of 10-15 mbsl (Fig. 4.2, 4.3). The *Porites-Amphistegina* facies is dominated by small-diameter branches of *Porites* and mud in the mudstone to wackestone matrix, which indicates low energy conditions. A shallow water depth is indicated by the abundance of *Halimeda*, red algae, and *Porites*. Moderate to high sedimentation rates are indicated by the absence of domal and platy corals that are intolerant of rapid deposition.

The *Porites-Amphistegina* facies represents **coral thickets** that grew in a **low energy** environment. This facies is similar to Hunter's (1994) *Porites baracoaensis* Association. Hunter (1994) described the Association as abundant branching colonies of *Porites* that occur as a small patch reef. He also explained that profuse growth of branching corals in muddy substrates under low energy conditions was common during this phase of bank development. Hunter (1994) suggested a bathymetry of 10-30 m, which also seems a reasonable water depth for this facies.

The Rhodolite-Coral-Amphistegina facies

This facies is found at a depth of 110 mbsl, 70 mbsl, and 0 mbsl (Fig. 4.2) in areas located close to the present day edge of the island. Although it depends where the shoreline was at the time, this could have been the edge of the bank during Miocene times. A **shallow bank edge** environment is proposed for this facies. Rhodolites, large-diameter branches of *Porites* and *Stylophora,* and the range in matrix from wackestone to packstone indicates a depositional environment with moderate to high-energy conditions. *Porites* and *Stylophora* probably developed during moderate energy conditions. They were broken up during higher energy events and eventually became nuclei for rhodolites (Fig. 4.4B). Reid and Macintyre (1988) surveyed rhodolites from the eastern part of the Caribbean and noted that rhodolites with coral nuclei were common on platform ridges and shelf edges where water was 20 to 30 m deep. In modern lagoons on Grand Cayman, rhodolites form around broken pieces of *Acropora cervicornis* in turbulent waters 0 to 2 m deep behind the reef crest (Jones and Hunter, 1994a). Analogy with the rhodolites in the modern lagoons around Grand Cayman suggests that rhodolites in this formation probably indicate high energy, shallow water conditions. The abundance of branching and domal corals indicates that sedimentation rates were moderate.

This facies is similar to Willson's (1998) Rhodolite Coral Fragment Rudstone to Grainstone Facies. Willson (1998) suggested a bathymetry of 5-30 m; however, water depth was probably at the shallower end of that range considering the abundance of rhodolites, red algae, and *Halimeda*.

The Rhodolite-Branching Coral-Amphistegina facies

This facies occurs at a depth of 85-88 mbsl, 35 mbsl, and 0 mbsl (Fig. 4.2, 4.3) in an area close to the present day edge of the island. As with the previous facies, this setting could have been the Miocene edge of the bank depending on the location of the shoreline. The Rhodolite-Branching Coral-*Amphistegina* facies probably represents a **coral thicket** that grew on the **bank edge**. The abundance of small diameter branching corals indicates a low energy environment; however, the abundance of spherical rhodolites indicates high-energy conditions. The range in the matrix from wackestone to packstone implies a range in energy conditions from low to high. The nuclei of the rhodolites (<2 cm) are composed of broken pieces of *Porites* or *Stylophora*. These branching corals developed during low energy conditions and were broken during higher energy events to become nuclei for rhodolites. The spherical to ellipsoidal morphology of the rhodolites is probably a result of more frequent turning in shallow, higher energy conditions. Sedimentation rates were moderate to high indicated by the dominance of branching corals.

This facies is similar to Willson's (1998) Rhodolite Finger Coral Floatstone to Rudstone Facies. Willson (1998) suggested a distal bank edge environment, which is intermediate between a branching coral thicket and bank edge setting. Willson (1998) suggested a bathymetry of 5-30 m; however, water depth was probably at the shallower end of that range considering the dominance of rhodolites.

4.4. INTERPRETATION

The main controls on deposition of sediments that now form the Cayman Formation are water depth and energy levels. High-energy conditions are indicated by the presence of rhodolites and fragmented corals. Associated high-energy matrices are dominated by packstones, with local grainstones (Fig. 4.6A). Low energy conditions are indicated by platy corals, thin diameter branching corals, and matrices composed of wackestones and mudstones (Fig. 4.6B). The abundance of rhodolites in areas from the perimeter of the island indicates that the edge of the bank during Miocene times was exposed to higher energy conditions. The tendency for baffling corals to dominate the center of the bank implies that this was a low energy environment.

Halimeda, red algae, large benthic foraminifera, and hermatypic corals are present in the succession in varying numbers. All of these organisms require light

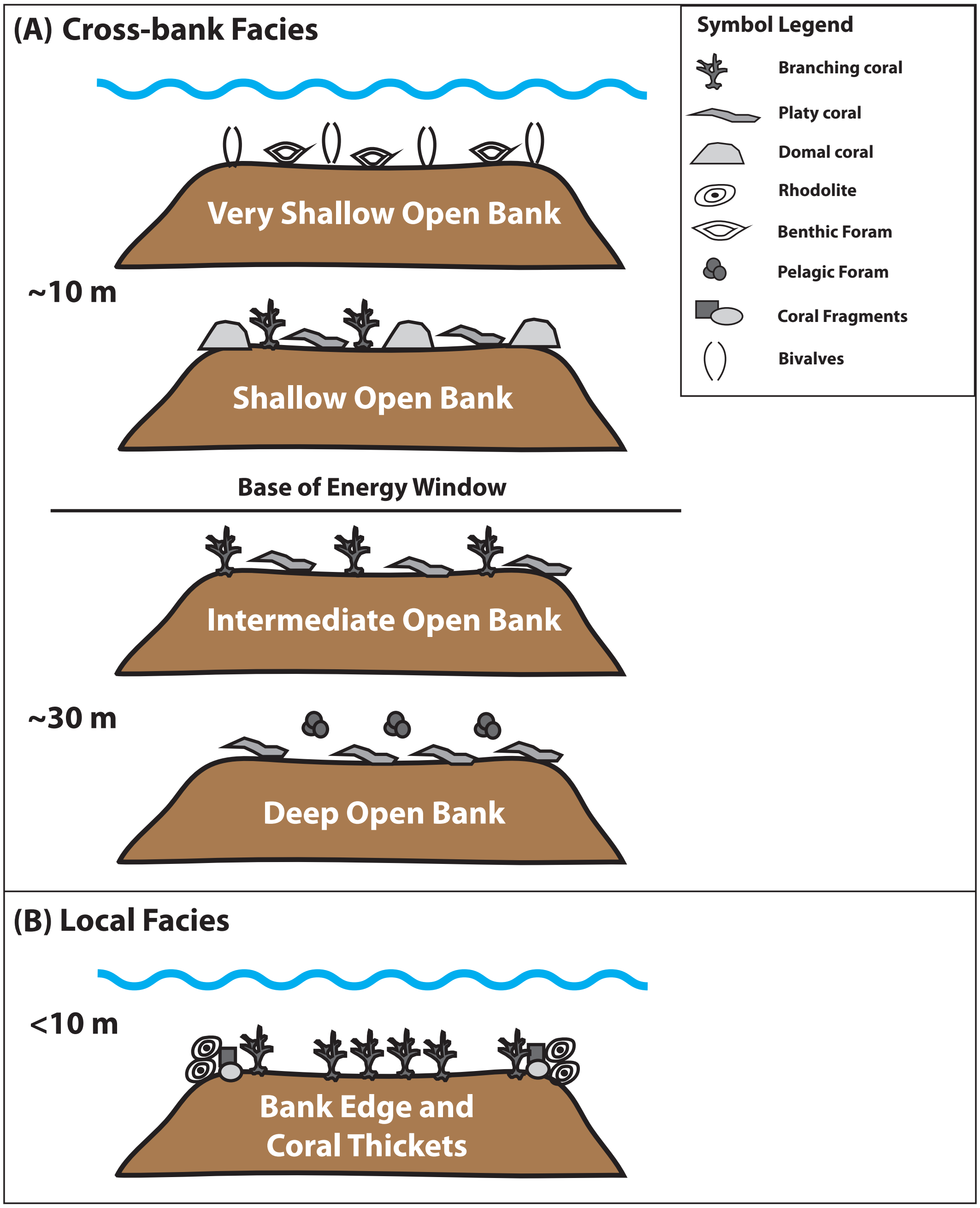

Figure 4.5. Schematic model of deposition on the open bank. (A) Depositional model of cross-bank facies with relative position of the energy window. Within the energy window there is constant energy. Below the energy window there is periodic energy. (B) Depositional model of local-facies. At shallow depths, position on the bank can affect energy levels. The bank edge is subject to higher energy. The center of the bank is subject to lower energy.

and are therefore constrained to the photic zone, which may reach depths down to 100 m in clear waters (James and Wood, 2010). Benthic foraminifera, which are abundant in the matrices in the Cayman Formation, are not directly dependent on light conditions. They feed, however, on light dependent phytoplankton.

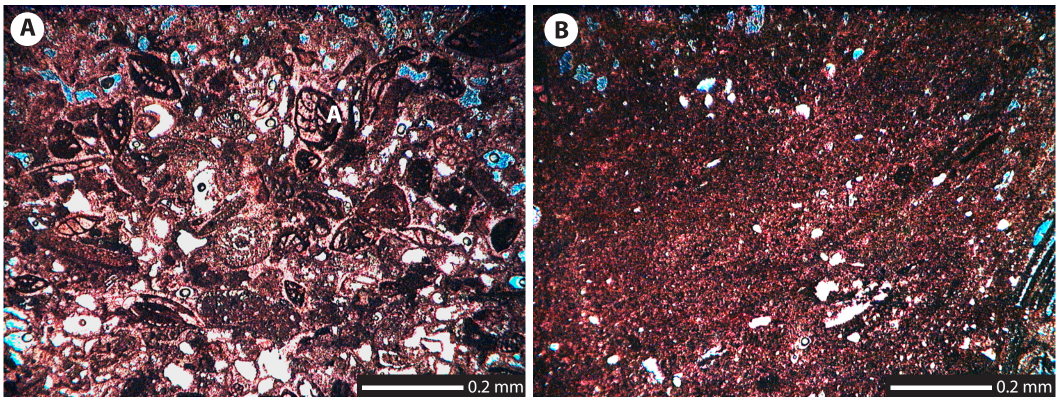

Figure 4.6. A = *Amphistegina*.
(A) Packstone matrix composed of *Amphistegina* (BOG#1) 17 m.
(B) Mudstone matrix (NSC#1) 123 m.

The direct dependence on the photosynthesizing activities of phytoplankton may have a strong controlling effect on the distribution of foraminifera in the Cayman Formation. Hunter (1994) suggested that the abundance of *Stylophora*, *Montastrea*, *Porites*, and *Leptoseris* in the Cayman Formation is indicative of an environment with water depth that was likely between 10-30 m.

4.5 SYNOPSIS

Deposition of sediments that now form the Cayman Formation took place on an open bank with the main controls being water depth and energy levels (Fig. 4.5). Facies can be divided into cross-bank facies and local facies based on their lateral distribution. The energy window, at a depth of 0-20 m, controlled cross-bank facies' energy levels. At shallower depths, energy levels of local facies were controlled by position on the bank.

Facies indicate that water depth varied across the bank; however, they also change vertically through time. Facies change vertically throughout the depositional history as a response to changes in water depth over time. These changes in sea level can be used to interpret the local sea level history on the bank and can be compared to eustatic changes in sea level.

CHAPTER FIVE:

SEA LEVEL AND THE CAYMAN FORMATION

5.1. SEA LEVEL INTERPRETATION

As water depth changed through time and modified the depositional environment, so did the facies in the Cayman Formation change. The succession can be viewed as an 'oceanic dip-stick' that reflects changes in sea level and/or the position of the islands as determined by tectonic movement. Information gained from facies architecture and paleoenvironment interpretations reveal the following important points.

1. Facies in the Cayman Formaton can be divided into cross-bank facies and local facies. An energy window at a depth of 0-20 m controlled the depositional environment of cross-bank facies (Fig. 5.1A). Shallow water environments within the energy window were subject to constant high energy conditions, and fine sediment was swept off the bank. Deeper water environments below the energy window were subject to periodic energy conditions, and there was less off-bank sediment movement. At shallow depths, position on the bank can control energy levels and the depositional environment of local facies. Sediment on the bank edge was subject to higher energy conditions whereas sediment on the center of the bank was more protected (Fig. 5.1B).
2. The Cayman Formation can be divided into lower and upper sequences, S1 and S2. The boundary between the two sequences is a transgressive surface.
3. The boundary between S1 and S2 is between 70-90 mbsl and is placed at the base of the laterally continuous stratigraphic level of the *Leptoseris*-*Amphistegina* facies. The depth of the transgressive surface spans

20 m because of lateral variation in the thickness of the *Leptoseris-Amphistegina* facies across the bank. In wells HHD #1 and QHW#1 (60 m and 70 m respectively), the true depth of the transgressive surface cannot be determined. These wells are shallower than nearby wells, and the transgressive surface is probably not intersected.

4. Each sequence is characterized by a shallowing upward trend. Generally in each sequence, deeper water coral assemblages with planktonic foraminifera grade into shallower water coral assemblages and benthic foraminifera sand (Fig. 5.1C).
5. The local sea level history of Grand Cayman has probably been impacted by global changes in sea level. Understanding changes in global sea level is critical to understanding the geologic history of Grand Cayman.

5.2. TECTONIC AND EUSTATIC CONTROLS

Suess (1906) first defined eustasy as a global-scale change in sea level. Global sea level position is a delicate balance between the volumetric capacity of ocean basins (tectono-eustasy) and the total volume of ocean water (glacio-eustasy) (Revelle, 1990). The interplay of tectonics (subsidence/uplift) and sedimentation in an oceanic basin result in localized deviations from global sea level position. Carbonate depositional environments are particularly influenced by sedimentation rate because continued accumulation of sediments will reduce the accommodation space (water depth) and eventually stop production of the carbonate factory (James and Wood, 2010).

5.2.1. Tectonic Influence

Local tectonic history and its impact on the sedimentary record must be considered when determining the history of sea level changes in a regional basin,

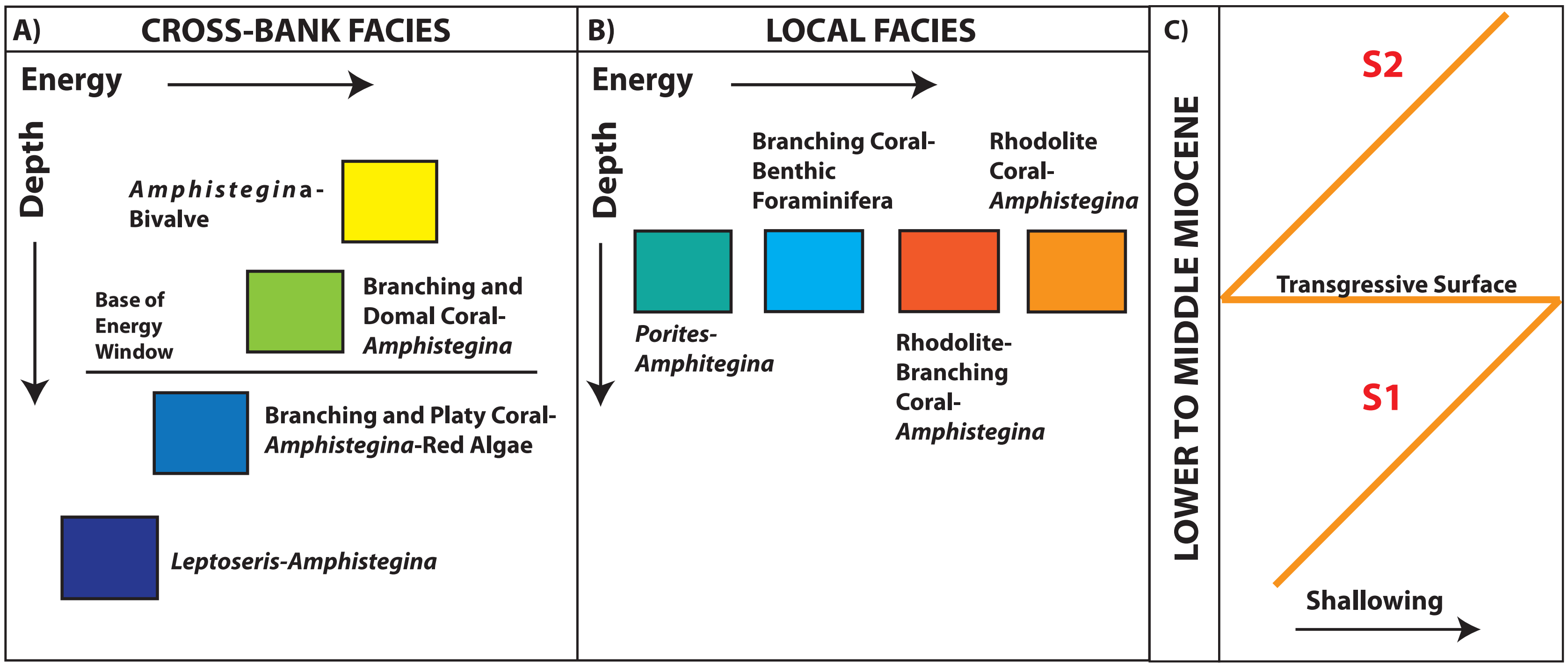

Figure 5.1. (A) Cross-bank facies plotted according to water depth and energy levels. (B) Local facies plotted according to water depth and energy levels. (C) Sea level curve constructed from facies. Two-shallowing upward sequences recorded by the facies during the Lower to Middle Miocene.

such as the Caribbean Sea. The interpretation of facies changes is simplified for carbonate build-ups that developed under tectonically stable conditions. Under tectonically stable conditions, tectonism does not influence changes in sea levels. Grand Cayman, however, is situated on a horst block in a tectonically active zone characterized by stress-related subsidence and uplift (Mann *et al.*, 1990; Leroy *et al.*, 1996). The Mid-Cayman Rise is an active spreading ridge (<2 cm/yr) (German *et al.*, 2010), and the Oriente transform fault is ~50 km south of Grand Cayman. The near horizontal appearance of Tertiary strata exposed on Grand Cayman indicates that there has been little, if any, structural impact on deposition over the last 5-10 million years (Jones and Hunter, 1989; Jones, 1994). If the island were tectonically active and moved relative to sea level, the rate of uplift or subsidence would have to match the rate of sedimentation to produce such a uniform sedimentary sequence. Presently, available data do not permit discrimination between these two scenarios. The same Tertiary carbonates on Cayman Brac experienced tectonic tilting, as indicated by the apparent dip of 0.5º to the west (Jones, 1994). Uplift and tilting occurred after deposition, as there is no evidence that it took place during deposition. The different structural histories of Grand Cayman and Cayman Brac reflect their positions on separate, tectonically isolated horst blocks. It is more likely that local sea level on Grand Cayman was primarily dictated by eustatic sea level changes; however, the possible influence of local tectonics cannot be ignored in such a tectonically active area.

5.2.2. Eustatic Influence

Global eustatic curves must be considered in order to assess the effects of eustasy on deposition. Interpreting the effects of eustasy on deposition of the sequences derived from the Cayman Formation in this study requires comparison to detailed eustatic curves such as those developed by Vail *et al.* (1977), Hallam (1984), Haq *et al*. (1987), and Miller *et al*. (2005). However, the amplitude and timing of global sea level fluctuations during the Tertiary is a subject of controversy. Well-known eustatic curves (Fig. 5.2) look very different and vary significantly in their interpretation of the number, timing, and magnitude of sea level changes. This is due to different authors deriving their eustatic curve from different methods.

Vail *et al*. (1977) presented the first eustatic sea level curve. It was derived by interpreting relative changes in sea level on seismic sections from the onlap and downlap of coastal deposits in depositional sequences. This method integrated seismic stratigraphy and sequence-stratigraphic analysis.

The eustatic curve proposed by Hallam (1984) was constructed using continental elevation data and various stratigraphic criteria including biogeography, organic evolution, and facies and isotope changes. Relative positions of sea level were determined by estimating shoreline positions for successive time intervals on a global scale and correlating them to transgressive/regressive and shallowing/deepening episodes for a given region. This eustatic curve is a more generalized, qualitative reconstruction. Relative sea level changes are recorded for first (200-400 Ma) and second (10-100 Ma) order cycles only, which means that interpretations for smaller time periods are not shown.

Haq *et al*. (1987) used seismic stratigraphy augmented with interpretations from sequence stratigraphic analysis to revise the eustatic curve constructed by Vail *et al*. (1977). Supplementary evidence from magneto-, chrono-, and biostratigraphies were integrated with sequences recognized in the subsurface and outcrop sections in different sedimentary basins. Correlation of the cycles of rising and falling sea level between numerous geographically separate regions demonstrated global synchroneity of events and was summarized as a eustatic curve.

The eustatic curve presented by Miller *et al*. (2005) is significantly different from the eustatic curves of Vail *et al*. (1977), Hallam (1984), and Haq *et al*. (1987). Based on their research, Miller *et al*. (2005) proposed that eustatic sea level changes were of considerably smaller magnitude than initial estimates. Their eustatic interpretations were derived from backstripping stratigraphic data, which is an inverse technique used to quantitatively extract sea level change amplitudes from the stratigraphic record. Sea level estimates from 9 to 0 Ma were derived using benthic foraminiferal $d^{18}O$ records because the stratigraphic record was incomplete from 7 to 0 Ma. The resultant sea-level curve aligned well with the backstripped record from 9 to 7 Ma. For comparison, Miller *et al*. (2005) derived another sea level curve from 9 to 0 Ma using global $d^{18}O$ data.

These authors have interpreted global sea level changes using varying techniques and as a result, their eustatic interpretations are very different. It is difficult to determine which eustatic curve is most accurate. The Haq *et al*. (1987) curve, however, will be used for interpretations in this study because (1) it is the most widely used eustatic curve in the scientific community, (2) it includes third order cycles (1-10 Ma) and shows a greater level of detail than other eustatic curves, and (3) the integration of different methods provides a greater diversity of support for the eustatic interpretations.

5.3. AGE OF THE CAYMAN FORMATION

Deposition of the Cayman Formation probably took place during the Lower to Middle Miocene (Jones, 1994; Jones and Hunter, 1994a). Precise dating of the Cayman Formation has been difficult because of the lack of age diagnostic fossils and the $^{87}Sr/^{86}Sr$ isotope ratios were reset by dolomitization (Pleydell *et al.*, 1990). Various considerations are used to place the Cayman Formation in

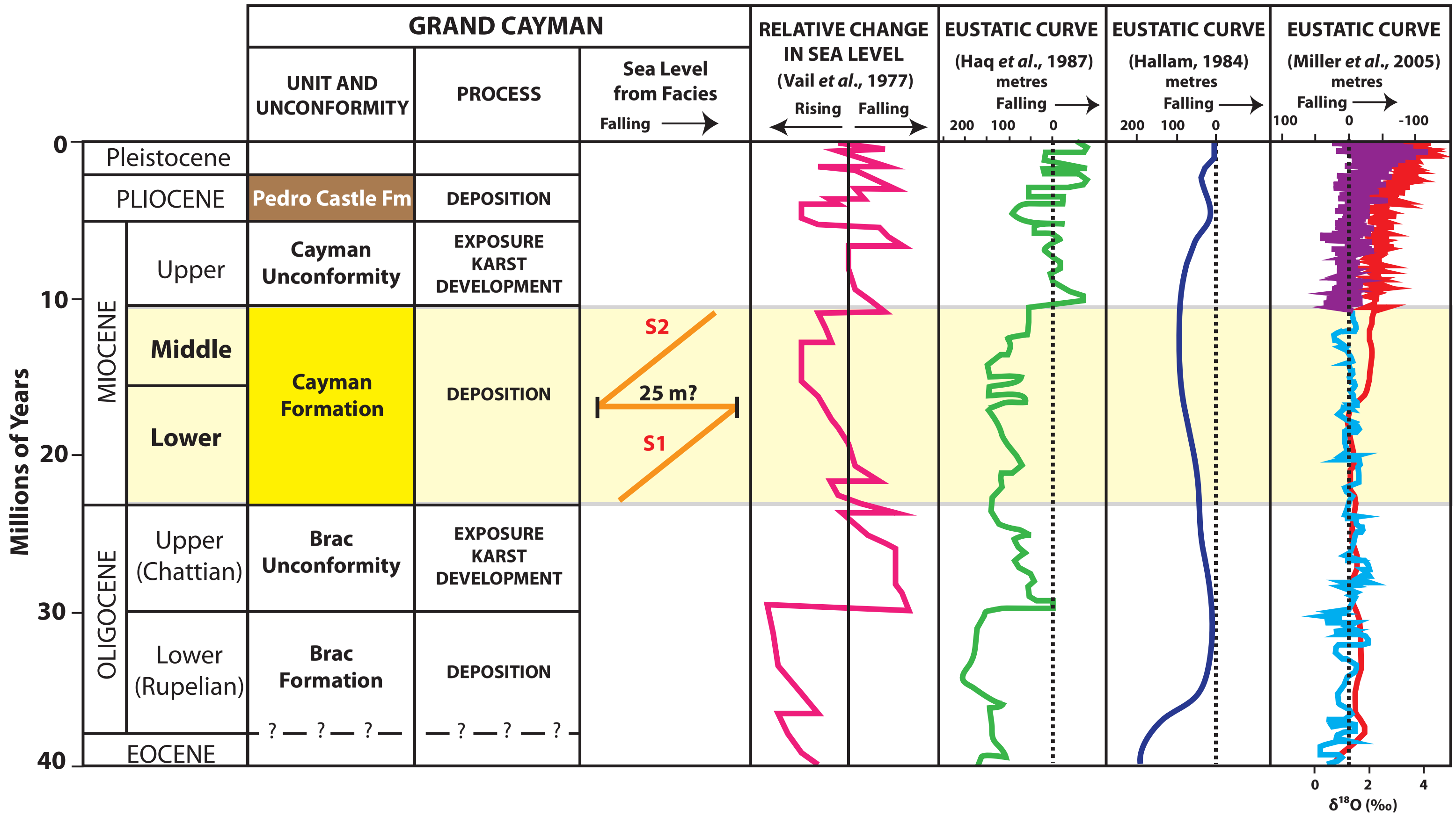

Figure 5.2. Correlation of Brac Formation, Cayman Formation, and Pedro Castle Formation and their interpreted depositional position to various interpretations of global sea level curves. Miller et al., (2005) integrated global sea level (blue) derived from backstripping stratigraphic data; global sea level (purple) derived from $\delta^{18}O$; and benthic foraminiferal $\delta^{18}O$ synthesis (red).

a chronological context within the Cayman Island stratigraphy, including its position between the well dated Brac Formation and Pedro Castle Formation.

The Lower Oligocene age of the Brac Formation was determined using foraminiferal biostratigaphy and $^{87}Sr/^{86}Sr$ ratios from limestone (Jones, 1994). Interpretation of the eustatic curve of Haq *et al*. (1987) indicates that there was a major highstand in the Lower Oligocene (Fig. 5.2). Haq *et al*. (1987) estimated that sea levels were ~150 m above present day sea level (Fig 5.2), and deposition of the Brac Formation can be related to this highstand. Deposition terminated in the late Lower Oligocene (Rupelian), and the Brac Unconformity developed following a major drop in sea level at the end of the Lower Oligocene (Fig. 5.2).

The Brac Formation is stratigraphically below the Cayman Formation. Taking into account the Brac unconformity that separates the Brac Formation and Cayman Formation and the lack of Upper Oligocene fossils, the timing for deposition of the Cayman Formation is the Lower to Middle Miocene. The *Amphistegina* dominated foraminifera fauna of the Cayman Formation corresponds to established Caribbean associations that imply a Miocene age for the formation (Jones, 1994).

A large eustatic drop in sea level during the late Upper Miocene (Messinian) led to the exposure, erosion, and karstification of the Cayman Formation on Grand Cayman (Jones and Hunter, 1994b). The erosional sequence boundary that formed as a result of the global lowstand is called the Cayman Unconformity (Jones, 1994). Initiation of the Messinian drop in sea level began 6.6 to 4.5 Ma (Kastens, 1992) and was maintained for approximately 1 Ma (Hayes and Frakes, 1973; Berggren and Haq, 1976; McKenzie *et al.*, 1984; Aharon *et al.*, 1993). The magnitude of the drop is the subject of much debate with estimates ranging from 30 m (Aharon *et al.*, 1993) to 180 m (Pigram *et al.*, 1992) below present day sea level. These lowstand estimates were derived from areas outside

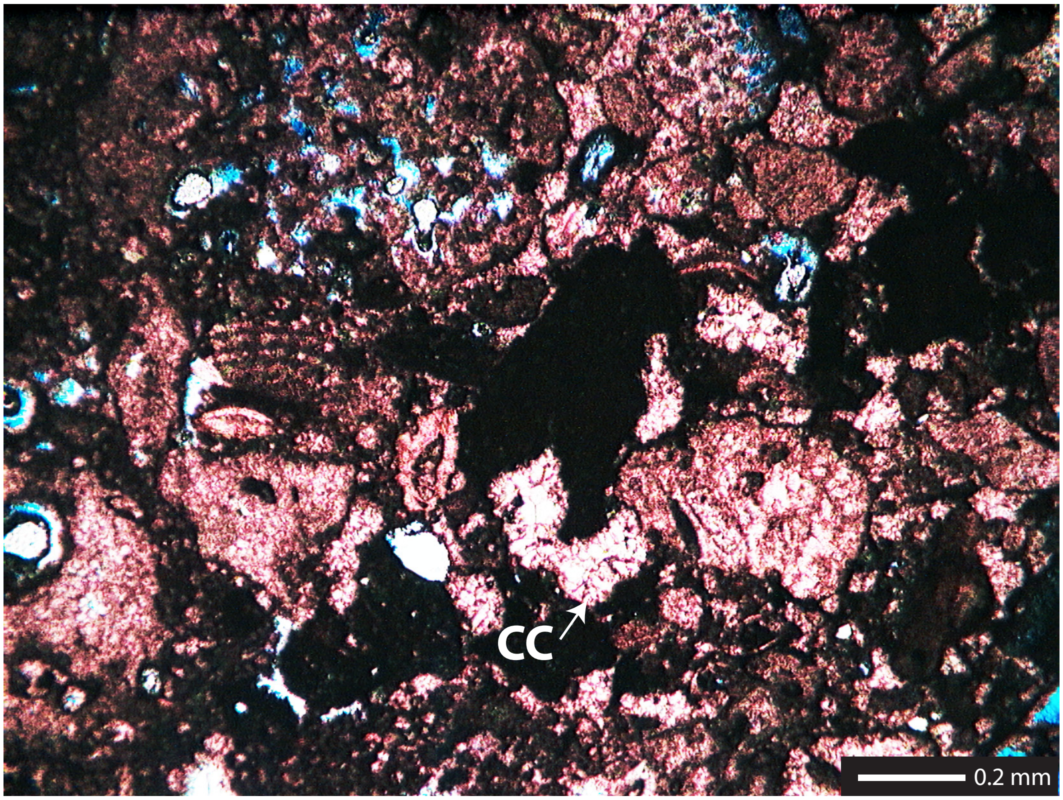

Figure 5.3. Evidence of recrystallization and diagenesis in limestone member of the Cayman Formation. Pores lined and filled with spar calcite cement (CC) (NSC#1) 6 m.

of the Caribbean. Based on evidence from Grand Cayman, Jones and Hunter (1994b) estimated that the Messinian drop in sea level was at least 41 m below present day sea level. The Messinian lowstand was a contributing factor to the well-documented Messinian Salinity Crisis in the Mediterranean, which resulted in the deposition of a thick evaporate succession (Adams *et al.*, 1977; Hsü *et al.*, 1977). This global lowstand is recorded on the eustatic curve (Fig. 5.2) of both Vail *et al*. (1977) and Haq *et al*. (1987) (Fig. 5.2).

The Pedro Castle Formation stratigraphically overlies the Cayman Unconformity. Comparison of the fossil assemblage to established Caribbean associations and measured $^{87}Sr/^{86}Sr$ ratios from limestone to oceanic Sr evolution curves (e.g., DePaolo and Ingram, 1985; Hess *et al.*, 1986; Hodell *et al.*, 1991) indicates that the Pedro Castle Formation is probably Pliocene in age (Jones, 1994). Deposition of this formation can be related to the first major Pliocene highstand following the Messinian lowstand event, which has estimated magnitudes of 80-100 m above present day sea level (Haq *et al*., 1987).

Both the Brac Formation and Pedro Castle Formation contain limestone that has been used to date each formation. Previous studies did not find limestone in the Cayman Formation (Jones, 1994; Jones and Hunter, 1994a); however, this study shows that limestone is found in parts of the Cayman Formation. NSC#1, for example, contains 120 m of limestone. The $^{87}Sr/^{86}Sr$ values in this well are consistent from 0-150 mbsl despite a major change in lithology at 120 mbsl from limestone to dolostone. Similar Strontium values for limestone and dolostone between 0-150 mbsl points toward modification of the original $^{87}Sr/^{86}Sr$ in the limestone. Diagenetic fluids and dolomitization can alter the original $^{87}Sr/^{86}Sr$ values in limestone. Recrystallization and diagenesis are readily apparent in the limestone in NSC#1 (Fig. 5.3), and the well is pervasively dolomitized from 120-150 mbsl.

The average $^{87}Sr/^{86}Sr$ ratios in NSC#1 are 0.70900-0.70906. These values correspond to an Upper Miocene age (DePaolo and Ingram, 1986; Hodell *et al.*, 1991). Jones and Luth (2003) determined that three phases of dolomitization took place on Grand Cayman, the first of which occurred during the Upper Miocene. The $^{87}Sr/^{86}Sr$ in the limestone and dolostone in NSC#1 corresponds to the first phase of dolomitization on the bank. If the first phase of dolomitization took place during the Upper Miocene, deposition of the Cayman Formation is older than Upper Miocene. This evidence further supports a Lower to Middle Miocene age for the Cayman Formation.

Interpretation of the Haq *et al*. (1987) eustatic curve (Fig. 5.2) also indicates that the Cayman Formation was probably not deposited during the Upper Miocene. During this time, sea level was at a lowstand (Fig. 5.2). Haq *et al*. (1987) estimated that sea level was overall 150 m above present day sea level during the Lower to Middle Miocene. Interpretations therefore point toward deposition during the Lower to Middle Miocene, as there was a significant highstand (Fig. 5.2).

5.4. COMPARISON OF EUSTATIC CURVES TO CAYMAN STRATIGRAPHY

Facies in the Cayman Formation record two shallowing upward sequences during the Lower to Middle Miocene. These are separated by a transgressive event. The transgression involved a sea-level rise of 20-25 m, this being based on interpretation of the facies. The geologic data collected from Grand Cayman, however, is inconclusive with respect to the precise date of deposition of the Cayman Formation, and it is a challenge to correlate the two shallowing upward sequences with known sea level curves from the Lower to Middle Miocene (Fig. 5.2).

Interpretation of the eustatic curve of Haq *et al*. (1987) indicates that sea level during the Lower to Middle Miocene was at a highstand, and the sediments of the Cayman Formation were probably deposited during this time. This eustatic curve also indicates that sea level fell below present day sea level until a major lowstand in the late Upper Miocene took place. This corresponds to the Cayman Unconformity at the top of the formation that developed as a result of the Messinian Lowstand event.

The amplitude of sea level change shown during the Lower to Middle Miocene on the eustatic curve of Haq *et al*. (1987) is much larger than the 20-25 m sea level change interpreted from this study. However, with the information that is available to date, it is not possible to determine how/where the two shallowing upward sequences fit onto the Haq *et al*. (1987) curve.

5.5. SYNOPSIS

The precise age of the Cayman Formation cannot be determined from Strontium data from the limestone member of the Cayman Formation because the original $^{87}Sr/^{86}Sr$ have been modified by diagenesis and/or dolomization. However, deposition of the Cayman Formation must have occurred prior to the earliest recorded dolomitization event on Grand Cayman. $^{87}Sr/^{86}Sr$ ratios from dolostones on Grand Cayman indicate an Upper Miocene age of dolomitization (Jones and Luth, 2003). It is therefore indicated that deposition of the sediments that now form the Cayman Formation occurred in the Lower to Middle Miocene. This is further supported by its foraminiferal assemblage, the development of the Cayman Unconformity during the Messinian lowstand, and its stratigraphic position between the Lower Oligocene Brac Formation and Pliocene Pedro Castle Formation.

Interpretation of the facies on Grand Cayman indicates that sea level rise during the Lower to Middle Miocene was 20-25 m. Presently, inaccurate dating of the Cayman Formation and variance in eustatic curves renders correlation of sea level changes interpreted from the Cayman Formation a challenge. The age of the Cayman Formation, however, cannot be determined until age diagnostic fauna and reliable Strontium isotope dates for Cayman Formation strata can be obtained from limestone.

CHAPTER SIX:

CONCLUSIONS

Detailed sedimentological analysis of accessible outcrop and samples from 12 wells that encompass the Cayman Formation on the eastern part of Grand Cayman has significantly improved the understanding of the complex depositional history of the succession. The following conclusions have been determined from this study:

1. Despite pervasive dolomitization and leaching of the succession, original facies are still evident.
2. The Cayman Formation in the study area can be divided into 8 facies. *Porites*, *Stylophora*, *Montastrea*, and *Leptoseris* corals are the major allochems that define the facies. Matrices are dominated by *Amphistegina* wacke-packstones.
3. Sediments of the Cayman Formation were probably deposited in water 10-30 m deep on an open bank setting. Depositional environments range from deep open bank, coral thickets, and bank edge to very shallow open bank.
4. Facies vary laterally across the bank, and the distribution was controlled primarily by water depth and energy levels. Cross-bank facies are laterally continuous, and an energy window at 0-20 m controlled sediment movement. Local facies are isolated across the bank. Facies indicative of higher energy were present on the bank edge. Facies indicative of lower energy were present on the center of the bank.
5. Facies vary vertically due to changes in water depth and energy levels over time. The facies succession in the Cayman Formation records two shallowing upward sequences separated by a transgressive event. Based

on facies interpretations, sea level rise during deposition of the Cayman Formation was between 20-25 m.

6. Changes in sea level are mainly due to global eustatic controls with a possible tectonic influence.
7. The significant lowstand in the Late Miocene is probably the Messinian lowstand event, and the Cayman Unconformity at the top of the formation probably developed as a result.
8. Deposition of the Cayman Formation is constrained to the Lower to Middle Miocene based mainly on its foraminiferal assemblage and stratigraphic position between the Lower Oligocene Brac Formation and Pliocene Pedro Castle Formation.
9. The precise age of the Cayman Formation cannot be determined from $^{87}Sr/^{86}Sr$ ratios from limestones from the Cayman Formation because values have been modified by diagenesis and/or dolomitization.
10. Variance in eustatic curves and inaccurate dating of the Cayman Formation renders correlating the shallowing upward sequences with sea level curves from the Lower to Middle Miocene a challenge.
11. Age diagnostic fauna and reliable Sr isotope dates for Cayman Formation strata need to be obtained before the age of the Cayman Formation can be determined.

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