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Sedimentology and Diagenesis of the Cayman (Miocene) and Pedro Castle (Pliocene) Formations at Safe Haven, Grand Cayman, British West Indies

by

Brent David Wignall ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science

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"....I have made this letter longer because I lack the time to make it shorter."

Blaise Pascal

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommended to the Faculty of Graduate Studies and Research for acceptance a thesis entitled SEDIMENTOLOGY AND DIAGENESIS OF THE CAYMAN (MIOCENE) AND PEDRO CASTLE (PLIOCENE) FORMATIONS AT SAFE HAVEN, GRAND CAYMAN, BRITISH WEST INDIES submitted by BRENT DAVID WIGNALL in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE.

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Date

Abstract

Sixteen drill core taken from the Safe Haven area on Grand Cayman record the sedimentology, facies architecture, and diagenesis of the Cayman (middle to late Miocene) and Pedro Castle (Pliocene) formations. The Cayman Formation is composed of skeletal grainstones and packstones that were deposited in a moderate to high energy open bank setting. The unconformity separating the Cayman and Pedro Castle formations is a karst surface that formed in the late Miocene and was subsequently modified by a stepped sea level rise in the late Miocene to early Pliocene. The skeletal wackestones and packstones of the Pedro Castle Formation accumulated between 4.8-2.5 Ma on an open bank environment under moderate water energies. Sedimentological and stratigraphic evidence points to gradually increasing water depths during deposition, and sea level reached a minimum high stand of 15 m above present sea level. The unconformity on top of the Pedro Castle Formation developed during a sea level lowstand (~2.4 Ma), and the Tertiary succession was subject to alternating meteoric and marine conditions until 130,000 years ago.

Diagenesis of the Cayman and Pedro Castle formations has been complex and encompasses recrystallization, dolomitization, calcitization, dissolution, speleothem precipitation, and calcretization. Dolomitization by marine or mixed waters took place in two phases, and earlier $^{87}Sr/^{86}Sr$ ratios were reset by the second period of dolomitization. Diagenetic zones reflect the influence of changing sea levels and associated water tables since the late Miocene.

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This thesis owes whatever clarity of thought and direction it has to the dashing red pen of my supervisor, Dr. Brian Jones. His dedication in the face of my Joycian predilections turned *Finnigan's Wake Revisited* into a scientific thesis. I also owe a huge debt...well, okay, a big debt... to the students, past and present, of the Farm menagerie. Kenton Phimester and Ian Hunter were the driving forces in the drilling program, and as such made my thesis possible. Assisting them over the four year program were Bill Kalbfleisch, Jennifer Vézina, Jason Montpetit, Anurag Shourie, Li Chun, Sam Ng, and an anonymous driller. Brian Jones even lent a hand on occasion. As well, I appreciate the help and support of other students in the group, David Hills, and Leonardo Piccoli.

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CHAPTER 1 : INTRODUCTION

Tertiary strata of the Bluff Group form the core of Grand Cayman, Cayman Brac and Little Cayman (Fig. 1). The Bluff Group encompasses the Brac (Lower Oligocene), Cayman (Middle to Upper Miocene), and the Pedro Castle (Pliocene) formations (Jones *et al.*, 1994b) (Fig. 2). Partially overlying and surrounding the Tertiary strata are the limestones of the Pleistocene Ironshore Formation. All four formations are unconformity bounded.

On Cayman Brac, the Brac, Cayman and Pedro Castle formations are well exposed because the strata dip 0.5° to the west (Jones and Hunter, 1994a). On Grand Cayman, however, the strata appear to be flat-lying (Jones and Hunter, 1989), and only the Cayman and Pedro Castle formations are exposed. The Brac Formation has not been found on Grand Cayman, despite a well on the northeast corner of the island that reached 94 m below sea level (bsl). Furthermore, exposures of the Cayman and Pedro Castle formations provide limited stratigraphic sections because of the subdued, low-lying topography of the island. As a result, the type sections designated for the Cayman and Pedro Castle formations at Pedro Castle Quarry are 5.5 and 2.5 m in thickness, respectively (Jones and Hunter, 1989). These limited sections restrict study of the vertical successions in the two formations. This problem is compounded by the fact that the Cayman Formation rarely outcrops on the western part of Grand Cayman, and the Pedro Castle Formation is exposed only in the vicinity of Pedro Castle (Fig. 1B). In an effort to address this situation, Jones *et al.* (1994b) designated a well on the western part of Grand Cayman as a reference section for the Pedro Castle Formation. To date, however, most study of the Cayman and Pedro Castle formations comes from the

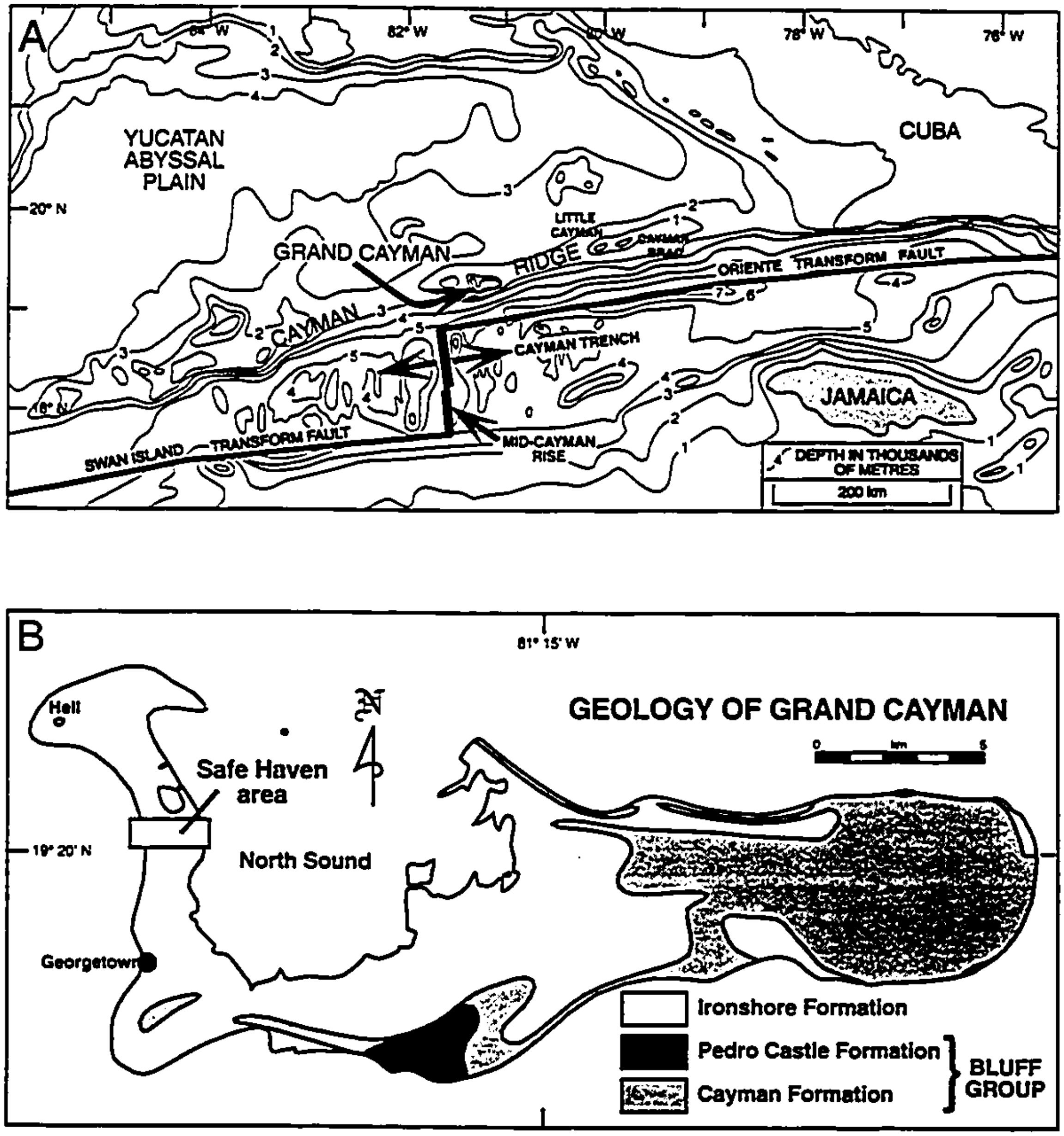

Fig. 1. Tectonic setting and location of the Safe Haven area
A) tectonic setting of the Cayman Islands, BWI (modified from Pleydell *et al.*, 1990)
B) Location of the Safe Haven area on Grand Cayman, and the surficial geology of the island (modified from Jones and Hunter, 1994b).

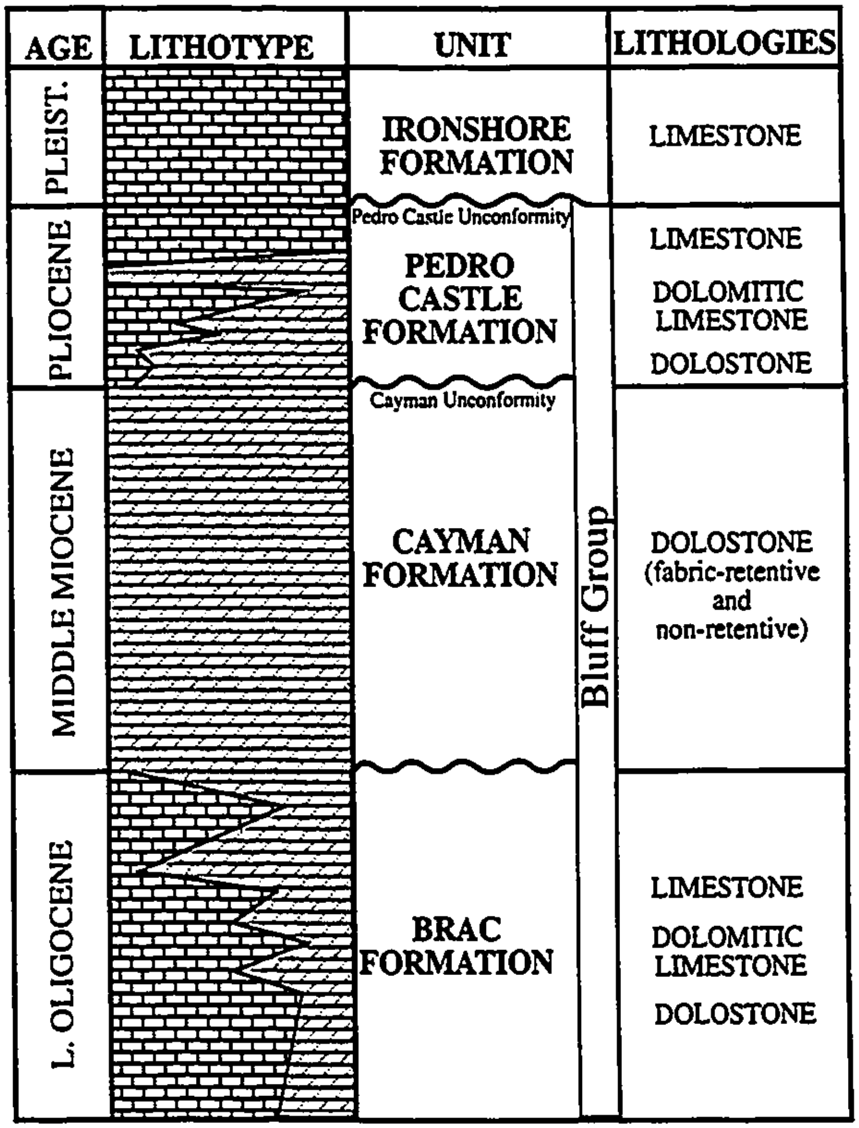

Fig. 2. Stratigraphy of the Cayman Islands (after Jones et al., 1994b).

stratigraphically limited exposures on the central and eastern parts of the island (e.g., Pleydell, 1987).

The Safe Haven area of west Grand Cayman is now a PGA-rated golf course. Prior to opening of the course, the Safe Haven management gave permission for the drilling of fifteen wells on the property. In the course of drilling, both the Cayman and Pedro Castle formations were penetrated. Ten wells are aligned along a 1.5 km east-west transect, with five outlying wells to the north and south (Fig. 3). The deepest well reached a depth of 53.15 m, whereas the other wells reached an average depth of 30 m. In most wells, core recoveries calculated for ten foot coring intervals were between 0% and 100%, with an average of approximately 60%.

This wealth of subsurface information from the Safe Haven area provides the basis for more detailed study of the Cayman and Pedro Castle formations than has been previously possible on the western part of Grand Cayman.

OBJECTIVES

Using this data base, the objectives of this study are:

1. to describe the sedimentological characteristics of the Cayman and Pedro Castle formations in the Safehaven area,
2. to characterize facies architecture and depositional regimes of the Cayman and Pedro Castle formations,
3. to describe and interpret the Cayman and Pedro Castle unconformities,
4. to determine the influence of the Cayman and Pedro Castle unconformities on the sedimentation and diagenesis of the Tertiary succession, and

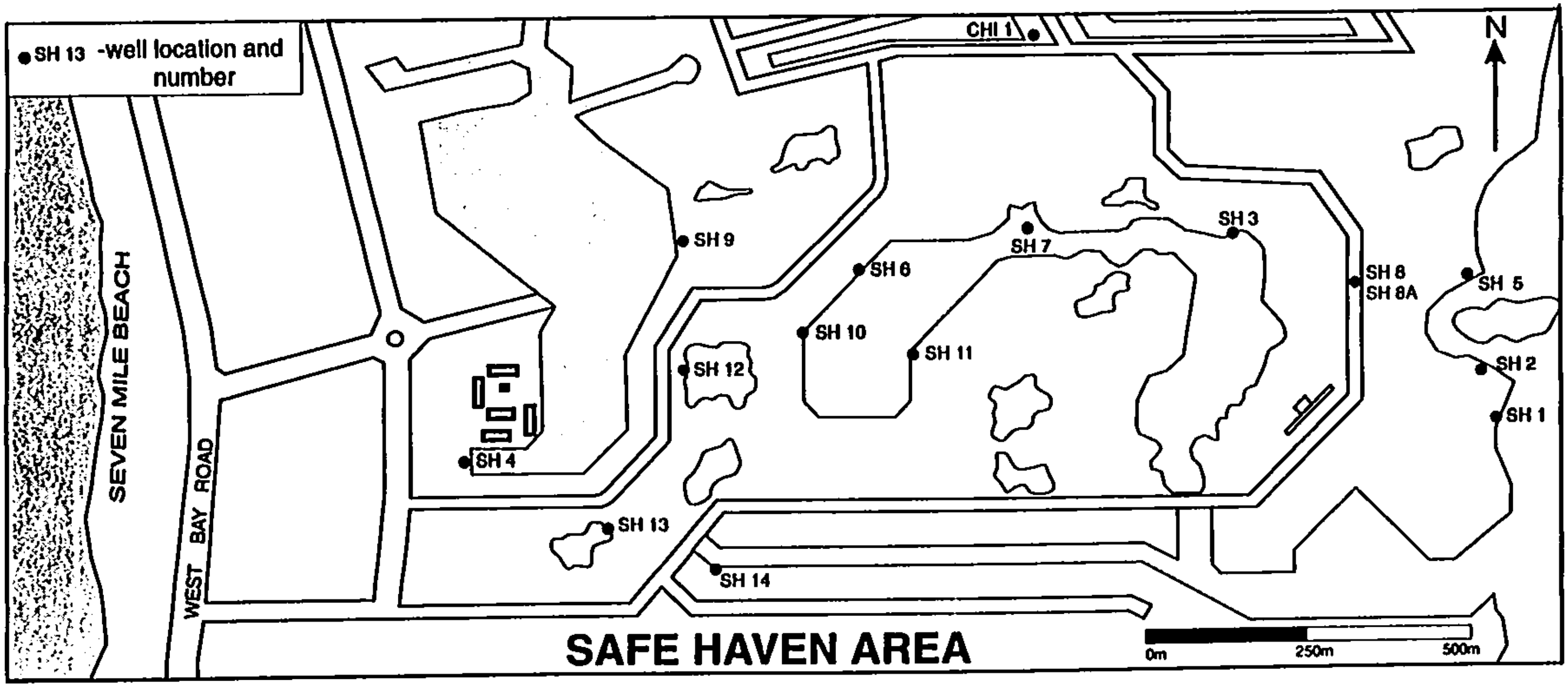

Fig. 3. Well locations at the Safe Haven and Crystal Harbour developments (see Fig. 1b. for location of study area).

5. to characterize and interpret the diagenetic fabrics present in the Cayman and Pedro Castle formations.

LOCATION

The Cayman Islands are exposed prominences on the Cayman Ridge and consist of Grand Cayman, Cayman Brac and Little Cayman (Fig. 1a). Grand Cayman is the largest island with a land area of 197 km^2 (Spencer, 1985).

The Safe Haven area, located on the western peninsula of Grand Cayman (Fig. 1b), is an extremely flat, low-lying area with an average elevation of 1.5m above sea level. Safe Haven is bounded on its eastern margin by North Sound. To the west is Seven Mile Beach, which is on the protected leeward margin of Grand Cayman. The Crystal Harbour Development lies to the north of Safe Haven, and to the south is undeveloped mangrove swampland (Fig. 3).

STRATIGRAPHY OF THE SAFE HAVEN AREA

Topography is extremely subdued on the western peninsula of Grand Cayman, and the Tertiary strata are overlain by the Ironshore Formation. The only surface exposures of the Cayman Formation on the western peninsula are at Hell, and on a low ridge which parallels the south coast (Fig. 1b) (Jones and Hunter, 1994a). The Pedro Castle Formation is never exposed.

In the Safe Haven area, the Cayman and Pedro Castle formations are both found in the subsurface. The Ironshore Formation is also present, although it is covered by material from dredging operations and thus is no longer exposed at the surface. The Cayman and Pedro Castle formations, and the unconformities that bound them, are never exposed in the Safe Haven area, and therefore have not been subject to surface karsting since the deposition of the Ironshore Formation.

The Cayman Formation is pervasively dolomitized whereas the Pedro Castle Formation is composed of limestone, variably dolomitized limestone, and dolostone. The Ironshore Formation is composed of limestone, with variable replacement of aragonite by calcite (Shourie, 1993). No dolomite has been found in the Ironshore Formation.

In the Safe Haven area the Ironshore Formation is never more than 8 m thick. The Pedro Castle Formation achieves its maximum recorded thickness of 22.4 m in the eastern part of the Safe Haven area, and thins to less than 7.9 m in the west. The Pedro Unconformity is moderately undulatory, and is found at an average depth of 5.5 m (+- 1.5 m) below sea level. The Cayman Unconformity, which is at approximately 12 m below sea level in the west, drops to at least 30.5 m below sea level to the east over a distance of 1.6 km. The Cayman Formation therefore forms a ridge which rises to the west in the Safe Haven area, with an overlying wedge of Pedro Castle Formation that thickens to the east. The ridge formed by the Cayman Formation trends north-south along the western peninsula of Grand Cayman, although it has very little surface expression (Jones and Hunter, 1994a).

TECTONIC SETTING

The Cayman Islands are in an active tectonic setting (Fig. 1a). The Cayman Ridge, which trends westward from the Sierra Maestra Range of Cuba, is flanked to the north by the Yucatan Abyssal Plain and to the south by the Cayman Trench (Perfitt and Heezen, 1978). The Cayman Trench is a left-lateral strike slip boundary that has experienced a minimum of 200 km of slip since the early Eocene (Perfitt and Heezen, 1978). The development of the Cayman Spreading Ridge began in the early Oligocene (Perfitt and Heezen, 1978; Emery and Milliman, 1980). Spreading estimates based on thermal profiles of the resultant trough are 15-30 mm/yr (Rosencrantz *et al.*, 1988).

Subsidence of the Cayman Trough has had a drag effect on the southern slope of the Cayman Ridge, causing it to subside along a hinge line parallel to the trench at a rate of 0.1 mm/yr since the Oligocene (Emery and Milliman, 1980). The core of Grand Cayman has subsided at a lesser rate of 0.001-0.013 mm/yr (Emery and Milliman, 1980). The subsidence of the Cayman Ridge has allowed the development of a thick carbonate succession on the flanks and crest of the ridge, despite a general drop in sea level since the beginning of the Tertiary (Vail *et al.*, 1977; Hallam, 1984). An exploration oil well on the south side of Grand Cayman was still in Oligocene carbonate strata when abandoned at 397 m (Emery and Milliman, 1980).

The three islands are located on separate fault blocks that have experienced independent vertical movement since the Miocene (Woodroffe *et al.*, 1983; Woodroffe, 1988). It does not appear, however, that independent movement has taken place over the last 120,000 -130,000 years (Jones and Hunter, 1990).

SEA LEVEL HISTORY

Sea level histories recorded in the strata of Caribbean islands are commonly obscured by tectonic uplift and subsidence (e.g., Schubert and Szabo, 1978; Titus, 1986; Woodroffe, 1988; Bard *et al.*, 1990). Furthermore, numerous sea level curves developed by workers (e.g. Vail *et al.*, 1977; Olsonn *et al.*, 1980; Hallam, 1984; Haq *et al.*, 1987;

Dowsett and Cronin, 1990; Krantz, 1991) share little agreement on timing and magnitude of sea level change. Certain conclusions may, however, be drawn from the stratigraphy of Grand Cayman.

The presence of the Cayman and Pedro Castle unconformities in the Tertiary strata of Grand Cayman means that at least two major sea level drops have occurred since the Middle Miocene. The Cayman Unconformity, separating the Cayman and Pedro Castle formations, was produced during the terminal Miocene (Messinian) low stand (Jones and Hunter, 1994a). The low stand responsible for developing the Pedro Castle Unconformity, which separates the Pedro Castle and Ironshore formations, is problematic. The drop in sea level need not have been as large in magnitude or duration as the Messinian low stand because the Pedro Castle Formation does not record the same degree of karsting and erosion as the Cayman Formation (Jones and Hunter, 1989; Jones and Hunter, 1994a), and Pliocene sea level curves show frequent fluctuations (Krantz, 1991; Wardlaw and Terrence, 1991).

Most workers (e.g., Hallam, 1984; Haq *et al.*, 1987; Dowsett and Cronin, 1990; Krantz, 1991) show a major sea level rise at the start of the Pliocene. If the sediments of the Pedro Castle Formation were deposited as a result of this high stand, then the lowstand which initiated development of the Pedro Castle Unconformity may have been associated with the first major sea level drop in the Middle Pliocene. The karsting developed during this low stand would have been overprinted by karsting and marine processes associated with later sea level fluctuations.

METHODS

Core was recovered using a continuous-coring Winkie exploration diamond drill manufactured by JKS BOYLES. This system is capable of coring to depths exceeding 122 m in ideal conditions, although subsurface conditions in the Safehaven area rarely permit drilling much deeper than 40 m bsl. The core recovered is approximately 3.5 cm in diameter.

Fifteen wells were drilled in the Safe Haven area, with one more to the north at Crystal Harbour (Fig. 3). Of the sixteen wells, SH#1 and SH#9 had zero core recovery and were not logged. The remaining fourteen wells terminated between 14.79-53.68 m bsl, and yielded variable amounts of core.

The recovered core was split, logged and sampled for thin sections and SEM samples. In addition to the detailed log description of the core, ninety three thin sections and eleven SEM samples were examined. Most of the thin sections were stained for calcite and dolomite, using Alizarin red and Ferro-cyanide stains based on procedures outlined by Dickson (1965). Transmitted light and cathodoluminescent microscopes were used to examine thin sections.

Rock textures were described using Dunham's classification as modified by Embry and Klovan (1972). Coral recognition was based on comparison with plates and descriptions in Hunter (1993).

Dolomitization and recrystallization of the Cayman and Pedro Castle formations has resulted in highly variable degrees of fabric preservation. In some parts of the formation, microstructures such as mollusc shell chevron lamellae are preserved even in pervasively dolomitized rocks. Elsewhere, the dolomite is more massively crystalline and sucrosic and very little of the original rock texture remains. As a result, matrix and allochems with better preservational potential tend to achieve a diagenetically-induced predominance in the rock. This does not cause difficulty in naming the rock as intended under the scheme of Embry and Klovan (1972), but casts doubt on environmental interpretations, as well as limiting facies comparison. For this reason, this study follows the lead of Jones and Hunter (1994a), and consider allochems and matrix separately in interpreting the sedimentology of the Cayman and Pedro Castle formations. Matrix and associated cements may represent diagenetic imprint rather than original matrix materials. Conversely, allochems record at least some of the original sedimentary structure, and can be used to arrive at an idea of original depositional setting.

CHAPTER 2 : SEDIMENTOLOGY AND FACIES ARCHITECTURE OF THE CAYMAN FORMATION

SKELETAL COMPONENTS OF THE CAYMAN FORMATION

Skeletal components found in the Cayman Formation include branching corals (*Porites* and *Stylophora*), rare hemispherical and platey corals (e.g., *Montastrea, Siderastrea, Diploria, Leptoseris*), and even rarer solitary corals (e.g., *Trachyphyllia*). Non-framework organisms such as benthic foraminifera (*Amphistegina*, miliolinids), *Halimeda*, coralline and encrusting red algae, molluscs, echinoderms, and bryozoans are commonly preserved in these rocks.

Preservation of the allochems is variable. Red algae and benthic foraminifera typically show the best preservation, possibly due to their original magnesium-calcite composition. Red algae are commonly identifiable in hand sample by their dense, chalky appearance. *Halimeda* is generally discernible in hand sample as well-preserved plates, or as negative molds. In some cases *Halimeda* is evident in thin section only as partially preserved fragments. Echinoderm fragments show excellent preservation, commonly maintaining uniaxial crystal orientation despite dolomitization. Bivalves and gastropods are invariably leached, as are the hemispherical, platey, and solitary corals. *Porites* is generally well preserved, although leaching and calcitization has obscured the skeletal structure of some specimens. *Stylophora*, found only as negative molds, is recognizable by its distinctive corallite imprints. Well-preserved casts of sponge borings are evident in the moulds of this coral (cf. Pleydell and Jones, 1988). Other allochems such as bryozoans, coral fragments, and encrusting and pelagic foraminifera are poorly preserved, and usually recognizable only in thin section.

Allochems such as red algae and benthic foraminifera show the best preservation and therefore become the visually dominant skeletal components. Peferential preservation may have played as important a role in determining final relative abundances of skeletal components as did original sedimentary conditions. This leads to diagenetic overprinting of sedimentary facies, limiting interpretation and comparison of the sedimentology of the Cayman Formation dolostones. For this reason, recognition of litho- and biofacies becomes problematic in the Cayman Formation, and in most cases distinction between the two cannot be made.

FACIES OF THE CAYMAN FORMATION

Seven facies based on dominant skeletal components have been identified in the Cayman Formation at Safe Haven (Table 1). These facies have been linked to four distinct depositional environments, and for ease of understanding are grouped accordingly.

Sand Plain Depositional Environment

The Sand Plain depositional environment includes the *Halimeda*-coralline red algae, *Amphistegina*-coralline red algae, and mollusc-*Amphistegina*-*Halimeda* facies. The *Halimeda*-coralline red algae facies is the dominant facies.

The *Halimeda*-coralline red algae facies is composed of *Halimeda*, coralline red algae, gastropods and bivalves, and rare *Stylophora*. The molluscs are typically fragmented and bivalves only rarely articulated. Mud content in the matrix is variable. Although this facies is most commonly found as a packstone, it is also found as a

LITHOLOGY	FACIES	SKELETAL ALLOCHEMS	NON-SKELETAL ALLOCHEMS	DOMINANT ALLOCHEM	RARE ALLOCHEM	DOMINANT FRAMEWORK ORGANISM	BORINGS / TRACE FOSSILS	ENVIRONMENT
DOLOSTONE	*PORITES* BAFFLESTONE	*PORITES* BIVALVES GASTROPODS *HALIMEDA* *AMPHISTEGINA*	NOT OBSERVED	MOLLUSCS/ *HALIMEDA*	*STYLOPHORA*	*PORITES*	SPONGE BORINGS	*PORITES* REEF
DOLOSTONE	*PORITES* RUDSTONE	*PORITES* BIVALVES GASTROPODS *HALIMEDA* *AMPHISTEGINA*	NOT OBSERVED	PORITES/ *HALIMEDA*	*STYLOPHORA*	NOT OBSERVED	SPONGE BORINGS	
DOLOSTONE	*PORITES* FLOATSTONE	BIVALVES GASTROPODS *HALIMEDA* *AMPHISTEGINA* *PORITES* *STYLOPHORA*	NOT OBSERVED	MOLLUSCS/ *HALIMEDA*/ PORITES	RHODOLITHS	NOT OBSERVED	NOT OBSERVED	NEAR REEF
DOLOSTONE	*HALIMEDA* C. RED ALGAE PACK TO GRAINSTONE	*HALIMEDA* C. RED ALGAE *AMPHISTEGINA* BIVALVES GASTROPODS *STYLOPHORA*	NOT OBSERVED	*HALIMEDA* C. RED ALGAE	*PORITES*	NOT OBSERVED	NOT OBSERVED	SAND PLAIN
DOLOSTONE	*AMPHISTEGINA* C. RED ALGAE PACK TO GRAINSTONE	*AMPHISTEGINA* C. RED ALGAE *HALIMEDA* BIVALVES GASTROPODS *STYLOPHORA*	NOT OBSERVED	*AMPHISTEGINA* C. RED ALGAE	*PORITES*	NOT OBSERVED	NOT OBSERVED	
DOLOSTONE	MOLLUSC *AMPHISTEGINA* *HALIMEDA* GRAIN TO PACKSTONE	BIVALVES GASTROPODS *AMPHISTEGINA* *HALIMEDA* C. RED ALGAE	NOT OBSERVED	MOLLUSCS	CORALS	NOT OBSERVED	NOT OBSERVED	
DOLOSTONE	RHODOLITH LITHOCLAST GRAINSTONE	RHODOLITHS BRYOZOANS BIVALVES *PORITES* *AMPHISTEGINA*	LITHOCLASTS PELOIDS	RHODOLITHS	*STYLOPHORA*	NOT OBSERVED	SPONGE BORINGS/ BIVALVE BORINGS	HIGH ENERGY STORM DEPOSIT

Table 1. Facies of the Cayman Formation at Safe Haven.

grainstone, and as a wackestone.

The *Amphistegina*-coralline red algae facies is composed of *Amphistegina*, coralline red algae, *Halimeda*, gastropods and bivalves, and rare *Stylophora*. This facies is differentiated from the *Halimeda*-coralline red algae facies by the dominance of *Amphistegina*, less mud in the matrix, and consistently coarser grain sizes (0.5-2mm).

The mollusc-*Amphistegina* -*Halimeda* facies is characterized by coarse sand-sized (1-3 mm), well rounded mollusc fragments, *Amphistegina*, *Halimeda*, and coralline red algae. This is the most coarse-grained of the three facies and is typically a dense packstone or grainstone. Coral fragments are rare except where this facies flanks the *Porites* reef. In this association, the mollusc-*Amphistegina*- *Halimeda* facies forms a grainstone matrix around large *Porites* fragments.

Porites Rudstone and Bafflestone Facies

The *Porites* reef found in wells SH#6, SH#11, SH#7 and CHI#1 is characterized by the *Porites* rudstone facies and *Porites* bafflestones facies. The matrix between the coral fragments is composed of very coarse-grained (1-3mm) mollusc-*Amphistegina-Halimeda* grainstones. These grainstones are cross-stratified and individual grains show a high degree of rounding and abrasion. *Stylophora* is rare in the *Porites* rudstone facies and is absent from the *Porites* bafflestone facies.

Porites Floatstone Facies

The near-reef environment is primarily composed of the *Porites* floatstone facies. This facies consists of bivalves and gastropods, *Halimeda*, *Amphistegina*, *Porites* and rare *Stylophora* held in a grainstone matrix that is compositionally similar to the mollusc-

Amphistegina-Halimeda facies of the Sand Plain environment. The Sand Plain and Near-Reef sediments are differentiated by the presence of *Porites* fragments, and proximity to the *Porites* reef. The *Porites* floatstone facies is closely associated with the *Porites* Reef, and is of limited vertical and lateral extent.

Rhodolith-Lithoclast Grainstone Facies

This facies is composed of large (1-3cm) rhodoliths and lithoclasts, encrusting bryozoans, molluscs, and fragments of *Porites*. The rhodoliths commonly have fragments of *Porites* as their nuclei. The skeletal allochems and lithoclasts are commonly fractured and abraded, and vary in size from fine sand to large cobbles. Some intergranular voids are filled by micritic peloids.

The lithoclasts are wackestones and packstones that have the same skeletal composition as the *Amphistegina*-coralline red algae facies. Borings in the lithoclasts indicate lithification prior to deposition. Although rhodoliths are found throughout the Cayman Formation in the Safe Haven area, they are most common in association with these lithoclasts. The lithoclasts were probably derived from a hardground or erosional surface. There is, however, no evidence in the core of erosional surfaces associated with the hardground facies. This may be due to the fact that this facies is recorded low in the section (35-40m below sea level) in well SH#3. At these depths core recovery is generally poor.

FACIES AND DEPOSITIONAL ENVIRONMENT ARCHITECTURE

The Sand Plain depositional environment, which incorporates the *Halimeda*-coralline red algae, *Amphistegina*-coralline red algae and mollusc-*Amphistegina-Halimeda* facies, dominates the Cayman Formation in the Safe Haven area. The Sand Plain environment has a lateral extent of over 1.5 km east-west, and is interrupted only by the *Porites* Reef. Wells not penetrating the *Porite*s Reef or Near Reef sediments consist of Sand-Plain facies throughout their entire section. The three facies of the Sand Plain environment exhibit vertical inter-fingering on a metre-scale, and lateral variation between the facies is commonly less than the closest well spacing (≅ 200 m) (Figs. 4, 5).

Core from the deepest parts (40-55m bsl) of the Cayman Formation is dominated by *Halimeda*-coralline red algae and mollusc-*Amphistegina* packstone facies of the Sand Plain Environment. Corals are rare, except in wells SH#14 and SH#6. Up-section (35-45 m bsl) these facies change to grainstones of the same composition, but with increasing numbers of foraminifera and more robust molluscs. As well, grain size increases and there is more evidence of allochem abrasion and breakage. At 40 m bsl there is a gradual increase in branching coral abundance associated with the *Porites* reef facies. The shallowest part of the Cayman Formation section was recovered from the western end of the Safe Haven area. Core from that part of the section (15-30 m bsl) is characterized by packstones to wackestones that contain large, well-preserved *Halimeda* plates, robust molluscs, and coralline red algae.

Large-scale lateral variations in allochem distributions in the facies of the Sand Plain Environment are not readily discernible. The fact that the unconformity surface dips to the east, combined with poor core recovery in the lower parts of the Cayman Formation, makes it difficult to compare the eastern and western parts of the section. Some variations are, however, present. *Stylophora* and *Porites* are common in the western part of the section. To the east, SH#5 is characterized by mollusc-*Amphistegina-Halimeda* and

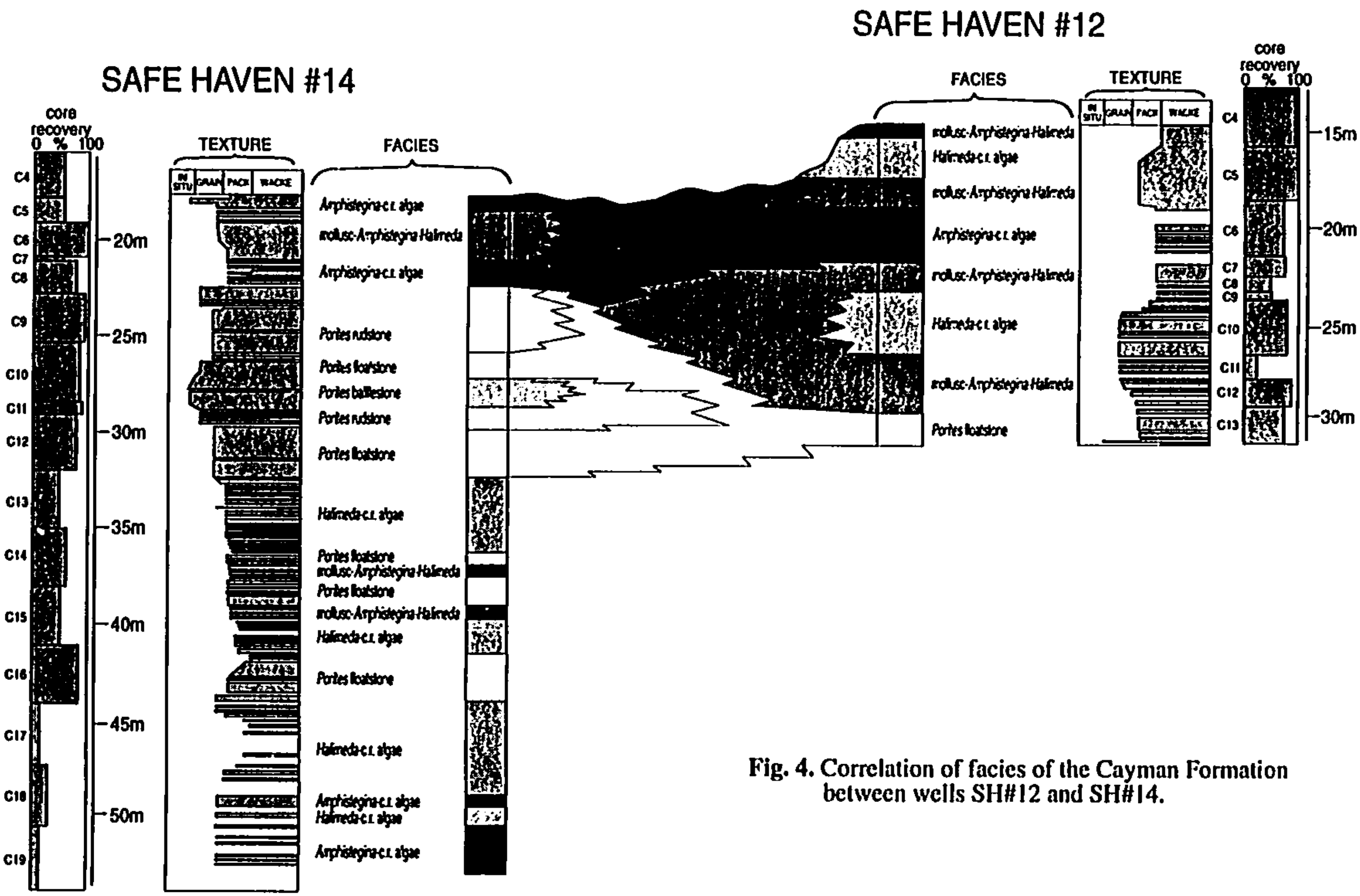

Fig. 4. Correlation of facies of the Cayman Formation between wells SH#12 and SH#14.

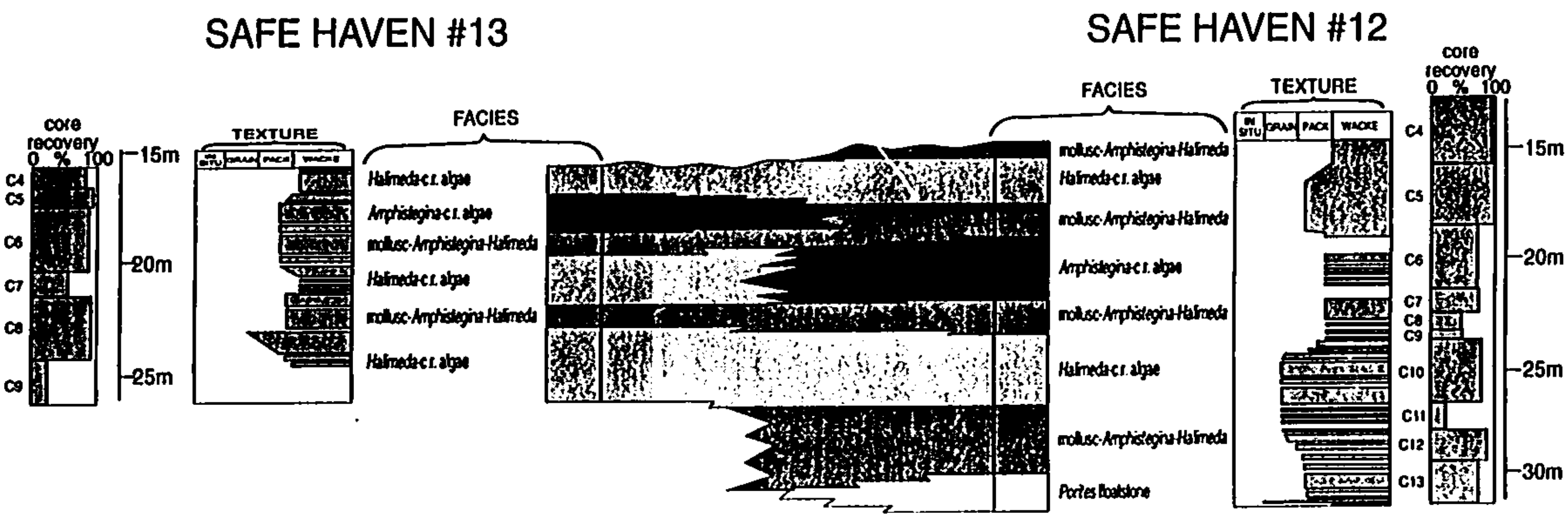

Fig. 5. Correlation of facies of the Cayman Formation between wells SH#13 and SH#12.

Halimeda-coralline red algae packstones and branching corals are rare. Hemispherical corals (*Montastrea, Siderastrea*) are found throughout the formation whereas solitary corals are primarily found in the eastern part of the study area.

The *Porites* Reef extends roughly north-south for at least 1 km, and is approximately 300 m wide (Figs. 6, 7). The thickest recorded part of the reef facies is in well SH#3, where it forms a 10 m interval (22-32 m bsl) of the section. The *Porites* Reef is constrained vertically by *Halimeda*-coralline red algae packstones, and passes laterally into *Porites* floatstones and mollusc-*Amphistegina-Halimeda* grainstones.

In wells CHI#1, SH#7 and SH#14, there is evidence of an erosional surface on top of the *Porites* Reef. Grains are truncated by this surface and sponge borings that cross-cut grains attest to lithification prior to erosion. This erosional surface may also be present in well SH#12 at 23.14 m. In this example the surface is encrusted by red algae, and there are no borings or grain truncations. These surfaces are not associated with the Cayman Unconformity.

DISCUSSION

Water Energy

Interpretation of the facies in the Cayman Formation suggests deposition under moderate to high energy conditions. Grain sizes are consistently coarse, ranging from coarse sand to cobble size. Evidence of breakage and abrasion, particularly in the upper part of the section, is common. Packstone and wackestone textures are preserved throughout much of the section, although the original matrix may have been silt-sized. Modern lagoons and shallow fore-reef environments on Grand Cayman are characterized

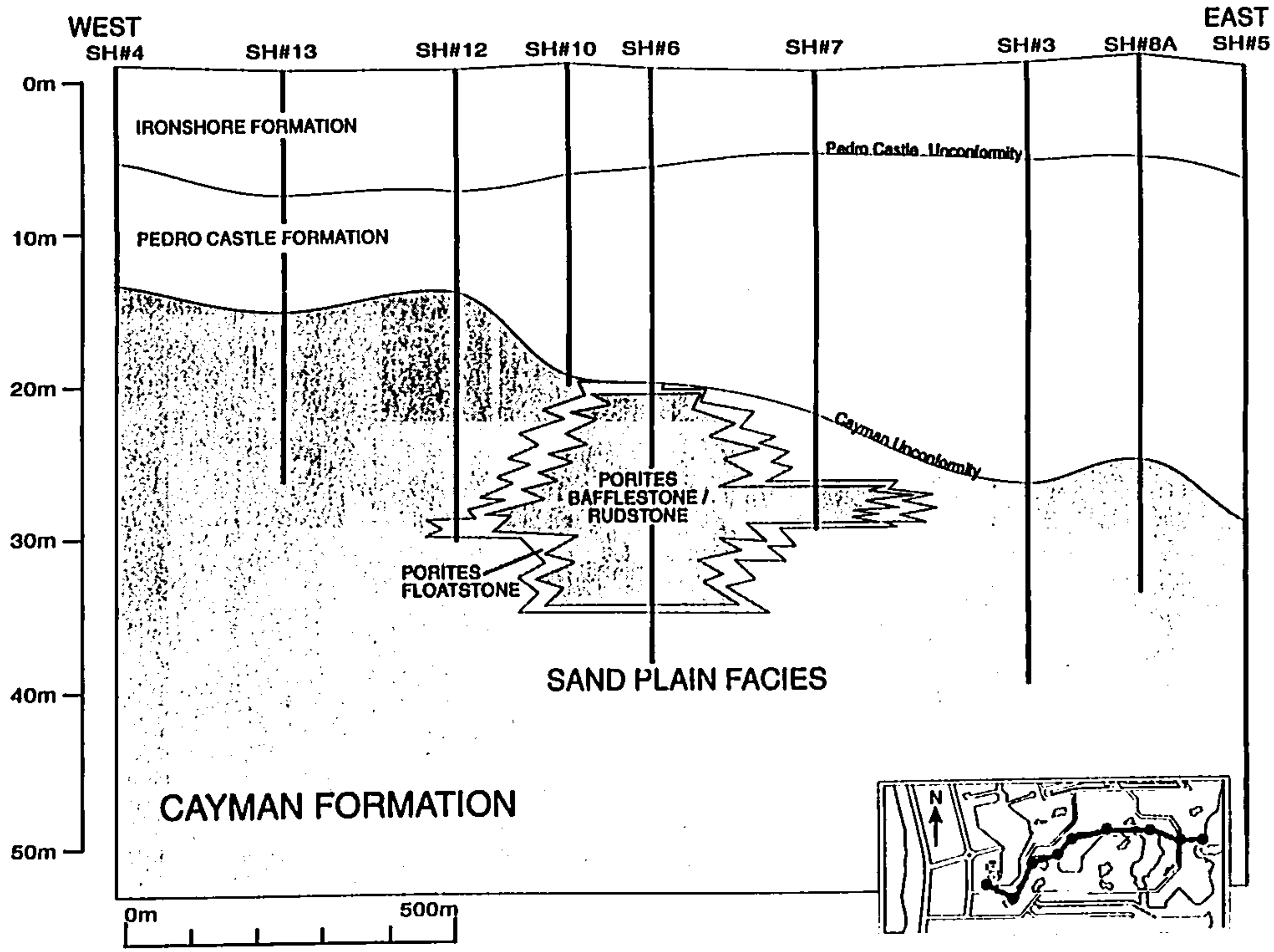

Fig. 6. West-east cross section of the Safe Haven area showing the *Porites* reef

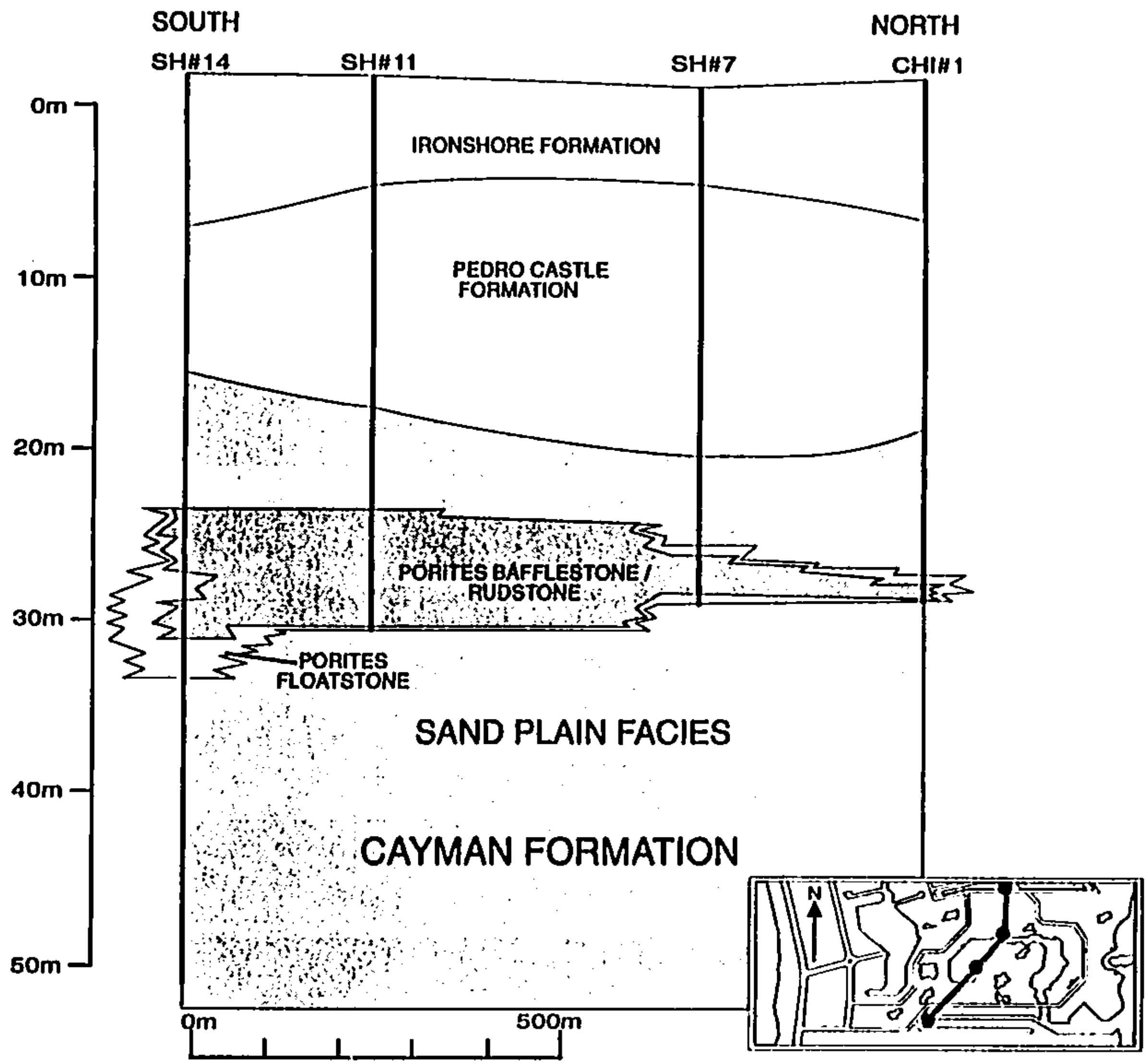

Fig. 7. North-south cross section of the Safe Haven area showing the *Porites* reef

by silts rather than mud (Bill Kalbfleisch, pers. comm.), and this may have been the case in the Miocene.

There is no clear evidence of cross-bedding or sedimentary structures in the facies of the Sand Plain Environment. This may be a function of bioturbation or simply due to the small core diameter precluding recognition of low angle laminations. Grainstones in the *Porites* reef facies are cross-bedded, indicating that the reef was periodically buried by shifting sand waves. The densely-packed *Porites* branches may have inhibited burrowing organisms and protected the sediments from reactivation by normal environment energies (i.e. fair weather waves or currents).

Water Depths

Environmental indicators consistently point to moderately shallow water depths in the Safe Haven area during deposition of the sediments of the Cayman Formation. The presence of red and green algae indicate that the sea-floor environment lay in the photic zone, and the coarse grain sizes and textures of the Sand Plain facies indicate that water depths were probably less than storm wave base. In modern settings, *Amphistegina* and miliolinid foraminifera are the dominant foraminifera found in unrestricted waters at depths of 10-30 m (Poag and Tesslar, 1981; Venec-Peyre, 1991).

Porites found in the Cayman Formation are not as robust as massive hemispherical and branching colonial corals commonly found in high-energy surf zones. Nevertheless, the dense clusters of *Porites* would have required at least moderately energetic, well circulated waters, and well lighted conditions. It is seems probable, therefore, that the *Porites* reef grew in water depths of less than 40m of water (e.g., Frost and Langenheim, 1974).

Based on these indicators, a depositional depth of 10-40m is suggested. Evidence of breakage and abrasion of grains, along with mollusc disarticulation may indicate a shallower depth range. The predominance of photophyllic biota such as green and red algae make this environment similar to partially-drowned modern-day banks like the Serranilla Bank of the Nicaraguan Rise or the Cay Sal Bank of the Bahamas. The Serranilla Bank is characterized by scattered corals and thin accumulations of *Halimeda*-mollusc-foraminifera sands at a depth of 7-30 m bsl (Triffleman *et al.*, 1992). Cay Sal Bank is characterized by seagrasses, algae, sponges, molluscs, echinoids, and rare corals at depths of 10-20 m bsl, with sediment accumulations attaining maximum thicknesses of 10 m (Goldberg, 1983; Hines and Steinmetz, 1984). Based on the similarities in the skeletal constituents of the sands found in these environments and the Cayman Formation at Safe Haven, the depth range of the Miocene sediments may therefore be further constrained to a range of 10-30 m bsl. Depths greater than 10 m limit the ability of framework organisms to accrete and keep pace with sea level changes (Schlager, 1981), and this might account for the lack of framework reefs in the Safe Haven area.

Reef Development

The dense accumulation of *Porites* fragments and *Porites* bafflestones in the west-central part of Safe Haven area is herein considered a *Porites* reef. The geometry of the *Porites* baffle- and rudstone facies in the subsurface probably reflects the morphology of the reef zone at the time of its development (Figs. 6, 7).

High energies indicated by the cross-bedded, coarse grainstones must have influenced the construction of this reef. The relative fragility of the *Porites* (1-1.5 cm in diameter) does not, however, indicate a high energy surf zone (e.g., Frost and Langenheim, 1974). More probable is that the reef developed in a deeper setting of 15-25 m where swell energy influenced sea floor sediment and maintained good water circulation (e.g., Goreau, 1963; Frost and Langenheim, 1974). Given that bathymetry and water energy levels are closely linked, the alignment of the *Porites* reef probably reflects a bathymetric trend and zone of energy flux. It may also be that dominant swell or current energies were directed in an east-west or west-east direction, in which case the *Porites* reef trend would resemble leeward shelf edge reefs found today on Grand Cayman (Blanchon and Jones, 1995).

With most of Grand Cayman lying to the east, it is tempting to suggest that the *Porites* reef in the Safe Haven area was a fringing reef. There is no firm evidence, however, that the *Porites* reef played a role in sheltering more inboard areas. A study of a modern fringing reef and lagoon on Grand Cayman (Kalbfleisch, 1995) noted sediment fining and allochem variation in lagoonal sediments within 0.5 km of the reef. Core from the eastern-most well at Safe Haven, SH#5, does have a generally finer-grained texture than more western wells. This core has rare *Stylophora* and *Porites* in mollusc-*Amphistegina* and *Halimeda*-coralline red algae packstones. The fine-grained nature of the sediment and the consistently fine-grained mud or micritic matrix may indicate lower energies of deposition. Certainly this would be expected of an environment which supports *Halimeda* and red algae, but few corals. This transition does not appear to be linked to the reef trend, however, as it is 0.5 km away from the reef, and no transition is apparent in core from intervening wells. Additionally, the depth range suggested for the

Porites reef means it would not have acted as an energy barrier to the degree that surf-zone fringing reefs do in the modern.

Porites is the only major framework organism in the reef zone. *Stylophora* is rare, and solitary, platy and massive hemispherical corals are absent. This may be related to water energy and sediment movement. Constant sediment movement by waves and currents would smother most platy and hemispherical forms, whereas solitary corals would be uprooted and buried (Vaughn, 1918). The rarity of *Stylophora* may indicate a competitive advantage on the part of *Porites*, such as a faster growth rate or the dense branching morphology that would smother *Stylophora* growths. The fact that hemispherical, and in particular solitary, corals are present inboard of the reef zone indicates that conditions were more hospitable.

The *Porites* reef in the Safe Haven area is the best developed reef yet found in the Cayman Formation (Hunter, pers. comm.). The reasons for its development are unclear, but certain conclusions may be drawn from its construction. The fact that only fast-growing, sediment-shedding *Porites* forms are present indicates the environment was sediment stressed (cf. Frost and Langenheim, 1974, p. 329). Hemispherical and solitary corals could not survive in this environment. The coarse-grained, cross-bedded nature of the rudstone and bafflestone matrix further indicates shifting sands periodically inundated the reef.

This zone of *Porites* bafflestones and rudstones is therefore interpreted as a *Porites* reef which trended approximately north-south, possibly following a bathymetric trend. The environment was energetic, analogous to shallow fore-reef areas where *Acropora cervicornis* dominates in the modern (e.g., Tunnicliffe, 1983). The *Porites* reef acted as a sediment baffle for constantly shifting sands, but as with modern stands of *Acropora cervicornis*, was not a major barrier to swell and current energies.

Open Bank Setting

By the time of deposition of the strata of the Cayman Formation at Safe Haven, Grand Cayman was an isolated bank in an open ocean setting (Perfitt and Heezen, 1978; Emery and Milliman, 1980). The few recorded instances of reefs in the Cayman Formation make it unlikely that the island developed as an atoll (Jones and Hunter, 1994b). Given the sediment types, energy levels and water depths recorded in the Safe Haven section and elsewhere on Grand Cayman (e.g., Jones *et al.*, 1994b) the lack of massive framework reefing indicates an isolated bank setting.

The Cayman Formation on Cayman Brac is an example of Miocene bank deposition in the Caribbean (Jones and Hunter, 1994b). Energy levels and water depths (15-30 m) appear to have been similar, and the fauna nearly identical to the Cayman Formation at Safe Haven. The Cayman Formation on Cayman Brac differs from the Safe Haven section in that it contains no evidence of reef development. Furthermore, the Cayman Formation on Cayman Brac contains significant amounts of mudstone and sparse wackestones that are not found in the Safe Haven core.

The presence of mudstones typically indicates a low energy setting, although Jones and Hunter (1994b) stated that energy levels varied both spatially and temporally on Cayman Brac. Coarse grainstones and rhodolith rudstones attest to periods of high energy. The evidence of low energy deposition may be a function of a more complete vertical section on Cayman Brac. Core recovery at Safe Haven appears to be from an upper section of the Cayman Formation and is from a laterally restricted area.

The lack of reefs in the Cayman Formation on Cayman Brac is not easily explained, except that a combination of tilting, erosion and limited outcrop exposure may have removed or hidden any evidence of reef development. Certainly, the *Porites* reef at Safe Haven is one of only two reefs recorded in the Cayman Formation on Grand Cayman (Hunter, pers. comm.).

Modern bank environments in the Caribbean, which are small in area (less than 2000 km^2) and at moderate water depths (less than 40 m bsl), are typically denuded over most of their area of sediment by strong cross-bank currents (e.g., Goldberg, 1983; Triffleman *et al.*, 1992; Hine *et al.*, 1994; Jones and Hunter, 1994b). These banks are characterized, therefore, by thin (1-3 m), discontinuous veneers of coarse-grained sediment that overlie hardground surfaces. Sediment may accumulate in topographic lows, but is rarely more than 5 m thick (Hine and Steinmetz, 1984). Coral reefs are of limited extent and usually develop on the windward margin of the banks.

The only hardground recorded in the Safe Haven Cayman section is atop the *Porites* reef. Elsewhere in the section, hardground surfaces are not evident, or not obviously erosional in nature. The rhodolith-lithoclast grainstones in well SH#3 are similar to the rhodolith rudstones associated with erosional surfaces on Cayman Brac (Jones and Hunter, 1994b). It is therefore possible that hardground surfaces are present, but not easily discernible, in the Safe Haven core. Close examination of 5 m sections of Sand Plain sediments with better than 90 % core recovery, however, has revealed no evidence of erosional surfaces. Uninterrupted sediment thickness on this scale is greater than that accumulating on most Caribbean open bank settings today (e.g., Hallock *et al.*, 1988;

Triffleman *et al.*, 1992; Hine *et al.*, 1994). The only exceptions to this are on leeward margins of banks where relict rims may accumulate sediment, or sinkholes trap shifting sand waves (e.g., Hines and Steinmetz, 1984, Triffleman *et al.*, 1992). In order for the Safe Haven location to accumulate the thicknesses of sediment observed, therefore, the area must have been, a) sheltered from cross-bank currents or, b) located in an area where sediment was preferentially trapped by antecedent morphology or reef buildup.

Open Ocean Currents and Bank Sheltering

Today, Grand Cayman experiences a westward current averaging 30 cm/sec which can be detected down to depths of 300 m bsl (Darbyshire *et al.*, 1976). Such currents do not appear to have affected the sediment distribution in the Safe Haven area, suggesting that strong ocean currents were not present around Grand Cayman during the Miocene, or that the Safe Haven area was preferentially sheltered.

It is generally accepted that the westward Caribbean current affecting Grand Cayman today was present as early as the late Cretaceous (e.g., Berggren and Hollister, 1974; Ladd and Watkins, 1980; Brunner, 1984; Stanley, 1986). The strength of ocean currents in the Caribbean have, however, varied over time. The development of the Lesser Antilles in the early Tertiary caused the Caribbean current to wane (Ladd and Watkins, 1980; Stanley, 1988). Brunner (1984) found evidence that the currents flowing through the Yucatan channel strengthened in the late Pliocene and Pleistocene in response to glacial cycles and closure of the mid-America seaway. It is therefore possible that the late Oligocene and Miocene successions on the Cayman Islands were deposited during a period of decreased ocean current strength. Whether conditions were calm enough to allow thick accumulations of sediment is still doubtful. Despite ongoing subsidence, all evidence points to water depths consistently between 10-30 m. Even in the absence of strong ocean currents, isolated banks within storm wave base would be subject to sediment winnowing by storms. Alternatively, the sediments may have been allowed to accumulate in the Safe Haven area because of sheltering from currents and major storm paths. Sheltering would suggest a significant energy barrier existed to the east. Reefs have not, however, been recorded in the Cayman Formation on the east end of the island. Finally, the lack of an elevated rim of bedrock or framework reef to trap sediment in the Safe Haven area implies that either a rim existed further to the west, or that sediment input was of such volume that storm and current activity could not keep pace in sweeping sediments off the bank. Given the small size and isolated setting of Grand Cayman, it seems unlikely that such huge volumes of sediment could have been produced.

CHAPTER 3 : THE CAYMAN UNCONFORMITY

The Cayman Unconformity is a karstified surface that separates the Cayman and Pedro Castle formations. The unconformity developed in the Late Miocene (Messinian) as a result of a sea level low stand related to glaciation in the Southern Hemisphere (Jones and Hunter, 1994a). Jones and Hunter (1994a) suggested that the low stand lasted 1.5 million years.

Although the true Cayman Unconformity exists as an unconformable contact between the Cayman and Pedro Castle formations, this relationship is rarely evident in outcrop on Grand Cayman. In most locations, erosion of overlying strata has resulted in the Cayman Formation being exposed, or else directly overlain by the Pleistocene Ironshore Formation. This is most evident on the eastern half of Grand Cayman, where the karst surface atop the Cayman Formation is topographically subdued (Fig. 8). By comparison, the Cayman Formation on the western half of Grand Cayman is overlain by Pliocene and Pleistocene strata, and the unconformity has a minimum relief of 30 m. That this scale of relief is not reflected by the current topography of the island (Fig. 9) may be due to the fact that, where exposed, karsting originally developed during the Messinian sea level low-stand was modified during subsequent low-stands (Ng, 1990). The subdued Holocene topography of Grand Cayman is an overprinting of what was initially a high relief surface atop the Cayman Formation (Jones and Hunter, 1994a). Additionally, the topography and textures associated with the Cayman Unconformity have been preferentially preserved where it is overlain by the Pedro Castle Formation. The Safe Haven subsurface therefore records the characteristics of the Cayman

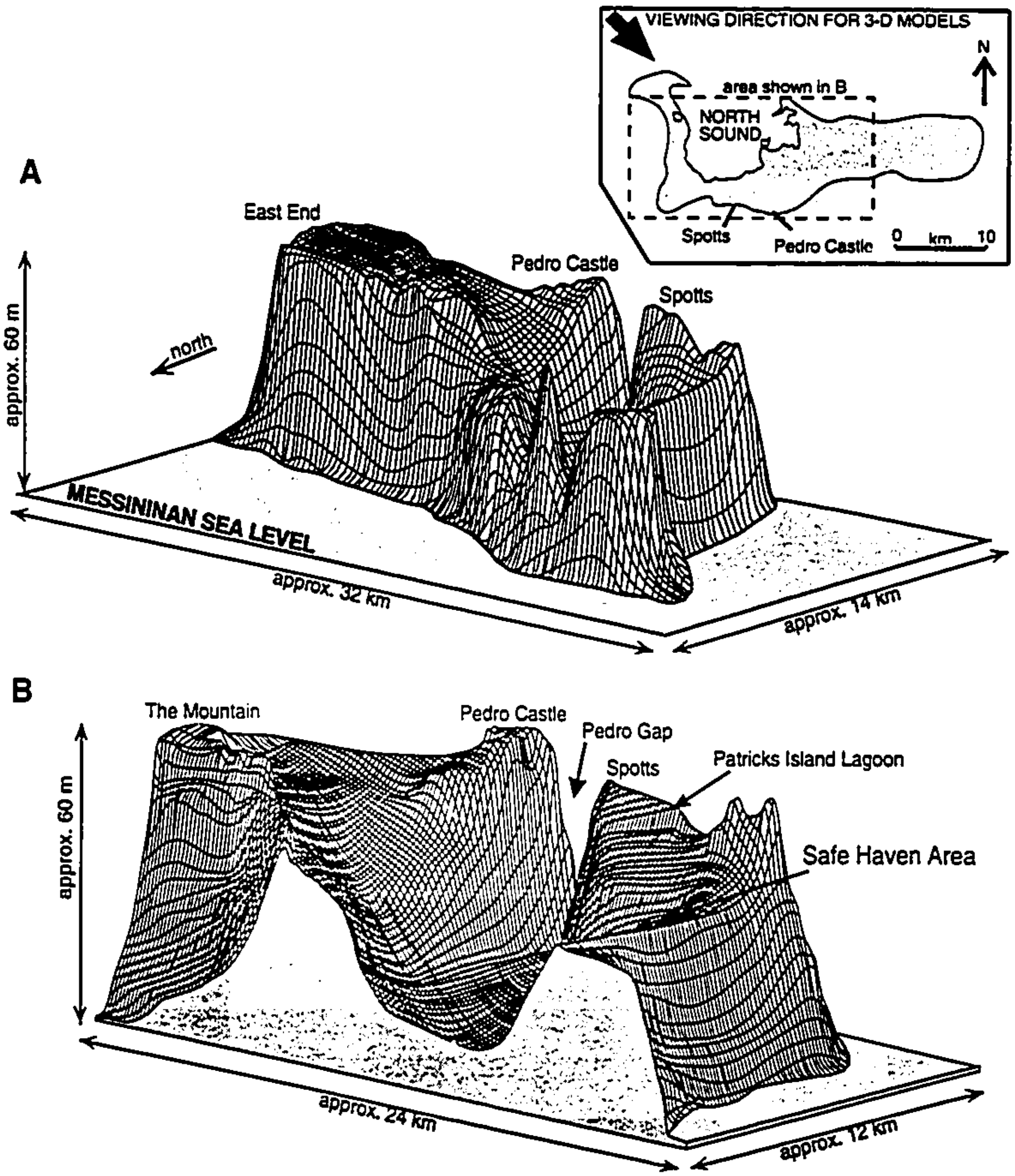

Fig. 8. 3-D representation of the Cayman Unconformity based on surface and drill core information (modified from Jones and Hunter, 1994b).

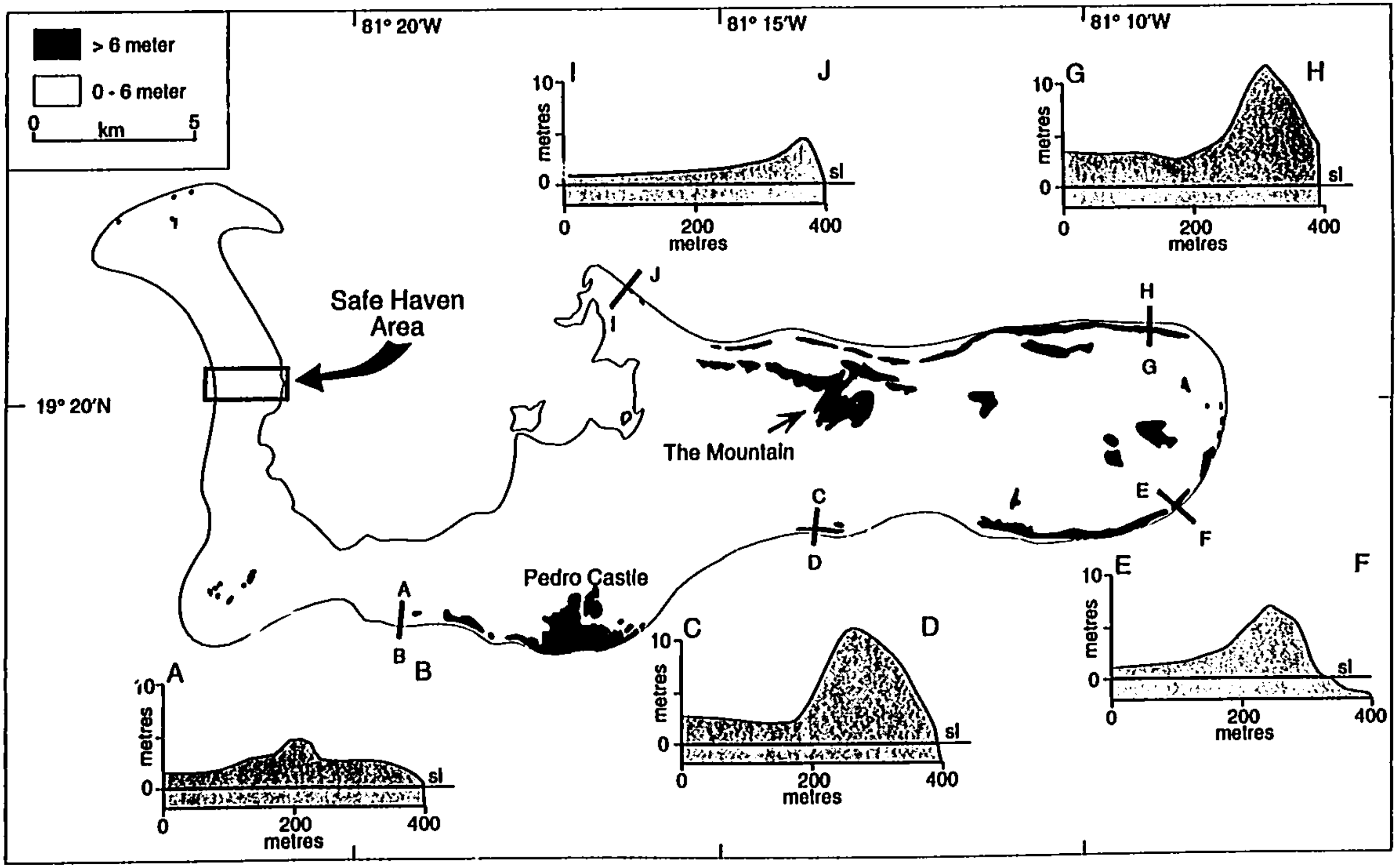

Fig. 9. Peripheral ridge (modified from Jones and Hunter, 1994b).

Unconformity to a degree not found in most exposures of the Cayman Formation.

KARST SURFACE TOPOGRAPHY

The dominant topographic features of the Cayman Unconformity are a peripheral ridge that surrounds most of the island (Fig. 9), and a depression on the western half of Grand Cayman, under what is today North Sound (Fig. 8).

The peripheral ridge, which essentially delineates the western depression, is not continuous. The ridge is highest and most continuous on the southern, eastern, and northern coasts. On the western half of Grand Cayman the peripheral ridge rarely reaches the surface, and is discontinuous. Jones and Hunter (1994a) found major breaks in the ridge west of Pedro Castle (Pedro Gap) and along the north side of North Sound (Fig. 8). Pedro Gap appears to be at least 4 km wide, with a minimum depth of 20 m bsl. No data are available for the Cayman Unconformity surface along the north side of North Sound, with the exception of a small remnant of the Cayman Formation exposed above sea level at Fisherman's Rock.

The Cayman Unconformity is, for the most part, topographically lower on the western end of Grand Cayman than elsewhere on the island. On the eastern half of Grand Cayman the peripheral ridge reaches elevations of 11 m asl, whereas at Safe Haven the ridge achieves a maximum elevation of 12.8 m bsl. The dizzy height of 20 m asl reached by the Cayman Formation at "The Mountain" is never attained on the western peninsula of Grand Cayman.

The Safe Haven area is located on the western part of the peripheral ridge. There, the peripheral ridge is found only in the subsurface, and the Cayman Unconformity dips eastward at a slope of 0.6° (Fig. 10) from the ridge crest into the bowl-shaped depression under North Sound. A south-north transect at Patrick's Island Lagoon (Fig. 8) also records a gentle northwards slope of 0.3° on the unconformity surface into the depression (Jones and Hunter, 1994a). The maximum recorded depth of the Cayman Unconformity in the Safe Haven area is 29.4 m bsl, in well SH#5. A well drilled in a paleosink hole on the northeast corner of the island (QHW#1) penetrated 40.6 m of Pedro Castle Formation before encountering the Cayman Formation. Given that sink holes usually reach a maximum depth corresponding to sea level, the minimum base level achieved by the Messinian low-stand must have been 41 m bsl (Jones and Hunter, 1994a). This suggests the depression under North Sound may be much deeper than the 29.4 m bsl recorded in SH#5.

Despite the gentle 0.6° slope of the Cayman Unconformity in the Safe Haven area, the surface is irregular, with at least two highs that are 3-5 m above the general slope (Fig. 10). These highs are composed of dolomitized wackestones and packstones of the Cayman Formation and there is no evidence suggesting they were formed by constructional processes. This may indicate that the highs are of erosional origin. As well, there is no evidence that these features formed through differential collapse of the Cayman Formation. If the immediate surrounding areas had dropped down relative to the highs, these low areas should be below the 0.6° line of best fit. Instead, the highs appear to break the slope, and cannot both be incorporated onto a line of best fit.

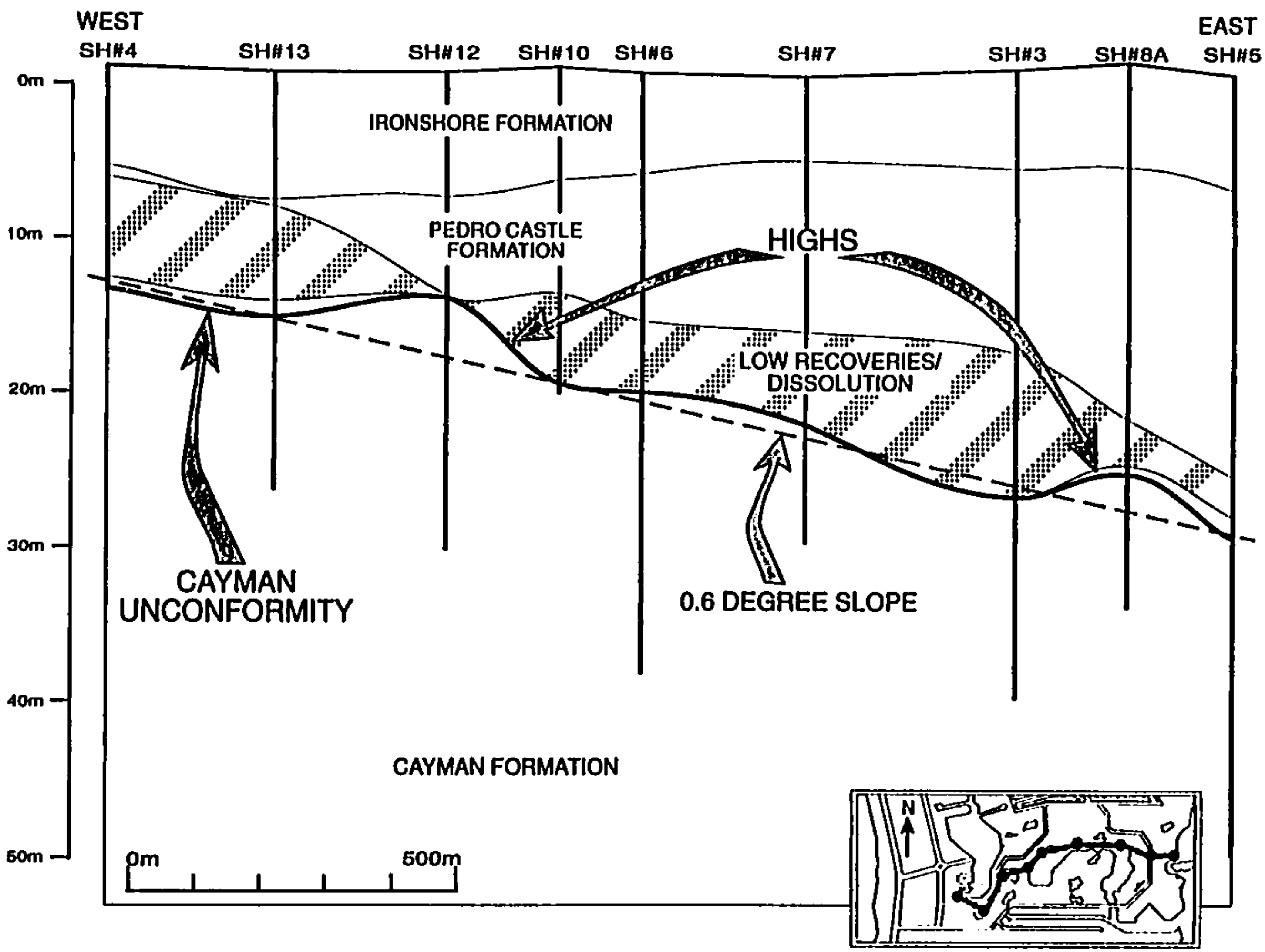

Fig. 10. Features associated with the Cayman Unconformity.

FEATURES OF THE CAYMAN UNCONFORMITY

The karst surface at the top of the Cayman Formation shows a variety of surficial features that vary according to exposure and location. Bored black phytokarst and calcretes are characteristic of exposed rocks of the Cayman Formation (e.g. Folk *et al.*, 1973; Squair, 1988; Jones, 1989). These phytokarsted areas develop into rugged terrains, with towers that have a vertical relief of 3-4 m (Folk *et al.*, 1973). In the subsurface, and where the Cayman Unconformity is exposed at Pedro Castle Quarry, there is no evidence of phytokarst, nor is there clear evidence of paleosol development. Only one well in the Safe Haven area, SH#14, has what may be calcrete nodules in a 10 cm interval 4 m below the Cayman Unconformity.

Where the Cayman Unconformity is evident in Safe Haven core, it is characterized by a case-hardened, well-cemented interval that extends 1-2 m into the Cayman Formation. Bivalve and sponge borings in the unconformity surface are filled by sediments of the overlying Pedro Castle Formation. This relationship is also found in exposures at Pedro Castle Quarry (Jones and Hunter, 1989).

Establishing the boundary between the two formations rests on criteria that vary depending on location. In most cases, the case-hardened surface of the unconformity serves as an important marker horizon during drilling. The decrease in drilling speed as friable dolo-limestones of the Pedro Castle Formation give way to hard dolostones of the Cayman Formation is so marked that the Cayman Unconformity can be usually be pinpointed while drilling is in progress. Indeed, a characteristic of the Cayman Unconformity is that the rocks of the Pedro Castle Formation immediately overlying the unconformity are dolomitized and leached, with low core recoveries and poor textural preservation (Fig. 10). In comparison, rocks immediately under the Cayman Unconformity typically show good textural preservation, with matrix and allochem microstructures preserved to a degree not found elsewhere in the Cayman Formation. Core recoveries in the upper 4 m of the Cayman Formation are commonly 100%.

In some of the cores recovered from the Safe Haven area, dolostones of the Pedro Castle Formation immediately overlying the unconformity are nearly identical to the upper dolostones of the Cayman Formation. In these cases, recognition of the unconformity surface must depend on evidence of boring and grain truncation, rather than on changes in lithology, sedimentary textures, or drilling behavior. This illustrates the point that the characteristics that serve to differentiate the two formations are primarily diagenetic in nature, rather than sedimentological. Because many of the diagenetic fabrics recorded in the Safe Haven area cut across the Cayman Unconformity, recognition of the boundary between the two formations can become problematic if the surface atop the Cayman Formation is not recovered in core.

SUB-AERIAL AND MARINE EROSION

The Cayman Unconformity, where preserved in the Safe Haven core, has been modified by marine processes. Bivalve and sponge borings are evident on the surface, as are red algal encrustations. This is also true of the unconformity surface preserved at Pedro Castle Quarry (Jones and Hunter, 1989). Additionally, the rugged, black, phytokarsted surface that is typical of the Cayman Formation in sub-aerial exposures is not evident in the Safe Haven or Pedro Castle Quarry locales. This suggests that marine processes destroyed sub-aerial surface karst features. The amount of rock removed by these processes is open to conjecture, but the relief of the phytokarsted surfaces developed on exposed rock of the Cayman Formation suggests it must have been a minimum of 1-3 m.

There is no evidence of calcrete or soil horizons in the Cayman Formation, despite the fact that the Messinian lowstand was of sufficient duration to allow the development of a mature soil profile (e.g., Harrison,1977). As well, despite a major drop in temperature in temperate regions at the end of the Miocene (e.g., Barron, 1974), climatic conditions in the tropical latitudes were not significantly different from today (Adams *et al.*, 1990; Flower and Kennet, 1994). It is probable then, that soil horizons did form, but were erased or removed by later erosional processes. Calcretes and root systems developed in the overlying Pliocene and Pleistocene sediments commonly extend 3-4 m beneath the surface. Although paleosol development on the Messinian surface may not have been as extensive or deep as that developed on the Pliocene and Pleistocene surfaces, a significant volume of rock would still have been removed to erase all evidence of paleosol formation. Jones and Hunter (1994a) suggested the rainfall patterns across the island may have caused an accelerated rate of erosion on the western half of Grand Cayman. Even were this the case, it is inconceivable that karsting in the Safe Haven area proceeded at such a rate that soil horizons were removed as fast as they could form. Either soil-forming and vegetative processes halted for some time prior to inundation of the island, or erosion of the Cayman Formation must have taken place after sea-level rose in the late Miocene or early Pliocene.

MARINE PLANATION TERRACES

Removal of a meter or more of rock from the top of the Cayman Formation would have significantly modified the topography of the Cayman Unconformity. This suggests that the highs on the Cayman Unconformity at Safe Haven are not a result of sub-aerial erosion. Certainly, the highs bear more than a passing resemblance to wave-cut terraces on Grand Cayman today. Blanchon and Jones (1995) described similar marine planational terraces on Grand Cayman that formed in response to a stepped Holocene sea-level rise. It seems probable that the highs on the Cayman Unconformity developed in the same way, and that sea level rise following the Messinian lowstand was not a continuous upward rise (Fig. 11). This would have meant sea-level stillstands of short duration situated at 28 m and 16 m bsl.

CASE-HARDENING

Karst surfaces that are exposed, with little or no vegetative cover, develop case-hardened horizons at the surface that are less susceptible to dissolution and physical breakdown (Stringfield *et al.*, 1977). Karst surfaces overlain by permeable material or plant cover tend to be poorly indurated, and have much more local relief than the sheet-like rock surface that develops where no cover exists. In tropical and sub-tropical latitudes the factors that give rise to these different situations are related to topography, climatic, and vegetative differences between locales. In general, areas with extensive vegetation cover and high rainfalls develop a high-relief local topography, and case-hardening is removed by a constant undercutting (Stringfield *et al.*, 1977; Mylroie, 1988). These processes accentuate the tower and pinnacle terrains that develop in karsted areas.

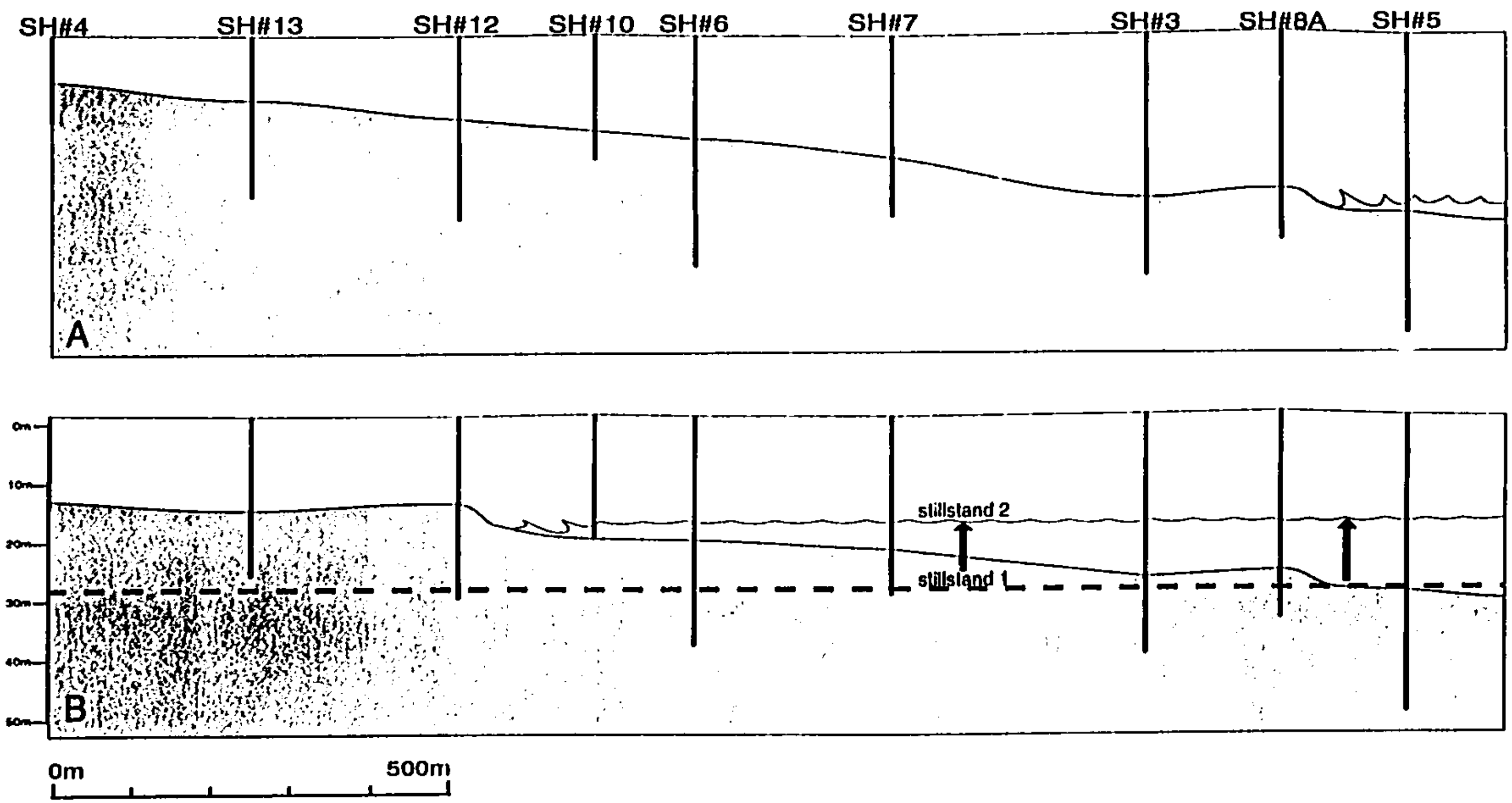

Fig. 11. Highs on the Cayman Unconformity may have developed as marine terraces formed by a stepped sea level rise. A) The lower high formed as a result of shore face erosion during stillstand 1 at 28 m bsl. B) A sea level rise and stillstand at 16m bsl formed the second high.

Karst-induced case hardening of exposed Tertiary rocks on Grand Cayman has been well documented (e.g., Folk *et al.*, 1977; Squair, 1988; Jones, 1989). This usually takes the form of a grey to black crust on the weathered surface of the rock, with a hard, well-cemented zone immediately beneath the weathered surface. The case-hardening, however, appears to be a surface phenomenon that does not extend more than a few centimeters into the Cayman Formation.

The case-hardening of the Cayman Unconformity in the Safe Haven area does not appear to have been formed as a result of karsting. The evidence for marine modification of the surface is clear, whereas the phytokarst that so typifies the exposed dolostones of the Cayman Formation is not evident in the Safe Haven cores. As well, the lowest estimate of the amount of rock removed by marine erosion, based on the geometry of the terraces recorded in wells SH#12 and SH#8A, would be 1-3 m. Case-hardening due to surface karst processes would thus have extended 4-5 m into the Cayman Formation, an unusual situation. Finally, although the unconformity surface appears to be smooth and regular, it is doubtful that this is an artifact of a smooth, hardened paleo-karst surface. Such surfaces, when exposed to physical weathering, tend to break apart in slabs (Mylroie, 1982). This promotes uneven weathering, with cap-rock remnants of the case-hardened surface forming highs, and uncapped areas eroding preferentially to form lows. There does not appear to be any difference between the hardened rock forming the highs on the Cayman Unconformity and rock of the neighbouring low areas. In light of these arguments, it would appear most probable that the hardening of the Cayman Unconformity was related to marine cementation following shoreface erosion associated with a rising sea level. Unfortunately, no clear evidence of marine cements is preserved in the upper strata of the Cayman Formation.

SYNOPSIS

The Cayman Unconformity developed as a karst surface during a sea level lowstand at the end of the Messinian. This surface was subsequently modified by a stepped marine transgression. No clear evidence remains of karst or vegetative processes, whereas borings and encrustation of the surface attest to a marine environment. In the Safe Haven area, topographic and textural features associated with the Cayman unconformity are due to marine, rather than sub-aerial, processes.

CHAPTER 4 : SEDIMENTOLOGY AND FACIES ARCHITECTURE OF THE PEDRO CASTLE FORMATION

The Pedro Castle Formation is divided into six biofacies (Table 2). These facies are differentiated on the basis of skeletal components, and reflect variations in depositional environments and faunal communities in the Safe Haven area during the Pliocene.

SKELETAL COMPONENTS FORAMINIFERA

Skeletal components found in the Pedro Castle Formation include benthic foraminifera (*Amphistegina, Archaias,* miliolinids), pelagic foraminifera (Globorotalids), *Halimeda*, echinoderms, gorgonian spicules, bivalves, gastropods, bryozoans, encrusting and coralline red algae, and ostracods. Solitary, free-living corals (*Trachyphyllia*) and branching corals (*Stylophora, Porites*) are common, whereas hemispherical and platey corals (*Leptoseris, Montastrea sp., Montastrea limbata*) are rare. Rhodoliths and intraclasts are locally common.

Although allochem preservation is variable, skeletal components are typically better preserved than in the Cayman Formation. Foraminifera are well preserved, although dissolution and fabric-destructive replacement of some specimens is evident. *Halimeda* is evident in hand sample and thin section as well-preserved plates, or as hollow molds. Well preserved echinoderm plates and spines are present as uniaxial crystals. Gorgonian spicules, bryozoans, and ostracods show good to poor preservation and are typically evident only in thin section. *Stylophora* is invariably leached, and identified on the basis of its corallite imprints. *Porites* is found as large, recognizable fragments in hand sample,

LITHOLOGY	FACIES	SKELETAL ALLOCHEMS	NON-SKELETAL ALLOCHEMS	DOMINANT ALLOCHEM	RARE ALLOCHEM	BORINGS / TRACE FOSSILS	ENVIRONMENT
LIMESTONE DOLOMITIC LIMESTONE	MOLLUSC *HALIMEDA* FORAM WACKE TO PACKSTONE	BIVALVES GASTROPODS *HALIMEDA* *AMPHISTEGINA* ECHINODERMS *STYLOPHORA* *PORITES*	+- RHODOLITHS	BIVALVES GASTROPODS *HALIMEDA*	CORALLINE RED ALGAE	NOT OBSERVED	BANK
LIMESTONE DOLOMITIC LIMESTONE	*STYLOPHORA* MOLLUSC FORAM WACKE TO PACKSTONE	*STYLOPHORA* BIVALVES GASTROPODS *AMPHISTEGINA* *HALIMEDA* *PORITES*	+- RHODOLITHS	*STYLOPHORA* BIVALVES GASTROPODS *AMPHISTEGINA*	CORALLINE RED ALGAE	NOT OBSERVED	BANK
LIMESTONE DOLOMITIC LIMESTONE	SOLITARY CORAL FORAM *HALIMEDA* WACKE TO PACKSTONE	*TRACHYPHYLLIA* *AMPHISTEGINA* *ARCHAIAS* MILIOLINIDS *HALIMEDA* GASTROPODS ECHINODERMS GORGONIA	+- RHODOLITHS	*TRACHYPHYLLIA* *AMPHISTEGINA* *HALIMEDA*	*PORITES* *STYLOPHORA*	NOT OBSERVED	BANK
LIMESTONE DOLOMITIC LIMESTONE	*HALIMEDA* MOLLUSC WACKE TO PACKSTONE	*HALIMEDA* *BIVALVES* GASTROPODS *AMPHISTEGINA* MILIOLINIDS ECHINODERMS PELAGIC FORAMINIFERA	+- RHODOLITHS	*HALIMEDA* BIVALVES *AMPHISTEGINA*	CORALS	NOT OBSERVED	BANK
DOLOMITIC LIMESTONE	FORAM MOLLUSC PACKSTONE	*AMPHISTEGINA* *ARCHAIAS* BIVALVES GASTROPODS *HALIMEDA* ECHINODERMS MILIOLINID FORAMINIFERA	INTRACLASTS RHODOLITHS	*AMPHISTEGINA* BIVALVES GASTROPODS	CORALS	NOT OBSERVED	LAGOON
DOLOMITIC LIMESTONE DOLOSTONE	RHODOLITH FORAM *HALIMEDA* PACK TO GRAINSTONE	*AMPHISTEGINA* MILIOLINIDS *HALIMEDA* BIVALVES GASTROPODS *PORITES* *CORALLINE RED ALGAE*	RHODOLITHS INTRACLASTS	RHODOLITHS *AMPHISTEGINA* *HALIMEDA*	NOT OBSERVED	SPONGE BORINGS	UNCONFORMITY COLONIZATION / LAGOON

Table 2. Facies of the Pedro Castle Formation.

although it is more commonly evident as small, well-preserved grains in thin sections. Solitary corals such as *Trachyphyllia* are typically leached, with the mold partially or completely filled by spar calcite. Rare specimens show partial preservation of internal structure. Massive hemispherical and platey corals maintain internal skeletal structure to some degree, although many specimens have been completely leached. These corals are recognized primarily on the basis of corallite mold imprints. Bivalves and gastropods are commonly leached and preserved as calcite spar casts, or are preserved as hollow molds. Some specimens maintain a recognizable molluscan shell structure when viewed in thin section. Red algae is well preserved, and has suffered far less dissolution than red algae in the Cayman Formation.

Compared to the Cayman Formation, the Pedro Castle Formation has a more diverse assemblage of skeletal components. This may be related to the fact that the Pedro Castle Formation has undergone the less diagenetic alteration than the Cayman Formation. Increased diversity of benthic foraminifera indicates, however, that the greater faunal variety in the Pedro Castle Formation may not be due to a lower degree of diagenetic overprinting. Given that benthic foraminifera are typically well-preserved in the Cayman Formation, specimens of *Archaias* and miliolinid foraminifera should still be evident if they were originally present in the sediments. That they are not can only be attributed to the fact that they were extremely rare at the time of deposition. Thus the increased skeletal variety of the Pedro Castle Formation may, in fact, be due to greater faunal diversity in the Pliocene.

Increased preservation of skeletal components and matrix materials in the Pedro Castle Formation allows delineation of biofacies. The only exception is at the top of the

Pedro Castle Formation, where calcretization related to the Pedro Castle Unconformity commonly obscures textures in the rock. The zone of calcretization rarely extends more than 3 m into the formation, and thus is not a significant impediment to recognition of allochems and sedimentary structures throughout most of the Pedro Castle Formation.

FACIES OF THE PEDRO CASTLE FORMATION

Rhodolith-foraminifera-*Halimeda* Facies

These packstones to grainstones are characterized by rhodoliths 1-5 cm in diameter, *Amphistegina*, miliolinid foraminifera, *Halimeda*, bivalves, gastropods, *Porites*, coralline red algae, and intraclasts. The rhodoliths commonly have small intraclasts, and less typically coral fragments, as their nucleii. This may be used as a criterion for differentiating this facies from the rhodolith-lithoclast facies of the Cayman Formation, wherein most of the rhodoliths have coral fragment nucleii. The intraclasts are 0.5-2 cm in diameter and are typically dolomitized wacke- to packstones similar to the mollusc-*Amphistegina-Halimeda* facies of the Cayman Formation. Borings in the intraclasts indicate they were lithified prior to deposition or encrustation by red algae. The red algae coatings are not bored. The remaining medium to very coarse-sand grain size allochems are surrounded by a matrix formed of variable amounts of mud, or calcite and dolomite cements.

Foraminifera-Mollusc Facies

The foraminifera-mollusc facies is characterized by *Amphistegina*, *Archaias*, bivalve, and gastropod fragment packstones. *Halimeda*, miliolinid foraminifera, echinoderm fragments, and rhodoliths are also common. Intraclasts are present, but rare. The skeletal components are typically medium to very coarse-sand sized, although many of the bivalves are large (3-5 cm), robust specimens. The benthic foraminifera are the dominant allochem - specimens of *Amphistegina* may form up to 30% of the skeletal components. Corals are scarce, and usually consist of *Stylophora* molds and *Porites* fragments. The matrix is composed of mud and calcite and dolomite cements.

Halimeda-Mollusc Facies

This facies is dominated by *Halimeda*, bivalves, and to a lesser extent, gastropods. *Amphistegina*, miliolinid foraminifera, echinoderm fragments, and pelagic foraminifera are also common. The sediments usually form wackestones or packstones, and skeletal components are typically medium- to very coarse sand-size. The bivalves found in this facies are generally large (3-5cm) and robust, although small, thin-shelled specimens are also present. Although corals are rare in this facies, *Stylophora* molds are more common than in the foraminifera-mollusc facies.

Solitary Coral-Foraminifera-_Halimeda_ Facies

This wackestone to packstone is characterized by numerous solitary corals, most notably *Trachyphyllia*, of which at least two species are present (*Trachyphyllia* n. sp., *Trachyphyllia bilobata*). *Amphistegina*, *Archaias*, miliolinid foraminifera, *Halimeda*, gastropods, echinoderm fragments, and gorgonian spicules are also common. Apart from the dominance of free-living corals, there is little to differentiate this facies from the *Halimeda*-mollusc and foraminifera-mollusc facies. In this solitary coral association, gastropods tend to be more evident in hand sample than bivalves. This is not apparent in thin section, and may reflect the fact that gastropods tend to be more robust and less susceptible to breakage than bivalves. Intraclasts are not evident, and rhodoliths less common than in the foraminifera-mollusc facies. Branching, hemispherical and platey corals are typically absent from this facies.

Stylophora-Mollusc-Foraminifera Facies

This facies is characterized by fragments of *Stylophora* embedded in bivalve-gastropod-*Amphistegina-Halimeda-Porites* wackestones to packstones. *Stylophora* is never found in life position, but the numerous fragments (up to 30% of rock volume) serve to differentiate this from other facies in the Pedro Castle Formation. The *Stylophora*-mollusc-foraminifera facies contains significantly more mud than other facies of the Safe Haven area. In addition, grain sizes of skeletal allochems are finer (fine to coarse sand). Although coralline red algae are found throughout most of the Pedro Castle Formation, it is notably rare in this facies.

Mollusc-*Halimeda*-Foraminifera Facies

This facies, the most common rock type found in the Pedro Castle Formation at Safe Haven, is characterized by bivalve-gastropod-*Halimeda-Amphistegina* wackestones to packstones. Texturally and compositionally, this facies is similar to the matrix of the *Stylophora*-mollusc-foraminifera facies, and is differentiated primarily by lesser amounts of *Stylophora*. Additionally, this facies tends to be less muddy than the *Stylophora*-mollusc-foraminifera facies. Rhodoliths are present in this facies, but are not an important sediment constituent, and coralline red algae are rare

FACIES ARCHITECTURE

As with the Cayman Formation, the facies of the Pedro Castle Formation show lateral and vertical variation that is on a meter-scale. In general, however, the facies of the Pedro Castle Formation have greater lateral continuity than facies in the Cayman Formation. Facies such as the rhodolith-foraminifera-*Halimeda* and foraminifera-mollusc facies can be traced as more or less continuous beds over distances of 0.7 km east-west (Figs. 12-14). This may be related to the fact that the facies identified in the Pedro Castle Formation can be considered true biofacies, whereas the facies identified in the Cayman Formation reflect, to a large degree, diagenetic overprinting.

Of the six facies recognized in the Pedro Castle Formation, only two tend to occupy a consistent position in the Safe Haven section. The rhodolith-foraminifera-*Halimeda* facies generally overlies the Cayman Unconformity and is of variable thickness, depending on the topography of the unconformity. The foraminifera-mollusc facies generally overlies the rhodolith-foraminifera-*Halimeda* facies, and is most common in the lower part of the Pedro Castle Formation. Indeed, *Amphistegina* as a percentage of skeletal components tends to decrease upsection. The remaining four facies are found throughout the Safe Haven section without any apparent vertical or lateral restriction.

The solitary coral-foraminifera-*Halimeda* facies forms isolated pods throughout the succession. In the western half of the Safe Haven area, this facies lies more or less on top of the Cayman Unconformity, interlayered with the rhodolith-foraminifera-*Halimeda* facies. To the east, the solitary coral zones may be found anywhere in the section, although topographic highs on the Cayman Unconformity appear to have been focal points for *Trachyphyllia* colonization (Fig. 15).

The *Stylophora*-mollusc-foraminifera facies is less widespread than the solitary coral association. This facies is concentrated in the upper half of the Pedro Castle Formation,

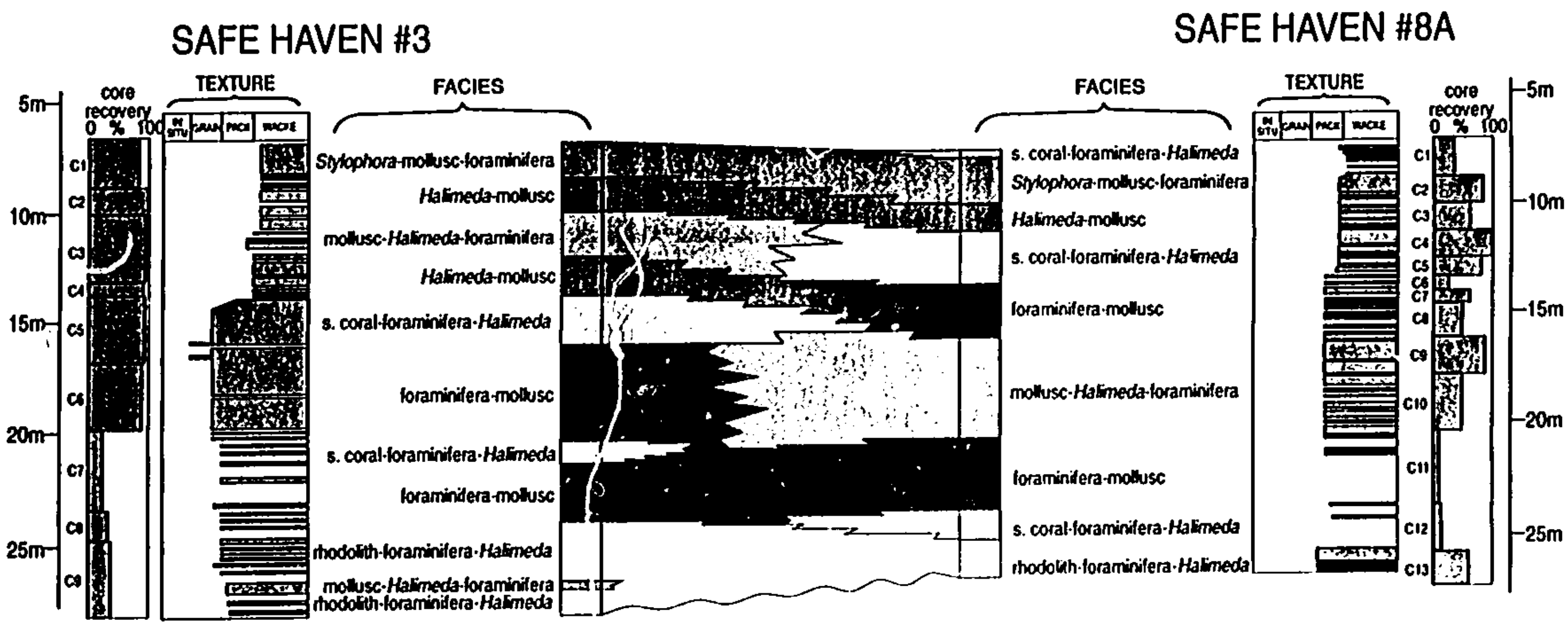

Fig. 12. Correlation of the facies of the Pedro Castle Formation between wells SH#3 and SH#8A

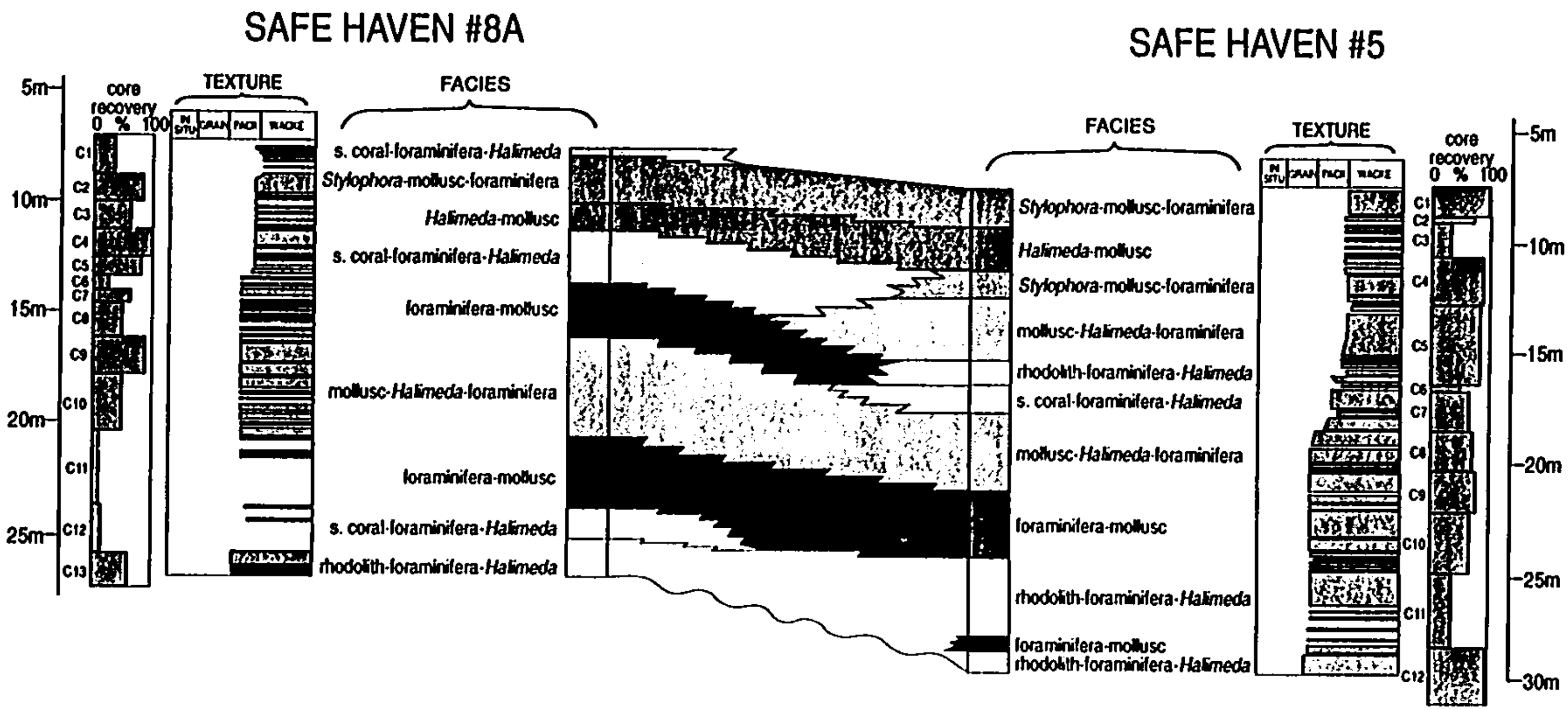

Fig. 13. Correlation of facies of the Pedro Castle Formation between wells SH#8A and SH#5.

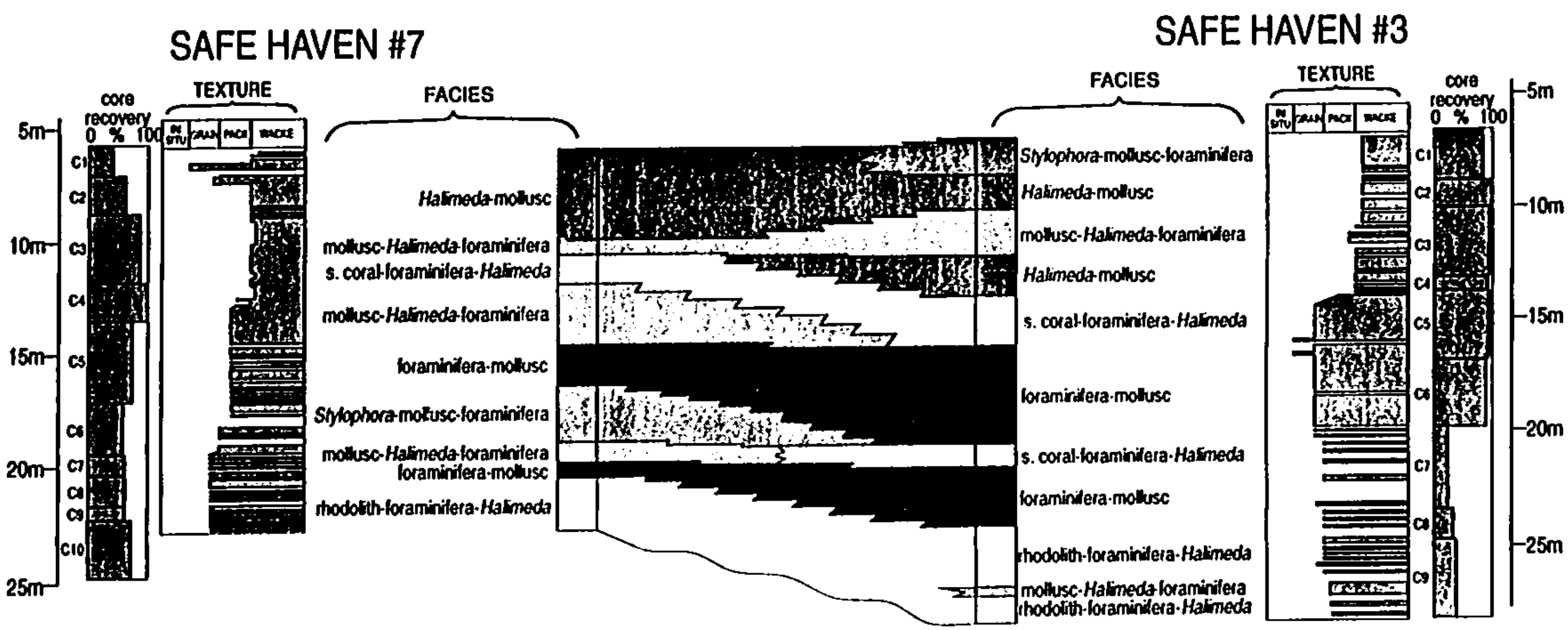

Fig. 14. Correlation of the facies of the Pedro Castle Formation between wells SH#7 and SH#3.

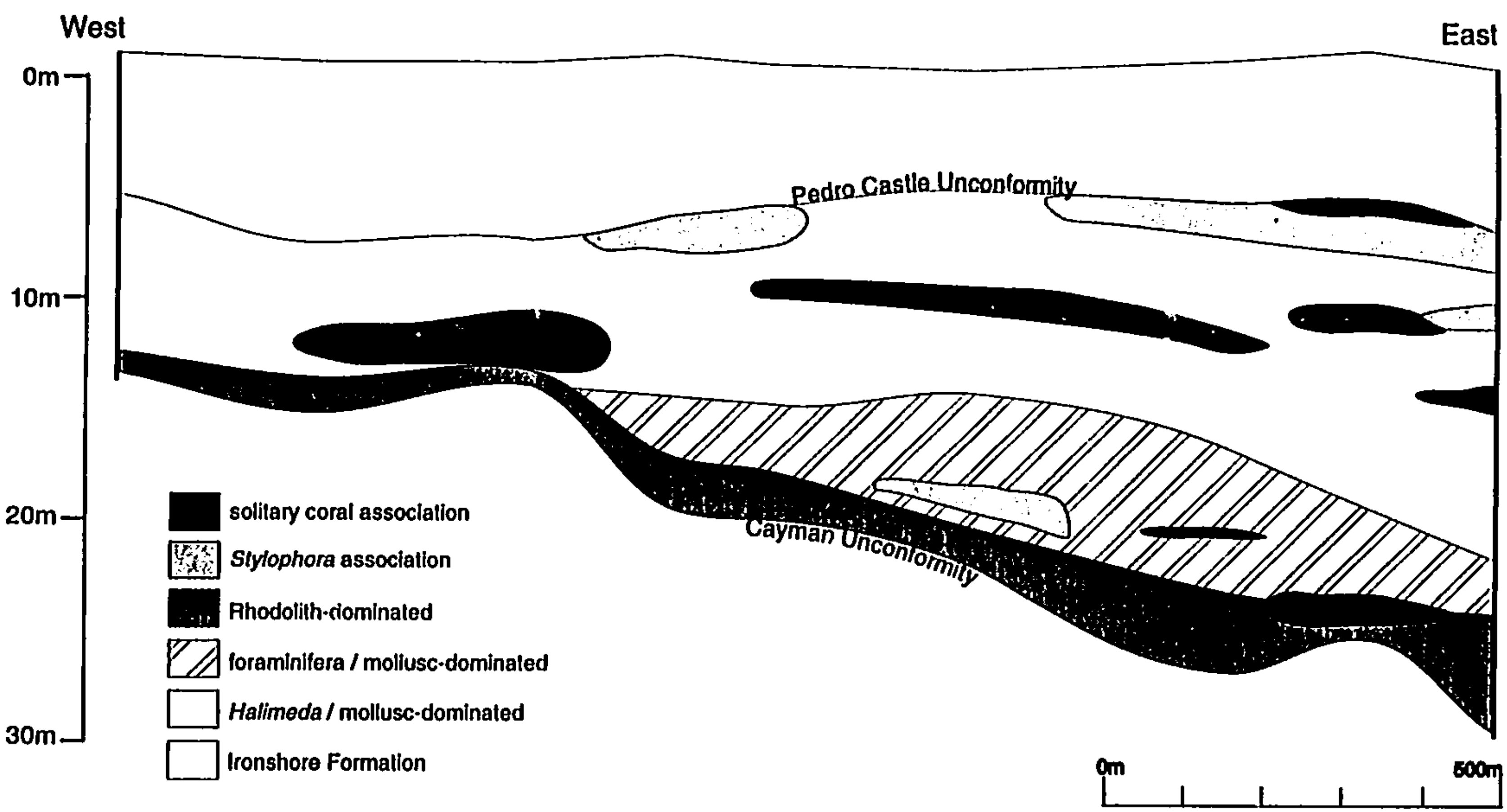

Fig. 15. A west-east cross section showing generalized facies distribution in the Pedro Castle Formation.

and in the eastern end of the Safe Haven area.

The *Halimeda*-mollusc facies occupies no particular stratigraphic zone in the section, although it appears to be most common in the upper half of the Pedro Castle Formation, where it grades laterally into the *Stylophora* and solitary coral associations. The mollusc-*Halimeda*-foraminifera facies tends to dominate the lower part of the formation. Similarly, increasing amounts of *Halimeda* towards the top of the succession account for the *Halimeda*-mollusc facies dominating the upper half of the Pedro Castle Formation.

Beside spatial variations of facies, there are important variations the distribution of specific skeletal components. Robust bivalves and gastropods tend to be found in the lower and middle parts of the formation. Pelagic foraminifera species are most common in the upper 10 m of the succession, and are represented primarily by Globorotalids. *Archaias* and miliolinid foraminifera are most common in the lower parts of the section, although they are never as prevalent as *Amphistegina*.

DISCUSSION

Water Depths and Energies

The presence of photophyllic biota such as *Halimeda*, *Stylophora*, and *Porites* indicate the sea floor lay within the photic zone. The general scarcity of framework corals does not allow for a precise estimation of depth, but may indicate deeper water conditions than during the Miocene (>10 m). This is based on comparison with similar *Halimeda* and foraminifera-dominated sediment accumulations that are associated with sparse reef development on deep (10-40 m bsl) modern banks in the Caribbean (e.g., Goldberg, 1983; Triffleman *et al.*, 1992; Hine *et al.*, 1994).

Lower water energies than those that affected the sediments Cayman Formation are indicated by the muddier textures of the Pedro Castle Formation. Whereas the Cayman Formation sediments are dominated by coarse grain-sizes in packstones to grainstones, the Pedro Castle Formation is characterized by finer grained wackestones to packstones. Faunal evidence does not provide direct proof of lower energy levels, but the presence of *Archaias* may indicate a more sheltered environment (Seglie, 1970; Wright and Hay, 1971). This need not, however, be taken as proof that water depths were deeper than storm wave base. The morphology of the underlying Cayman Unconformity may have served as a cup-shaped sediment trap and energy baffle, allowing accumulation of fine sediment that might otherwise have been carried away by storms and ocean currents. This relationship is found on modern banks of the Caribbean, where fine sediments accumulate in shallow surficial depressions despite strong cross-bank currents (e.g., Hine and Steinmetz, 1984; Glaser and Droxler, 1991). The fact that the strata of the Pedro Castle Formation fine up, however, indicates that water depths and resultant energies controlled sedimentation to a greater degree than the unconformity surface. If the morphology of the buildup were the dominant control, a coarsening-upward trend would be expected as sediment filled the central depression and the Safe Haven area became less sheltered (Fig. 16).

Although Pliocene water energies appear to have been lower in the Safe Haven area than during the Miocene, there was still sufficient energy to mobilize the rhodolith gravels and foraminifera-mollusc pack to grainstones at the bottom of the section. This may be a result of high energies associated with the initial transgression at the end of the Miocene. Upsection, finer grain sizes and muddier wackestone textures atest to a general

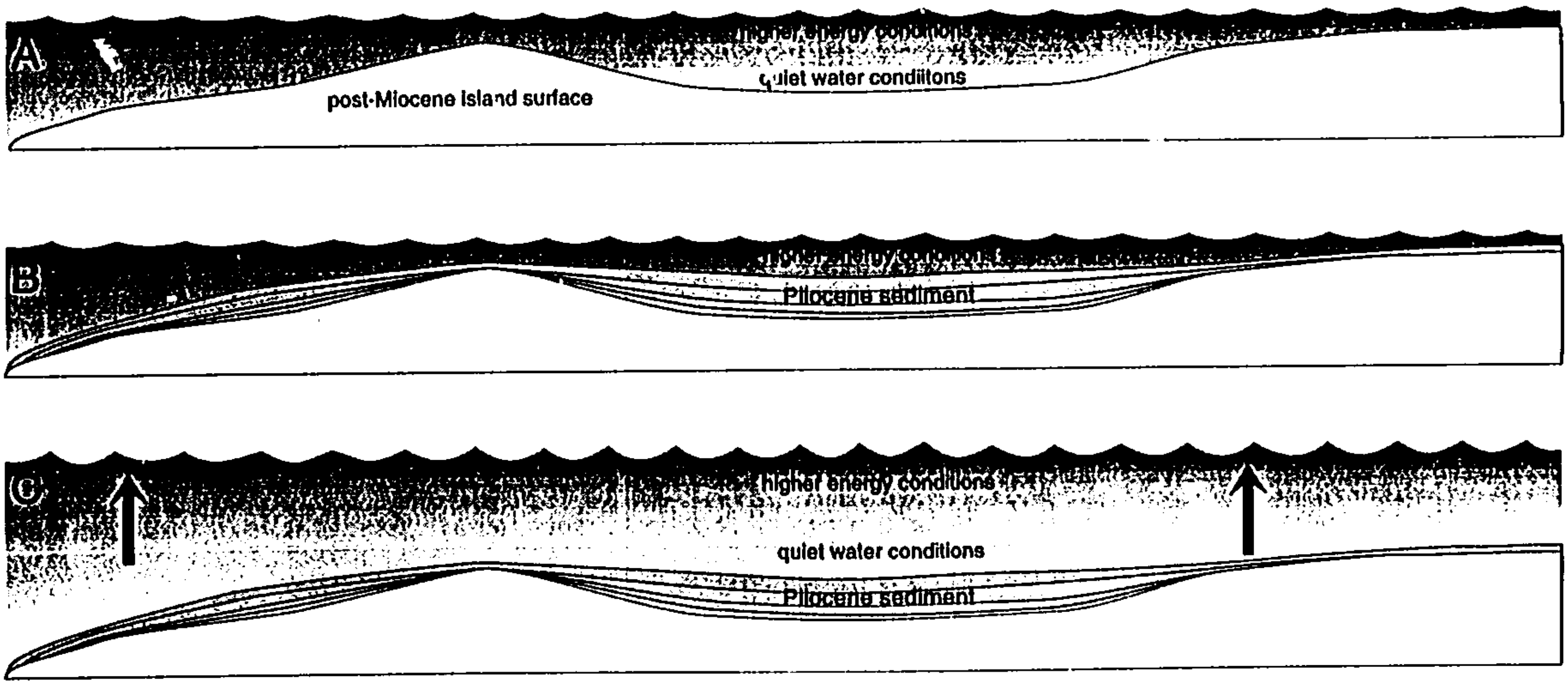

Fig. 16. The effects of antecedent topography versus sea level change. A) Initial transgression of sea level would have allowed preferential sheltering of the lagoon in North Sound depression. B) accumulating sediment would have begun to fill the depression, bringing the depositional setting up into the higher energy part of water column unless C) sea level continued to rise.

decrease in energy with time, most probably due to increasing water depths. Therefore, the water energies recorded in the Pedro Castle Formation show temporal, if not spatial, variations.

It would appear then, that the Pedro Castle Formation records a gradual increase in water depth. This is also supported by the presence of pelagic foraminifera in the top 10 m of the formation. Pelagic foraminifera are typically found only in deep, open water sediments (Cushman *et al.*, 1954). Their presence in the upper part of the Pedro Castle Formation indicates the Safe Haven area was completely submerged, and that the morphology of the Cayman Unconformity did not restrict open ocean currents in the later stages of deposition of the formation.

Eustatic Sea Level Change

The maximum water depth under which sediments of the Pedro Castle Formation accumulated is open to debate, partly due to a lack of diagnostic fossil indicators, and partly because no absolute sea level curves have been developed for the early Pliocene. Curves derived for the U.S. middle Atlantic coastal plain (Krantz, 1991) and Enewetak Atoll (Wardlaw and Quinn, 1991) give a minimum sea level of 20 m bsl, and a maximum of 50 m asl in the early Pliocene. These values, based on unproven subsidence and uplift rates, are useful only for bracketing sea level positions for the period 4.8-3.3 Ma. More concrete evidence is available on Grand Cayman, where the Pedro Castle Formation outcrops at Pedro Castle Quarry. At that location the formation is found at an elevation of approximately 15 m asl (Jones, pers. comm.). The Pedro Castle Quarry section may represent a part of the Pedro Castle Formation that is not preserved at Safe Haven, but it does serve to give the minimum sea level highstand attained in the early Pliocene on Grand Cayman. Additionally, an unknown amount of rock was removed from the top of the Pedro Castle Quarry section, and sea level was undoubtably much higher, perhaps as much as 10-15 m. This sea level would completely inundate the current island surface of the western peninsula, and would account for the sediment fining and pelagic foraminifera recorded from 5-15 m bsl in the Pedro Castle Formation at Safe Haven. In general, the Pedro Castle Formation appears to have been deposited in greater water depths than the Cayman Formation.

Restriction and Circulation

During the initial stages of deposition of the Pedro Castle Formation, the peripheral ridge developed on the Cayman Formation probably impeded water circulation. If sea level rose slowly, or "stepwise" as discussed previously, there would have been a period when the Safe Haven area experienced restricted conditions. If sea level rose rapidly, however, it is unlikely that restricted conditions persisted for any length of time before the Safe Haven area and the peripheral ridge on the western peninsula were completely inundated, allowing ocean currents to circulate across the Safe Haven area.

Foraminiferal evidence indicates that the Safe Haven area experienced initial restriction that decreased over time. Although *Amphistegina* is the dominant foraminifera found in the Pedro Castle Formation, *Archaias* and miliolinid foraminifera are also common in the lower parts of the formation. *Archaias* and miliolinid foraminifera are typically found in sheltered lagoonal or bank settings (e.g., Cushman *et al.*, 1954; Wright and Hay, 1971; Martin and Wright, 1988), and are considered indicative of more restricted settings than those dominated by *Amphistegina*. The presence of different species of foraminifera in the Pedro Castle Formation may be a result of allochem transport, whereby foraminifera from a more restricted setting were carried into a less restricted area, or vice versa. Alternatively, *Amphistegina* does well in colonizing bare unconformity surfaces (Poag and Tresslar, 1981) and the dominance of *Amphistegina* in the lower part of the Pedro Castle Formation may be related to the initial transgression, rather than any other factor. Significant numbers of living *Amphistegina* have been found in sheltered settings on modern banks and lagoons normally dominated by *Archaias* and miliolinid foraminifera (e.g., Poag and Tresslar, 1981; Martin and Wright, 1988). Still, some tentative conclusions may be drawn. The peripheral ridge must have restricted water circulation to some extent, and this is probably reflected by the presence of *Archaias* and the miliolinid foraminifera in the lower parts of the Pedro Castle Formation. Increasing water depths, possibly in conjunction with the gaps in the peripheral ridge at Pedro Gap and the north side of the depression, would have lessened restriction after the initial colonization of the unconformity surface. This may account for the lower numbers of *Archaias* and miliolinid foraminifera in the upper part of the Pedro Castle Formation at Safe Haven.

Influence of the Cayman Unconformity on Sedimentation

The Cayman Unconformity influenced the Early Pliocene depositional environment in the Safe Haven area. In addition to the restriction of water circulation already discussed, the topography of the unconformity must have served as an energy baffle and sediment trap in the initial stages of deposition of the Pedro Castle Formation. This control is reflected in the facies "grain" of the Pedro Castle Formation. Whereas the facies of the Cayman Formation are more or less flat lying (Figs. 4, 5), the facies of the Pedro Castle Formation appear to drape the unconformity surface, and dip to the east (Figs. 12-14). This is most evident in the lower parts of the Pedro Castle Formation, and becomes less so upsection. This is probably due to the western depression filling with sediment, so that the Cayman Unconformity topography exerted less control on the Safe Haven environment. The initial stages of deposition recorded in the lower facies of the Pedro Castle Formation should therefore show the most evidence of this control.

The Cayman Unconformity is typically overlain by the rhodolith-foraminifera-*Halimedu* facies. The thickest accumulations of this facies are in the topographic lows in the eastern end of the Safe Haven area. The thinnest accumulations are found over the unconformity highs, and in the westernmost wells. This is to be expected, and reflects the tendency of sediments on the peripheral ridge to be swept down into more sheltered topographic lows by wave and current energies. Conversely, in the lower parts of the Pedro Castle Formation, the solitary coral-dominated facies tend to be found only over the unconformity highs to the east. This is probably due to the tendency of sediments to be shed from topographically higher areas.

A decrease in the control exerted by the Cayman Unconformity surface on later stages of deposition of the Pedro Castle Formation may be reflected by the fact that the solitary coral and *Stylophora* facies are most common in the eastern half of the Safe Haven area. This shows a general shift in colonization by corals to the east, towards the center of the bank. As sea level gradually rose and the western depression filled with sediment, Grand Cayman would have begun to more closely resemble a modern drowned bank, with unconsolidated sediment accumulating on the leeward parts of the bank before being swept off the margins by cross-bank currents (e.g., Triffleman *et al.*, 1992). The shift of coral colonization toward the center of the bank may have been in response to accumulating sediment burying corals and inhibiting their growth (e.g., Goldberg, 1983). Alternatively, the shift of the coral facies of the Pedro Castle Formation to the central parts of the buildup may have been in response to increasing water depth, with a subsequent decrease in water energy and light, and possibly nutrient input. Certainly, there does not appear to be any way in which the morphology of the Cayman Unconformity would have caused this shift.

Antecedent Topography versus Sea Level

How long the peripheral rim and high-lying areas of the Cayman Unconformity remained exposed as sea level rose is open to conjecture. If the unconformity highs discussed in chapter three are wave cut notches, and hence paleo-shoreface positions, then there was almost certainly a period when there was exposed land around the submerged Safe Haven area. The presence of the Pedro Castle Formation at Pedro Castle, however, indicates that most, if not all, of Grand Cayman was covered by water at the height of the transgression. Although the topography of the Cayman Unconformity influenced the early stages of deposition of the Pedro Castle Formation, the complete inundation of the western peninsula ensured that sea level, rather than antecedent topography, dominated the later stages of deposition.

CHAPTER 5 : THE PEDRO CASTLE UNCONFORMITY

The Pedro Castle Unconformity separates the Pedro Castle and Ironshore formations in the Safe Haven subsurface. The true Pedro Castle Unconformity is present only where it is overlain by the Pleistocene strata of the Ironshore Formation. The surface found on top of exposed Pedro Castle Formation strata has been altered by late Pleistocene and Holocene subaerial and marine processes and is not the true Pedro Castle Unconformity.

KARST SURFACE MORPHOLOGY

Unlike the Cayman Unconformity, the Pedro Castle Unconformity is topographically subdued, at an average depth of 5.5 m (+-1.5 m) bsl throughout the Safe Haven area (Fig. 10). The 3 m amplitude of the surface may be an exaggeration. The Ironshore Formation was rarely recovered during drilling, and the top of the Pedro Castle Formation is typically friable and cavity-ridden. As a result, the top of the formation was usually picked based on drilling characteristics, rather than core evidence. The presence of cemented zones separated by cavities made this difficult because drilling characteristics varied so much. As a result, the picks are only accurate to within 1 m, and are probably deeper than the actual position of the unconformity surface.

TEXTURES ASSOCIATED WITH THE PEDRO CASTLE UNCONFORMITY

The rocks beneath the unconformity surface are extensively calcretized, with most cores containing calcrete in the upper 3-4 m of the Pedro Castle Formation. Core from well SH#2 records extensively developed calcrete textures to 18 m bsl. In core, the calcrete is typically green to grey in colour, and friable or well-indurated depending on the degree of cementation. Concentrically-laminated pisoids, 0.1-2 mm in diameter, are common, as are plant root tubules (rhizoliths). Flowstones and other speleothem deposits are locally common, as are dissolution cavities and caves.

The Pedro Castle Unconformity does not have an associated case-hardened layer and there is no clear evidence of modification of the surface by marine processes. Borings, algal encrustation or other signs of colonization of the Pedro Castle strata are not evident in core.

TIMING OF THE DEVELOPMENT OF THE PEDRO CASTLE UNCONFORMITY

The Pedro Castle Formation was deposited after sea level rose following the Messinian sea level lowstand. Although sea levels rose and fell throughout the early Pliocene (Krantz, 1991; Wardlaw and Quinn, 1991), the first major long-term highstand did not take place until the Middle Pliocene, 3.5-2.5 Ma (Dowsett and Cronin, 1990). This highstand has been estimated at 35 m (+-18 m) asl, and lasted a minimum of 0.5 Ma (Dowsett and Cronin, 1990). Thus, the Pedro Castle Formation may have been deposited intermittently during a series of sea level transgressions and regressions lasting from 4.8-2.5 Ma. Cooling associated with a major glacial period commenced at 2.5 Ma, and sea levels fell to at least 25 m bsl (Krantz, 1991; Cronin *et al.*, 1994). Thereafter, sea levels fluctuated between 10 m asl and 50 m bsl with a cyclicity of 41 ka (Haq *et al.*, 1987; Krantz, 1991) until the major sea level rise 120 000 - 130 000 years ago that resulted in deposition of the Ironshore Formation (Jones and Hunter, 1991).

Based on this information, the Pedro Unconformity probably developed in the late Middle Pliocene, and was subject to intermittent subaerial and submarine conditions from 2.4 Ma to 130 000 years ago. The deposition of the Ironshore Formation effectively halted all surface karst or soil development atop the Pedro Castle Formation, and preserved the unconformity surface except in areas where subsequent erosion removed the Pleistocene overburden.

DISCUSSION

The presence of Pedro Castle Formation strata 15 m asl at Pedro Castle suggests that the formation once covered much of Grand Cayman. Today, the Pedro Castle Formation is found only in low lying areas on the western half of Grand Cayman, at Pedro Castle, and in sink holes on the eastern half of the island. Weathering of the Pedro Castle Formation must therefore have removed large volumes of rock, even prior to the deposition of the Ironshore Formation. That the Pedro Castle Formation does not display the same well-developed topography as the Cayman Unconformity may be due to the short duration of the sea level low stands at the end of the Pliocene. The Cayman unconformity developed over a period of 1.5 Ma, during which time sea level reached a minimum base level of 41 m bsl (Jones and Hunter, 1994a). Sea levels in the late Pliocene and early Pleistocene fluctuated extensively over relatively short periods (< 50 ka), and thus did not allow the same uninterrupted development of sub-aerial karst. Instead, marine and subaerial regimes of short duration resulted in a low-amplitude exposure surface with multiple generations of soil development and marine colonization. Any textures that developed during a sea level stand were overprinted by successive regimes.

The final exposure of the Pedro Castle Formation resulted in calcretization that obscured most of the antecedent textures in the upper 4 m of strata. The rapid sea level rise to 6 m asl 130 000 years ago did not result in shore face erosion of the flat unconformity surface, and the surface was preserved in the Safe Haven area.

CHAPTER 6 PETROGRAPHY AND PARAGENESIS OF THE CAYMAN AND PEDRO CASTLE FORMATIONS

The diagenesis of the Tertiary strata on Grand Cayman has been extensively studied (Jones *et al.*, 1984, Pleydell, 1987; Squair, 1988; Ng, 1990; Pleydell *et al.*, 1990; Ng *et al.*, 1992). Due to the subdued topography of Grand Cayman, those studies focused on surficial diagenetic features, stratigraphically limited outcrop sections, and chip samples from predominantly shallow wells. This is the first study to take advantage of the extensive subsurface data made available by the drilling program at Safe Haven. As a result, a more complete picture of the vertical and lateral architecture of the diagenetic fabrics of the Cayman and Pedro Castle formations is possible.

CAYMAN FORMATION

Matrix

The matrix of the Cayman Formation is composed predominantly of two types of dolomite. Type I, the most common dolomite, is formed of finely microcrystalline (< 10 μm) equant to bladed, cloudy, subhedral crystals. Type II dolomite is formed of slightly coarser microcrystalline (15-40 μm), euhedral crystals that are clear, or zoned, with cloudy cores. These dolomites correspond to the two types of matrix dolomite recognized by Ng (1990).

The cloudy nature of the type I dolomite crystals may be due to inclusions of calcite precursors (Ng, 1990). Dolostone formed of type I dolomite are fabric-retentive, to the extent of preserving skeletal microstructures such as mollusc shell chevron lamellae.

Both matrix and skeletal grains are composed of type I dolomite (Fig. 17a).

Type II dolomite is more variable than type I dolomite, and exhibits a number of distinct characteristics. Crystals that are zoned typically have a cloudy core surrounded by two to three bands of alternating luminescent and non-luminescent, clear dolomite. Unzoned crystals (Fig. 17b) do not display any inclusions, but are identical in terms of size and general morphology. Additionally, zoned and unzoned crystals are closely associated with each other. Where leached, the cores of type II dolomite crystals may be filled by calcite cement, and the whole crystal can be encased in larger, xenotopic calcite crystals. These textures correspond with the poikilotopic calcite-dolomite fabrics described by Pleydell (1987), Jones *et al.* (1989), and Ng (1990). Type II dolomite, unlike type I dolomite, forms fabric-destructive dolostones. Allochems and related sedimentary fabrics are commonly obliterated in these dolostones. Relict textures delineated by traces of the cloudy type I dolomite are evident in some samples.

The two types of matrix dolomite are closely associated, with millimeter-scale patches of type II dolomite surrounded by type I dolomite. Similarly, dolostones dominated by type II dolomite display fabric-retentive zones of type I dolomite. The two dolomites are not, however, the result of the same dolomitizing event. This is indicated by 1) differences in crystal morphology, 2) differing degrees of fabric-retention, and 3) palimpsest remnants of type I dolomite enclosed in type II dolomite. A minimum of two dolomitizing events is suggested. Furthermore, the evidence points to type II dolomites forming after, and recrystallizing, type I dolomites.

Fig. 17. SEM photographs of samples from the Cayman and Pedro Castle formations

a) type I dolomite maintaining internal structure of mollusc shell in the Cayman Formation (SH#12 61' 0")

b) type II dolomite rhombs in the Cayman Formation (SH#12 73' 10")

c) micritic matrix recrystallized to form calcite rhombs in the Pedro Castle Formation (SH#12 34' 0")

d) type A dolomite in the Pedro Castle Formation (SH#3 76' 0")

e) pore-lining dolomite cement in the Pedro Castle Formation (SH#3 76' 0")

f) poikilotopic calcite crystal (Pc) surrounding leached dolomite rhombs (D) in the Pedro Castle Formation (SH#3 76' 0")

Porosity

Porosity in the Cayman Formation is 0-30 %. The porosity may be effective or ineffective, depending on the types of primary porosity and the degree of dissolution and cementation. Additionally, porosity distribution on a local scale appears to be random with few discernible patterns.

Intercrystalline porosity is poorly developed in the dolostones of the Cayman Formation. This is due primarily to the polycrystalline grain sizes of matrix dolomites. Additionally, poikilotopic calcite and dolomite cements have overgrown the dolomite rhombs, and locally occlude any intercrystalline porosity.

Recrystallization and cementation of the dolostone obliterated most of the primary intergranular porosity. A notable exception is in the grainstones of the *Porites* reef facies, which maintain their primary intergranular porosity. Preferential leaching of the matrix dolomite also produced well developed, interconnected, secondary porosity, although this is on a local scale.

Small-scale fracture systems are evident in the core, but are not important either as voids or porosity connectors as they are filled by dolomite and calcite cements.

Most porosity in the Cayman Formation was formed by leaching of skeletal grains and large scale dissolution of the bed rock. Porosity formed in this manner ranges from caves and decimeter-scale voids left by branching and hemispherical corals, to the micrometer-scale voids found in partially dissolved *Amphistegina* and coralline red algae. These voids may be well interconnected or isolated from surrounding void spaces. In many cases, connection between pores is due to poorly developed intercrystalline porosity. As a result, although porosity is commonly as high as 30%, the effective porosity is variable, and unpredictable. This does not mean, however, that the overall effective porosity in the Cayman Formation is low. Although they are not usually evident in core, large scale fracture and joint systems are well developed throughout the formation (Jones, 1992b; Ng *et al.*, 1992). These solution enlarged fractures and joints allow free circulation of fluids, to the extent that it is possible to measure tidal fluctuations in bore holes, and surface ponding is rare as rain water quickly filters into the highly permeable Tertiary strata.

Dissolution

Dissolution of the dolostones in the Cayman Formation is pervasive but fabric selective. Skeletal grains originally formed of aragonite, such as molluscs, *Stylophora*, and solitary and massive colonial corals, are preferentially leached (Fig. 18a). Conversely, allochems originally composed of high and low magnesium calcite, such as coralline red algae and foraminifera, display the best preservation of skeletal fabrics, and the least dissolution. The fact that preservation of skeletal fabric is related to antecedent mineralogies indicates that allochem-specific dissolution took place prior to, or during, dolomitization. Additionally, many of these skeletal voids are partially filled by caymanite that was emplaced prior to dolomitization (Jones, 1992a).

There was further dissolution following dolomitization. This dissolution resulted in voids lined by coarse, late generation, unzoned dolomite crystals, whereas most dissolution voids clearly predating dolomitization are lined by microcrystalline isopachous cements. Many of these post-dolomitization voids are associated with

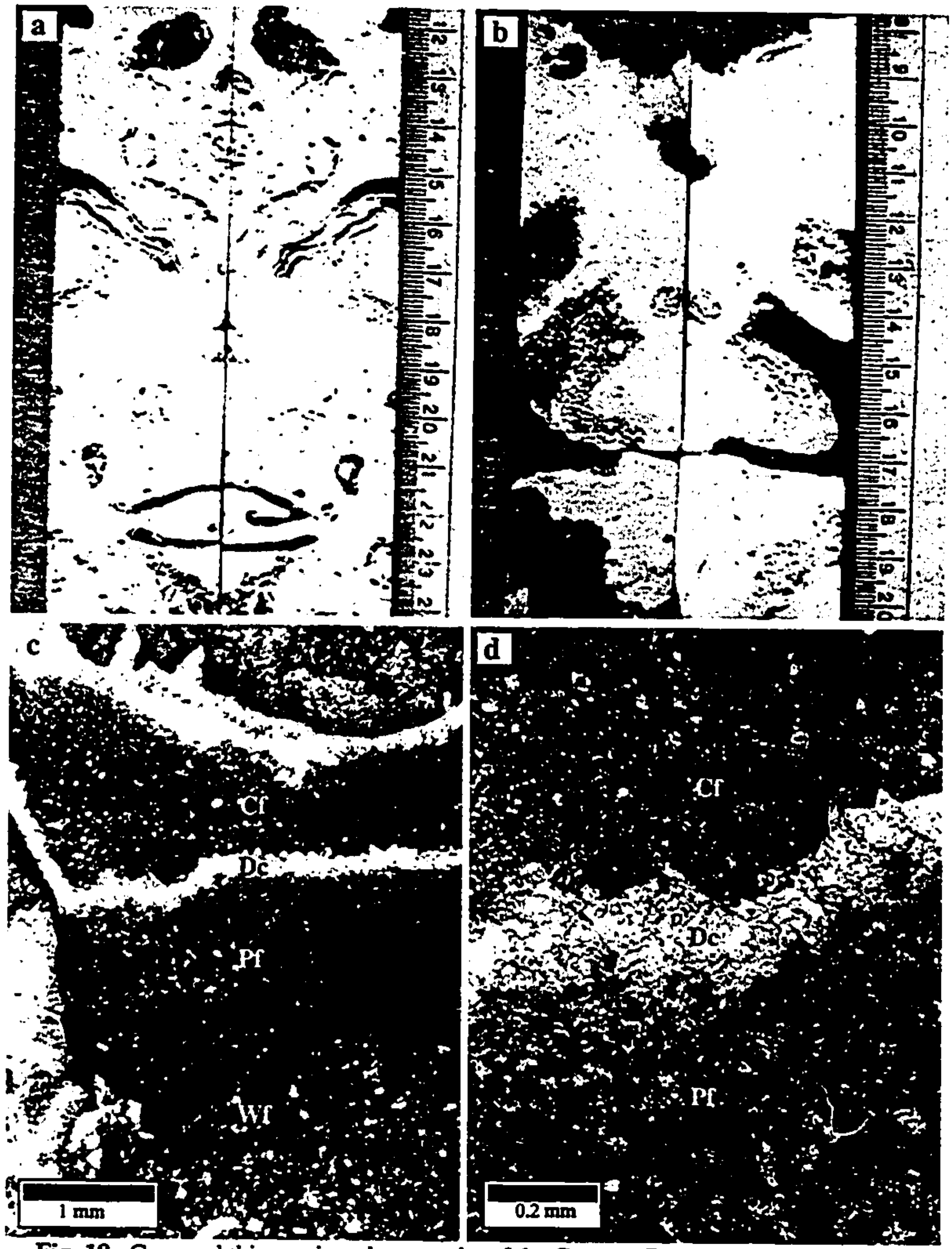

Fig. 18. Core and thin section photographs of the Cayman Formation

a) preferential leaching of molluscs and corals in Cayman Formation (SH#8A, 29.3 m)

b) calcitization reaction rims around *Stylophora* molds (SH#13, 21.1 m)

c) wackestone (Wf), peloidal (Pf), and Caymanite (Cf) cavity-filling sediments in the Cayman Formation, separated by 2nd generation dolomite cement (Dc) (SH#3 119'4")

d) close-up of photo c).

calcitization textures. Reaction rims are developed around permeability pathways such as *Porites* fragments, *Stylophora* molds and partially dissolved massive corals (Fig. 18b). These reaction rims display dissolution of matrix and skeletal fabrics, and calcite cementation. This is also true of most fractures filled by calcite cement.

Cements in the Cayman Formation

Dolostones in the Cayman Formation contain at least four generations of cement. Three of these are dolomite, and one is calcite.

The first generation dolomite cement is formed of cloudy, pore-lining, subhedral to euhedral crystals 10-40 μm long. This cement lines the walls of skeletal cavities, and predates any cavity-filling sediments (Fig. 19a).

The second generation of dolomite cement is texturally similar to the first generation cement. This cement overlies skeletal wackestone cavity-fill sediments, but predates any caymanite mudstones (Figs. 18c,d, 19a). In most cases this cement is not associated with dissolution features, and lines only intraskeletal and shelter porosity voids that were part of the primary porosity. This dolomite cement is commonly rooted on type 1 matrix dolomites. A cement of similar morphology also lines the walls of mollusc molds (i.e., is post-dissolutional), but its relationship to the two early generations of isopachous cement is unclear.

These cements correspond to first generation dolomite cements described by Jones *et al.* (1984) from samples of exposed Cayman Formation. These two generations of cement are also similar to cements described by Ng (1990), although in this case the sediment separating the cements appears to be a skeletal wackestone, rather than

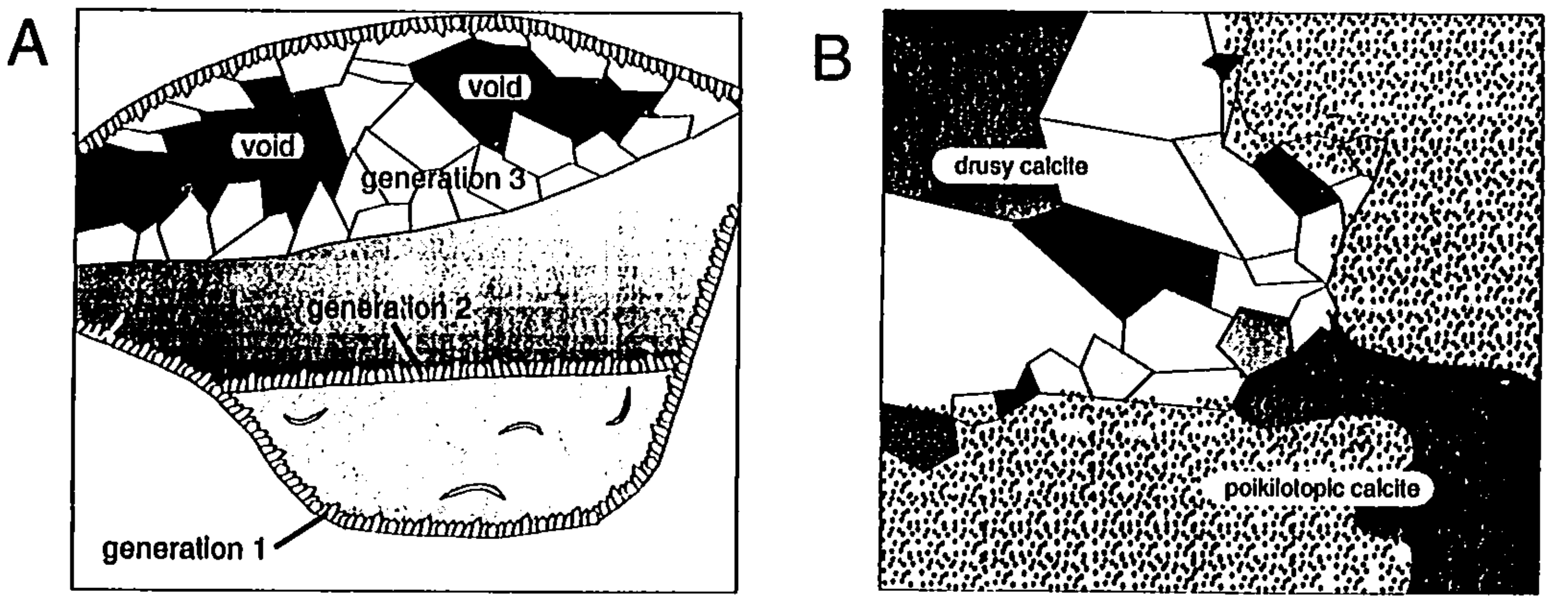

Fig. 19 Cement textures of the Cayman and Pedro Castle Formations.
A) Three generations of pore-lining cement in the Cayman Formation. Generation 1 and 2 are isopachous microcrystalline dolomite separated by skeletal wackestone. Generation 3 is a coarsely microcrystalline, equant euhedral, clear pore-lining dolomite. B) Poikilotopic calcite and drusy calcite textures common to both formations. In the Cayman Formation the incorporated matrix is composed of microcrystalline dolomite, in the Pedro Castle Formation it is matrix calcite.

caymanite mudstone.

The third generation of dolomite cement is a coarser microcrystalline (20-100 μm), euhedral, limpid dolomite. This cement is zoned, or clear and unzoned, possibly indicating it represents more than one phase of cementation. This dolomite is commonly associated with dissolution voids, and is rooted on type I and type II matrix dolomite (Fig. 20a). In rare cases this cement is rooted on cavity-filling sediments. This cement lines pores but rarely occludes them (Fig. 19A).

The fourth generation cement is a meso- to macrocrystalline, clear to cloudy calcite. The calcite cement has a variety of textures and morphologies that may represent multiple generations of cementation. As with Jones *et al.* (1984), these cements are treated as one generation because it is not possible, based on textural relationships, to distinguish different periods of precipitation.

The most common calcite cement is a macrocrystalline, equant, void-filling, euhedral to subhedral, clear to cloudy calcite with distinct triple enfacial junctions (Figs. 19B, 20b). Although this cement may incorporate relict dolomite rhombs or matrix material, it is rarely associated with dissolution or poikilotopic calcite-dolomite textures. This calcite cement is typically rooted on the matrix dolomites, or fills voids lined by the first or second generation dolomite cements. Locally, this cement also fills large voids that are ringed by calcitization reaction rims.

In many samples an anhedral to subhedral, non-equant cloudy calcite cement encloses remnants of the dolomite matrix and skeletal grains to form a poikilotopic fabric (Fig. 19B, 20b). For the most part, the dolomite embedded in these calcite crystals is type 2 matrix dolomite, and preservation of allochems and sedimentary fabrics in the

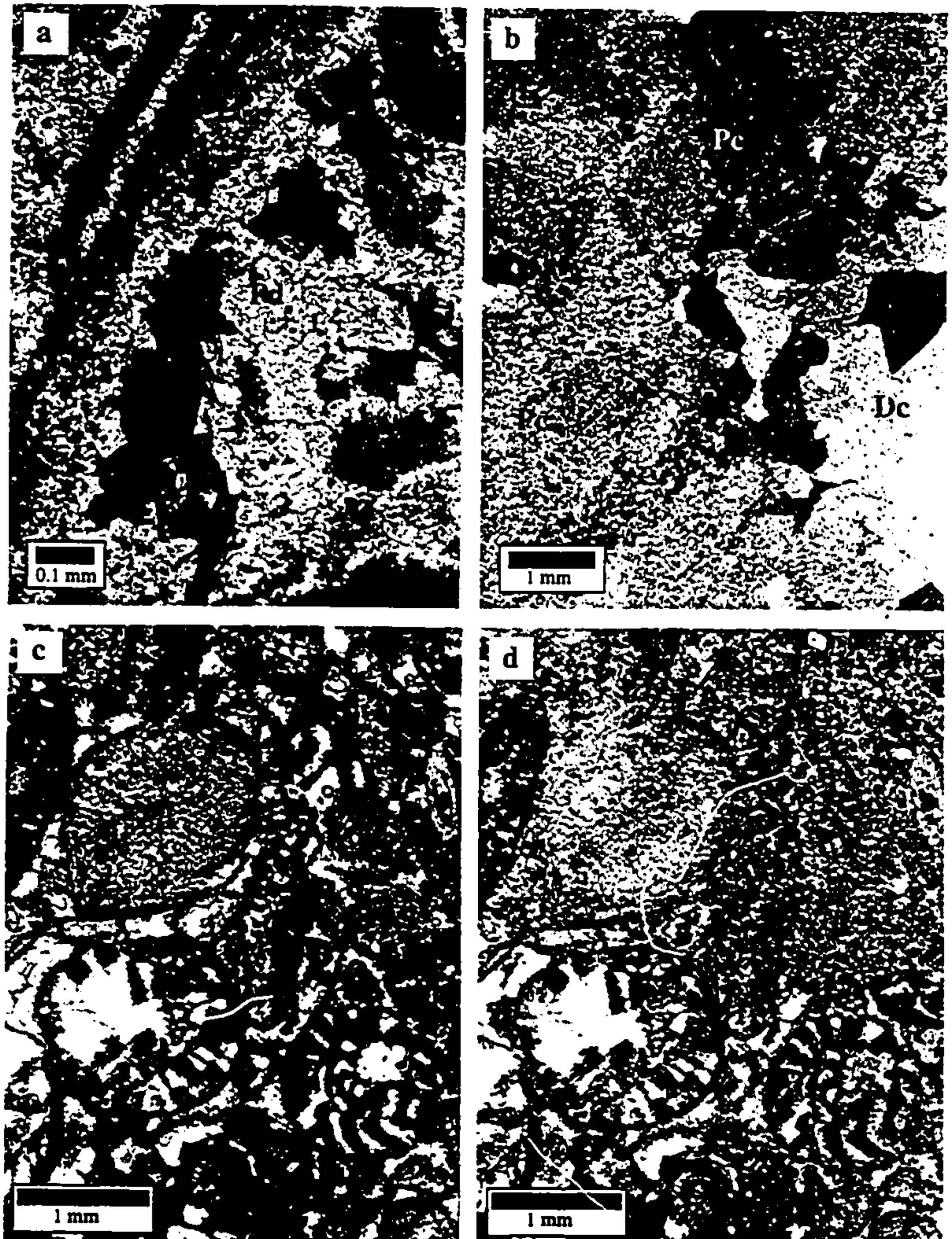

Fig. 20. Thin section photographs of the Cayman and Pedro Castle formations

a) pore-lining dolomite cement (Pd) in Cayman Formation (SH#12 90' 8")

b) poikilotopic (Pc) and drusy (Dc) calcite cements in the Cayman Formation (SH#3 117'11")

c) upper half of slide is mimic (type A) dolomite, lower part is calcite (uncrossed polars) (SH#8 56' 0")

d) same as c), crossed polars

calcitized dolostone is negligible. This poikilotopic calcite cement is closely associated with the equant, void-filling calcite, but is distinct due to the incorporation of large amounts of matrix dolomite, and its non-equant, non-euhedral grain shapes.

Microcrystalline (50-100 µm) euhedral calcite lines pores, and is associated with calcitization textures and permeability pathways. This calcite may be an arrested stage of the coarse, void-filling equant calcite cement. Conversely, the coarse equant calcite cement may be an overgrowth on early pore-lining calcite cements, and the two are distinct generations of cement.

Cavity-filling Sediments

Three types of sediments are found in cavities in the Cayman Formation. The earliest sediments are dominated by skeletal wackestones. Skeletal material in the wackestones include *Amphistegina*, mollusc fragments, and echinoderm spines. This sediment, which is found only in primary voids, is predated by the 1st generation dolomite cement and postdated by the 2nd generation dolomite cement (Fig. 19A). It appears, therefore, that this sediment was emplaced very early in the history of the rock, and is marine in origin.

Peloidal mudstones are found in some cavities, commonly in conjunction with the marine wackestone fill. The peloids are very small (< 0.1 mm) and have very diffuse boundaries (Fig. 17d). The peloidal cavity-fill is contemporaneous with or just post-dates the skeletal wackestones. Pleydell (1987) interpreted these peloidal mudstones as altered marine peloidal cements.

The third type of sediment filling cavities in the Cayman Formation is caymanite.

This multicoloured, laminated, dolomitized mudstone fills primary and secondary voids. The caymanite is composed of microcrystalline dolomite, and is fabric-retentive. It incorporates little skeletal material, and no peloids. This is in contrast with the caymanite described by Jones (1992a, b) which ranges from mudstones to skeletal grainstones. This may reflect the fact that most samples of caymanite described by Jones (1992a, b) came from near-surface settings, whereas the caymanite in the Safe Haven subsurface is found as deep as 20 m below the Cayman Unconformity. Coarse skeletal grainstones are not likely to have penetrated as far into the rock as fine sediment carried in suspension.

Sediments in caymanite may be of marine origin, or may be weathering products of limestones exposed to subaerial conditions (Jones, 1992a). The first two generations of cavity-filling sediment in the Safe Haven subsurface are clearly marine in origin, whereas the caymanite is more ambiguous, and may represent a non-marine weathering product. Whatever the case, the two earlier phases of cavity-filling sediments are separated from the caymanite by the second generation dolomite cement (Figs. 18c, 19A). This is contrary to Ng (1990), who found that the fine mudstone of the caymanite underlay, and thus predated, marine sediment cavity fills.

PEDRO CASTLE FORMATION

Matrix

The micritic matrix of the Pedro Castle Formation limestone has been recrystallized to form euhedral to subhedral, equant microcrystalline (10-15 µm) calcite crystals (Fig. 17c). Despite recrystallization, limestone composed of this calcite is well indurated and preserves original fabrics. Dissolution and replacement by coarse late-generation calcite and dolomite is indicated by partially dissolved microcrystalline calcite incorporated in the coarser calcite and dolomite crystals, and fabric destruction. In general, these zones are leached and friable, with very poor drilling recoveries. Fossil grains or matrix that remain are so altered as to be nearly indistinguishable in hand sample or thin section.

Dolomitization

The Pedro Castle Formation has been only partially dolomitized. Although dolomitization is locally pervasive, most of the Pedro Castle Formation is composed of limestone and dolomitic limestone. Diagenetic textures vary considerably, and the types of dolomite present are different from those found in the Cayman Formation.

Extensively dolomitized zones in the Pedro Castle Formation tend to be friable and fabric destructive. The fabric destruction does not appear to be a direct result of dolomitization; instead it is commonly due to later leaching and alteration of the dolo-limestones. For example, Pedro Castle Formation strata immediately overlying the Cayman Unconformity are, in some sections of core, a well indurated, 100 % dolomitized rock that is difficult to differentiate from the underlying Cayman Formation. In these cases, the division between the two formations rests solely on recognition of the unconformity.

The dolomite replacing the original limestone takes two forms. Type A is a finely microcrystalline (< 5 μm), subhedral to anhedral, etched dolomite (Fig. 17d). This dolomite is the most pervasive and fabric-retentive of the Pedro Castle Formation dolomites (Fig. 20c,d). Fabric-retentive dolostones overlying the Cayman Unconformity are composed primarily of this fine-grained dolomite.

Type B dolomite has euhedral, equant zoned crystals 10-30 μm long. This dolomite is morphologically similar to the type II matrix dolomite in the Cayman Formation, and exhibits leached cores with poikilotopic calcite-dolomite textures. This dolomite does not form fabric-retentive dolostones. In most cases, however, this dolomite is embedded in the fine-grained dolomite, or "floats" in a calcite overgrowth, and does not form large volumes of rock on its own .

In general, dolomitization of the Pedro Castle Formation is unlike that of the Cayman Formation. The type A dolomite that forms fabric-retentive dolostone in the Pedro Castle Formation does not correspond to the type I dolomite of the Cayman Formation. Type B dolomite does not form matrix in the Pedro Castle Formation, whereas its morphological equivalent in the Cayman Formation, type II, is primarily a matrix dolomite. Finally, dolomitization of the Pedro Castle Formation has not resulted in fabric destruction.

Porosity and Dissolution

Porosity in the Pedro Castle is 0-30 %, with an average of 10-15 %. As in the Cayman Formation, porosity is variable, and primarily due to secondary development of voids through leaching of skeletal material. In general, however, porosity is higher in the Pedro Castle Formation than in the Cayman Formation.

Intercrystalline porosity in the Pedro Castle Formation is poorly developed and preserved due to recrystallization of the matrix and late stage cementation. Primary intergranular porosity is common in the Pedro Castle Formation, although it has been altered by cementation and dissolution. Preferential leaching of skeletal grains forms most of the porosity, accounting for nearly 100 % of porosity in the more porous zones.

This leaching is pervasive and fabric destructive. Locally, calcite cementation isolated the matrix and skeletal fabrics from fluid passage, and this appears to have prevented dissolution of the rock by unsaturated fluids. Fabric retention in these zones is very high relative to more porous areas.

The processes of dissolution and cementation appear to successively overprint each other, and the Pedro Castle Formation is characterized by friable, leached strata that are interlayered with hard, well-cemented strata. With the exception of a leached zone at ~ 20 m bsl, and a zone of flowstone development at ~ 10 m bsl, these zones of dissolution and cementation are not consistent in stratigraphic position, and cannot be predicted. For example, wells SH#8 and SH#8A were drilled 5 m apart, but record radically different core recovery and textural preservation. Large cavities and tightly cemented zones common in SH#8 are for the most part absent in SH#8A.

Cements

Unlike the Cayman Formation, the Pedro Castle Formation contains only one phase of dolomite cement and several types of calcite cement.

The dolomite cement is pore-lining and microcrystalline (20-40 μm), and is morphologically similar to the type II matrix dolomites of the Cayman Formation (Fig. 17e). This dolomite cement exhibits zoning and poikilotopic calcite-dolomite textures, and may be genetically related to the Cayman Formation matrix dolomite (Fig. 17f).

Calcite cements in the Pedro Castle Formation show a wide variety of morphologies, ranging from spectacular euhedral, bladed, centimeter-scale crystals associated with calcretes, to finely microcrystalline, subhedral crystals that line voids (Fig. 21A, B).

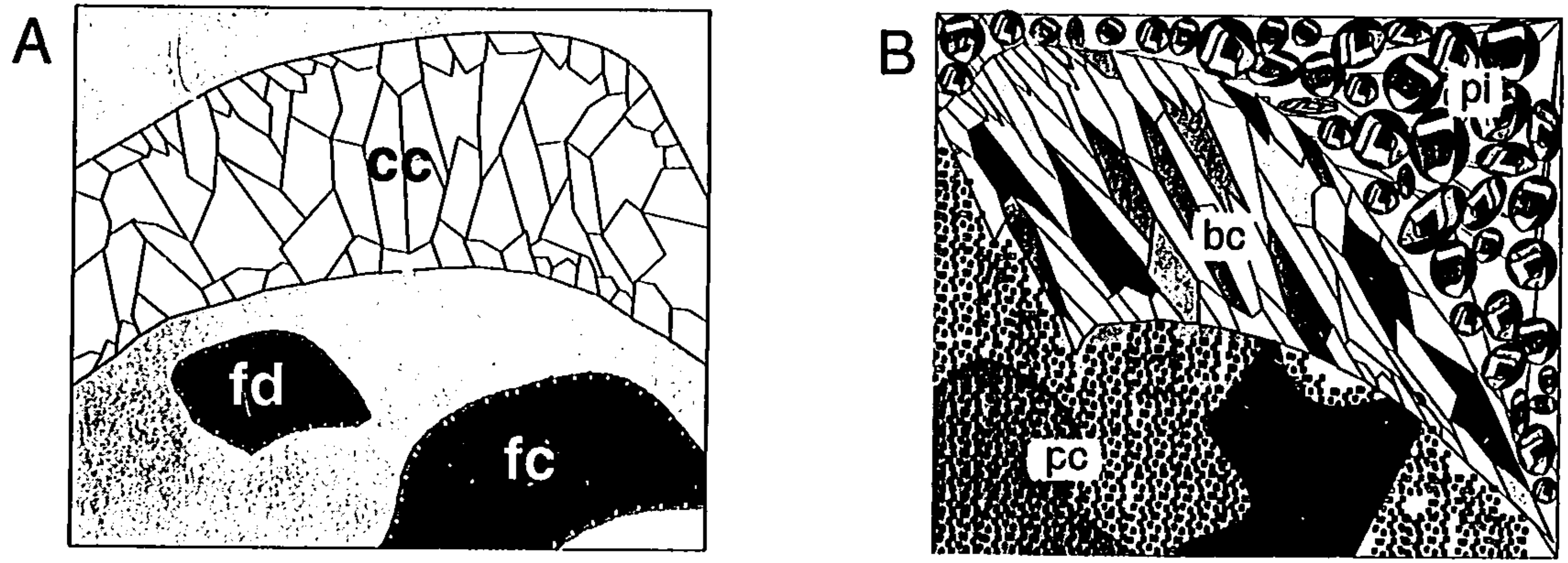

Fig. 21. Cements of the Pedro Castle Formation
A) Pore-lining dolomite cement (fd) is closely associated with pore-lining calcite cements (fc). Macroscopic pore-filling, clear, bladed drusy calcite cement (cc) fills many voids in the Pedro Castle Formation. B) Cements associated with calcrete textures are extremely varied. Poikilotopic calcite surrounds calcite matrix crystals (pc), and pisoids (pi). Void filling, bladed macroscopic spar (bc) is common, and is rooted on pisoids, matrix calcites and poikilotopic calcites.

Microcrystalline (< 0.1 mm), cloudy, pore-lining calcite cements are found throughout the formation. These cements, which typically line or fill small intraskeletal voids, are closely associated with the pore-lining dolomite cements. Despite the close association of dolomite and calcite cements in the Safe Haven area, however, interlayered dolomite-calcite-dolomite couplets reported by Jones *et al.* (1984) and Ng (1990) were not found.

Clear, macrocrystalline (0.5-4 mm) euhedral calcite cement fills many voids throughout the Pedro Castle Formation. Typically exhibiting a drusy morphology, this cement is characterized by fine, equant crystals lining pore walls that grade into large, bladed crystals towards the center of the void (Figs. 21A, 22a). This cement is associated with zones of flowstone development, and is identical to the coarse, void-filling calcite cements in the Cayman Formation.

Micro- to macro crystalline (0.1-5 mm), anhedral calcite cement is associated with calcitization textures. This clear to cloudy calcite fills irregularly-shaped voids around partially-dissolved dolomite crystals, and is identical to the coarse poikilotopic calcite found in the Cayman Formation (Figs. 17f, 19B). Not only are the dolomite crystals leached, but the calcite overgrowths also exhibit early signs of dissolution. This may indicate that the poikilotopic calcite is unstable in the fluid regime presently found in the Safe Haven subsurface.

Calcretes

Calcretization textures characterize the upper 3-4 m of the Pedro Castle Formation. In well SH#2, calcretes are found as deep as 18 m bsl, but this is an exceptional case in

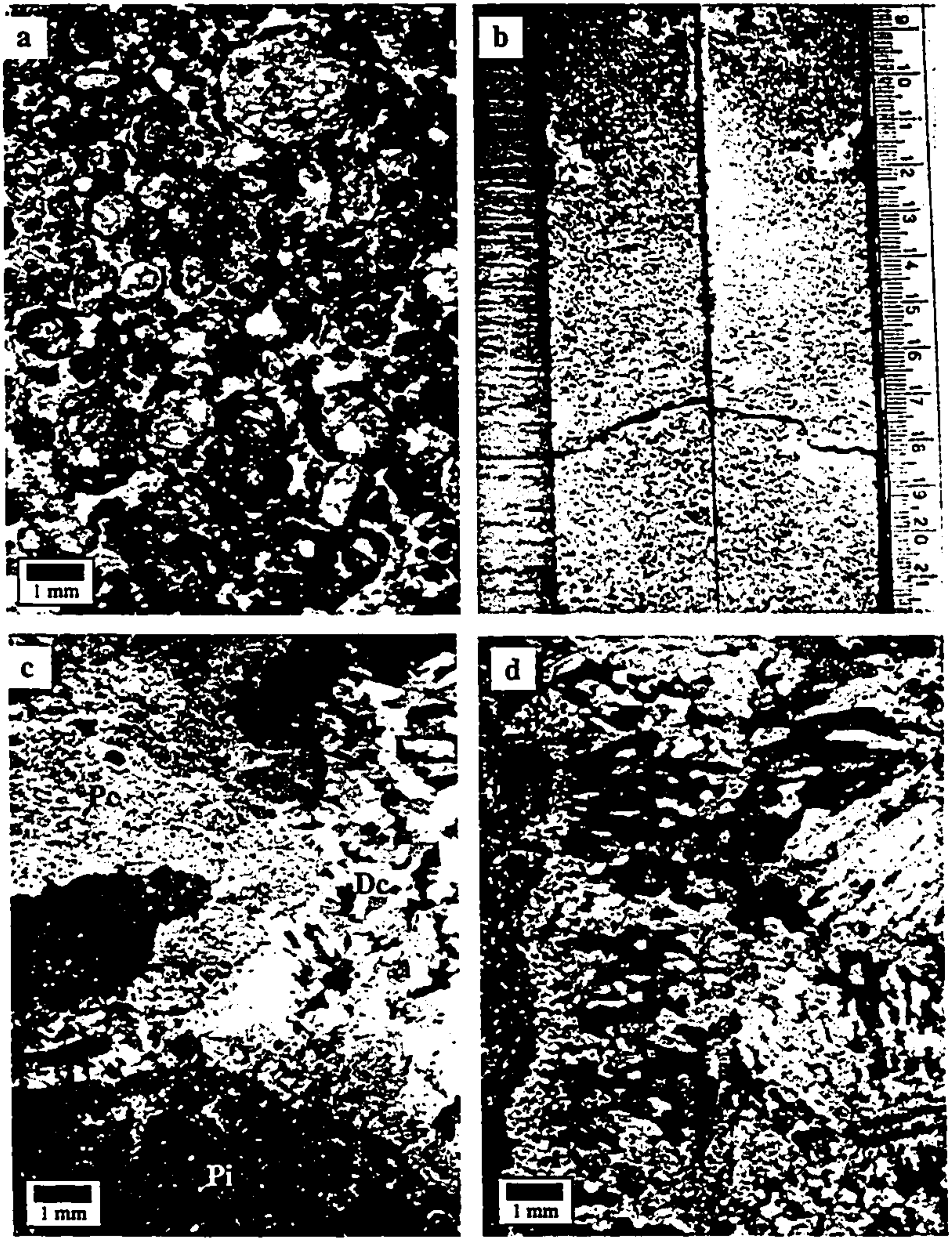

Fig. 22. Textures and cements associated with calcretization in the Pedro Castle Formation.
a) pisoids found in calcretized rock in the upper part of the Pedro Castle Formation (SH#2 30' 8")
b) calcretization commonly obscures original fabrics in core (SH#3 7.4 m)
c) poikilotopic (Pc) and drusy (Dc) calcite cements closely associated with pisoids (Pi) (SH#2 31' 4")
d) bladed cement rooted on pisoids (SH#7 25' 2")

the Safe Haven area. Although all core from wells drilled in the Safe Haven and Crystal Harbour Inlet areas include calcrete textures, the degree of calcretization ranges from very minor traces, to 1 m thick intervals in which original fabrics have been completely obscured (Fig. 22b).

In core, the calcrete is characterized by a green to grey colour, with numerous root casts. The root casts, typically 2-3 mm wide, have well-preserved cement sheaths. Concentrically laminated pisoids, 0.1-2.0 mm in diameter, are common in the calcretized zones (Fig. 22a) and contain relict inclusions of the precursor limestone. Some pisoids incorporate entire skeletal grains, most notably *Amphistegina*. For the most part, however, calcretization has overprinted the original sedimentary textures.

Spectacular cements are associated with the calcrete horizons at the top of the Pedro Castle Formation. Poikilotopic overgrowths surround partially dissolved calcite matrix and calcrete nodules (Fig. 22c). Closely associated with these poikilotopic calcites are splays of clear, bladed, void-filling centimeter-scale crystals (Figs. 21B, 22d).

Whereas most calcite cements in the Pedro Castle Formation display at least a moderate degree of luminescence, the poikilotopic cements associated with calcretes display only weak luminescence, and the clear, bladed cements are non-luminescent. This suggests that the these cements were precipitated in an oxidizing vadose or shallow phreatic environment (Smith, 1987). Because there is no evidence of microstalactic or vadose-miniscus fabrics, these cements were most probably precipitated in the shallow phreatic zone.

Luminescent, pore-lining, equant, clear, mesocrystalline (0.1-1 mm) cements line most voids, and consistently display layered zones of cement with alternating extinction when viewed through crossed polars. This pore-lining cement is morphologically similar to dolomite-calcite couplets described by Ng (1990), and may reflect variations in the position and chemistry of the water table.

In general, the cements associated with calcretes appear to have been precipitated at or near the top of the water table, and reflect a period when sea level was lower than present.

Cavity-filling Sediments

Unlike the Cayman Formation, strata in the Pedro Castle Formation contain only small amounts of cavity-filling sediment. This may be because the formations were exposed for different lengths of time following deposition. Alternatively, cavity and fracture systems were not extensively developed in the Pedro Castle Formation until after the deposition of the Ironshore Formation.

The most common cavity fill is a white mudstone that is similar in appearance to some varieties of caymanite in the Cayman Formation. In the Pedro Castle Formation, however, this mudstone is generally not dolomitized and does not display the range of colours found in the Cayman Formation caymanite. This mudstone is found in small voids and fractures near the top of the Pedro Castle Formation.

Cavity-filling skeletal sediment is rare, and found only near the top of the formation. Calcretization commonly overprints these sediments, and they are poorly preserved. Where they are discernible, these sediments contain mollusc and *Halimeda* fragments, as well as *Amphistegina*.

CALCITIZATION OF THE CAYMAN AND PEDRO CASTLE FORMATIONS

Poikilotopic calcite-dolomite, or calcitization fabrics on Grand Cayman have been attributed to preferential dissolution of unstable, early dolomite in the cores of zoned dolomite crystals (Fig. 17f) (Pleydell, 1987; Jones *et al.*, 1989). The leached zones were then filled by later calcite cements and were thus a result of time-separated processes, rather than concomitant dissolution and precipitation of dolomite-calcite couplets (Pleydell, 1987). These zones of calcitization, apparent in core as friable, chalky zones, are texturally equivalent to pulverulinite chalks described by Rose (1972) and Chafetz and Butler (1980). Isotopic evidence collected by Pleydell (1987) indicates that the calcitization was a result of a progressive freshening of pore fluids, possibly associated with sea level regression. Additionally, Ng (1990) found that calcitization fabrics were preferentially located along permeability conduits (e.g., joints and fractures), or at the water table zone.

Poikilotopic calcite-dolomite textures in the Pedro Castle Formation are different from those in the Cayman Formation. In most cases, alteration of the original limestone to dolostone is incomplete, and antecedent calcite is only partially leached and replaced by dolomite. The dolomite is in turn partially leached and replaced by coarse calcite cement. Additionally, dissolution of the poikilotopic calcite overgrowths is evident.

In the Safe Haven area, calcitization is most common along permeability conduits. Coral molds and vugs are commonly surrounded by chalky reaction rims that reflect calcitization of the dolomitic skeletal and matrix material. These calcitization textures cannot be clearly linked with a freshening of pore fluids on the basis of petrographic textures, but the late Miocene sea level lowstand of 40 m bsl (Jones and Hunter, 1994) would have allowed fresh water to come into contact with most strata in the Cayman Formation. Pleistocene sea level low stands affecting Grand Cayman (e.g., Blanchon and Jones, 1995) would also have served to expose the Pliocene and much of the Miocene strata to the meteoric regime.

Zones of dolomite dissolution and calcitization can, in some cases, be traced laterally. A distinct layer 3-5 m thick of dolomite dissolution and calcite precipitation in the Cayman and Pedro Castle formations cuts across the Cayman Unconformity with its top at ~ 20 m bsl. The top of a similar 5-8 m thick layer is found in the Cayman Formation at ~ 40 m bsl, although the distribution of calcite cement is not as pervasive. The consistent depth of these zones, as well as the fact that they cross formational boundaries, suggests that they are linked to paleo-water tables, and hence, paleo sea levels. The 40 m bsl zone corresponds with the Messinian minimum sea level lowstand of 41 m bsl (Jones and Hunter, 1994a). The 20 m bsl zone may correspond with a late Pliocene or Pleistocene sea level lowstand. An intertidal notch at 18.5 m bsl formed during a sea level lowstand ~ 7 ka before present (Blanchon and Jones, 1995), and this may be linked to the dissolution zone at 20 m.

CAVES AND SPELEOTHEM DEPOSITS IN THE CAYMAN AND PEDRO CASTLE FORMATIONS

Caves and dissoution cavities are present in both the Cayman and Pedro Castle formations. In core they are 0.1-2 m in thickness. The distribution of caves is random and impossible to predict in both formations. Wells SH#8 and SH#8A record completely disparate cavity and core recoveries despite their close proximity to each other. Similarly, attempts to correlate zones of cave development across the Safe Haven area met with no success. This is in the nature of karst terrains, but may also be due to the fact that zones of friable rock with low recoveries have the same drilling and recovery characteristics as cavity-ridden zones. The recognition of true cave development is thus difficult or impossible in most wells.

Speleothem deposits are, by definition, closely linked to cave development. A wide variety of speleothemic deposits are present in the Safe Haven area. These speleothems include thick flowstone deposits, pore-lining microcrystalline calcites, and void-filling bladed calcite spar. The Cayman Formation contains some coarse calcite spar that fills voids, but true banded flowstones and associated speleothems are found only in the Pedro Castle Formation. These precipitates are found throughout the Pliocene strata, but are most common in a zone 10-15 m bsl. Elsewhere on Grand Cayman, the Cayman Formation does contain extensive flowstone and speleothem deposits (e.g., Smith, 1987; Ng, 1990; Jones, 1992b). These are at locations at or above present sea level, and thus represent paleo watertable positions not recorded at Safe Haven.

PARAGENETIC ARCHITECTURE

Despite the chaotic nature of the diagenetic fabrics in the Cayman and Pedro Castle formations, some distinct zones and trends are present. This is due to the fact that the fluid regimes that gave rise to these zones were controlled by fluctuating sea levels. Meteoric and marine mixing zones associated with the water table on Grand Cayman are chemically "aggressive" zones (Smith, 1987), and form laterally extensive, but vertically restricted, diagenetic zones. Most of the paragenetic fabrics recognized in the Safe Haven subsurface reflect the influence of sea level, and show lateral continuity, irrespective of formational boundaries, mineralogies, or rock textures (Fig. 23).

Dissolution and calcitization in the Cayman Formation at 40 m bsl is apparent in all core from deep wells at Safe Haven. This zone, typically 5-8 m thick, is also recognizable in most wells on the island as a zone of diminished recoveries and difficult drilling. This is primarily a zone of dolomite dissolution, with crumbly, friable rock and poor textural preservation. Calcite precipitation is variable, and locally serves to indurate the rock, thereby increasing core recoveries without improving textural preservation. Calcitization textures are not always associated with this zone, although they are locally important.

Another zone of dissolution and calcitization at 20 m bsl is present in the Safe Haven area. This zone cuts across the formational boundary between the Cayman and Pedro Castle formations, and a drop in core recoveries in both formations is evident. In the Cayman Formation this zone is characterized by calcitization and poor textural preservation. The Pedro Castle Formation, on the other hand, exhibits an increased degree of dolomitization and limestone dissolution at this depth. For dolomitization and calcitization to occur in a laterally correlative zone indicates a fluid regime wherein both the dolostones of the Cayman Formation and the limestones of the Pedro Castle Formation were unstable. Ng (1990) has recorded modern dolomite and calcite cement precipitation in aquifers on Grand Cayman that reflect different degrees of meteoric mixing. The most likely candidate for formation of the 20 m bsl zone in the Safe Haven subsurface is therefore a chemically aggressive paleo-water table zone. This zone has not been recognized in core from the rest of the island, and may reflect only local ground water conditions

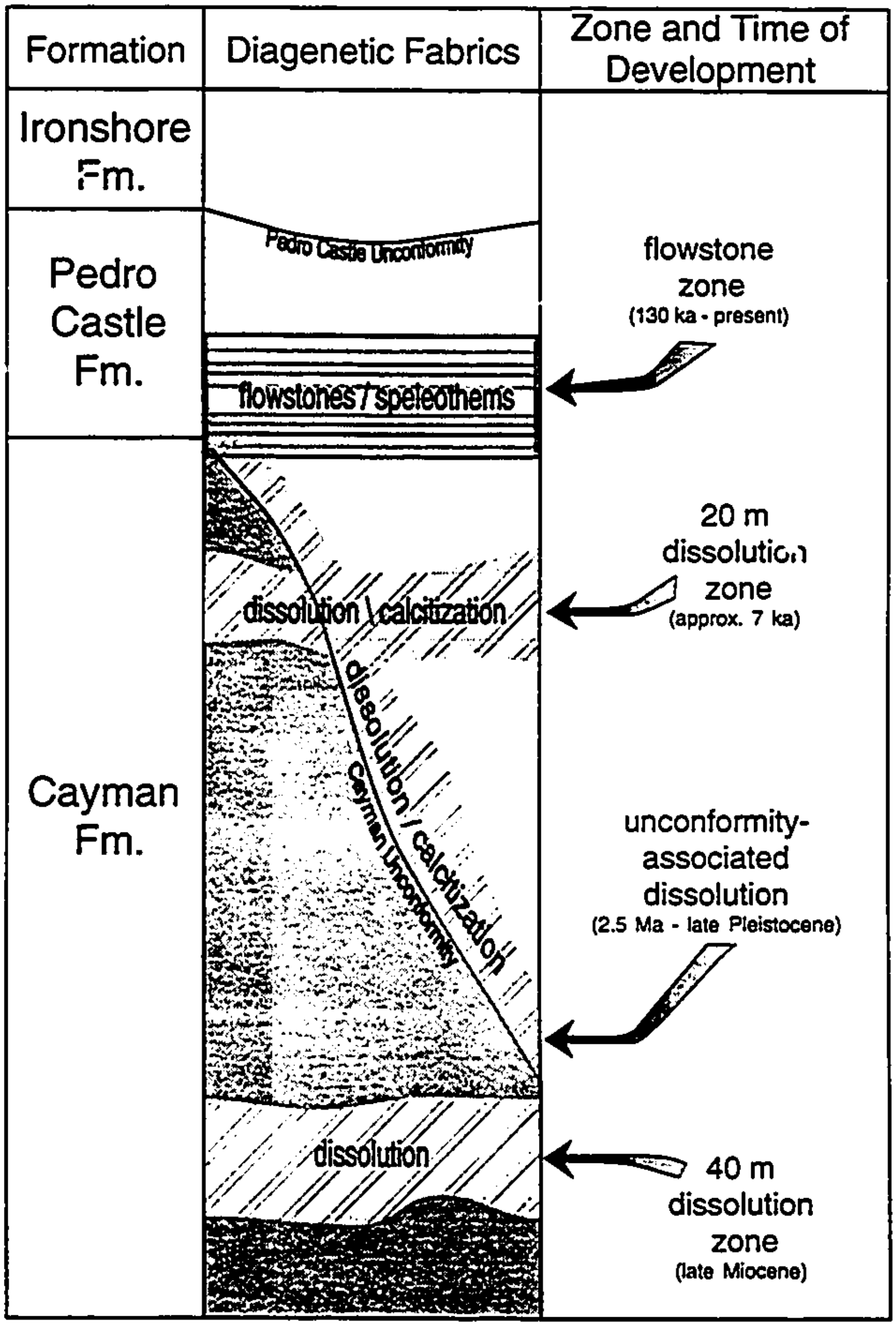

Fig. 23. Stratigraphic locations of major diagenetic zones in the Safe Haven area, and their approximate time of development.

Flowstones and other speleothem deposits are best developed between 10-17 m bsl in the Pedro Castle Formation. This highly variable zone is not easily traced laterally except when considering all the wells in the Safe Haven area. The association with caves is not clear, because caves are found throughout the Tertiary strata, whereas flowstones are found primarily in the Pedro Castle Formation. The stratigraphic position of the Pedro Castle Formation at Safe Haven means that it has spent a great deal of time in the shallow phreatic and vadose zones and has developed extensive speleothem deposits. The Cayman Formation preserves few speleothemic deposits, and this may be because it has experienced predominantly phreatic conditions over the last 5 ma. Deep phreatic regimes are subject to high P_{CO_2} conditions that give rise to dissolution and cave formation. In comparison, speleothem deposits are found primarily in vadose to shallow phreatic zones in communication with the atmosphere. The low P_{CO_2} conditions found in these settings are conducive to precipitation rather than dissolution, and cave development is superceded by speleothem formation (Dreybodt, 1981a, b; Mylroie and Carew, 1988).

Caymanite is most common in the upper 10 m of the Cayman Formation. This is not surprising given that the sediment forming the caymanite had to filter down through the rock from the land surface. Conversely, caymanite is rarely found below 38 m bsl in the Safe Haven area. This may be related to the dissolution zone at 40 m bsl. If the 40 m bsl zone represents a paleo sea level, then fluids carrying sediment from the unconformity surface down into the rock would probably have "dumped" their sediment load once the water table was encountered. In order for this to have taken place, the 40 m bsl zone had to develop contemporaneous with the deposition of the caymanite. Jones (1991) stated that this stage of caymanite deposition took place after deposition, lithification, and karstification of the Cayman Formation, but prior to the deposition of the Pedro Castle Formation. This suggests that the 40 m bsl dissolution zone may be associated with the late Miocene sea level low stand that led to the development of the Cayman Unconformity (Jones and Hunter, 1994). This is also in accordance with the idea that paleo-groundwater table positions can imprint laterally extensive volumes of rock (e.g., Mylroie and Carew, 1988).

A diagenetic trend not associated with paleo-sea levels is the dissolution of Pedro Castle Formation strata immediately overlying the Cayman Unconformity (Fig. 24). Strata immediately below the unconformity are typically well cemented and indurated. Strata immediately above the unconformity, on the other hand, are extremely friable. In many wells, the 3-4 m interval above the unconformity is characterized by core recovery approaching 0%. Although this zone is locally 100% dolomitized, it is for the most part formed of dolomitic limestones. Dissolution appears to be primarily leaching of calcite, with no replacement. The close association of this zone with the Cayman Unconformity suggest that the dissolution was a result of ground water flow being focused along the unconformity by the relatively impermeable rocks of the Cayman Formation. Groundwater percolating downward through the Pedro Castle Formation strata would be trapped and forced to move laterally *along* the unconformity surface, with the resultant preferential leaching of the permeable Pliocene strata (Fig. 24). The relatively impermeable upper strata of the Cayman Formation would have been little affected by the passage of these fluids.

PARAGENETIC HISTORY OF THE TERTIARY STRATA AT SAFE HAVEN

The earliest events following deposition of the Cayman Formation were the

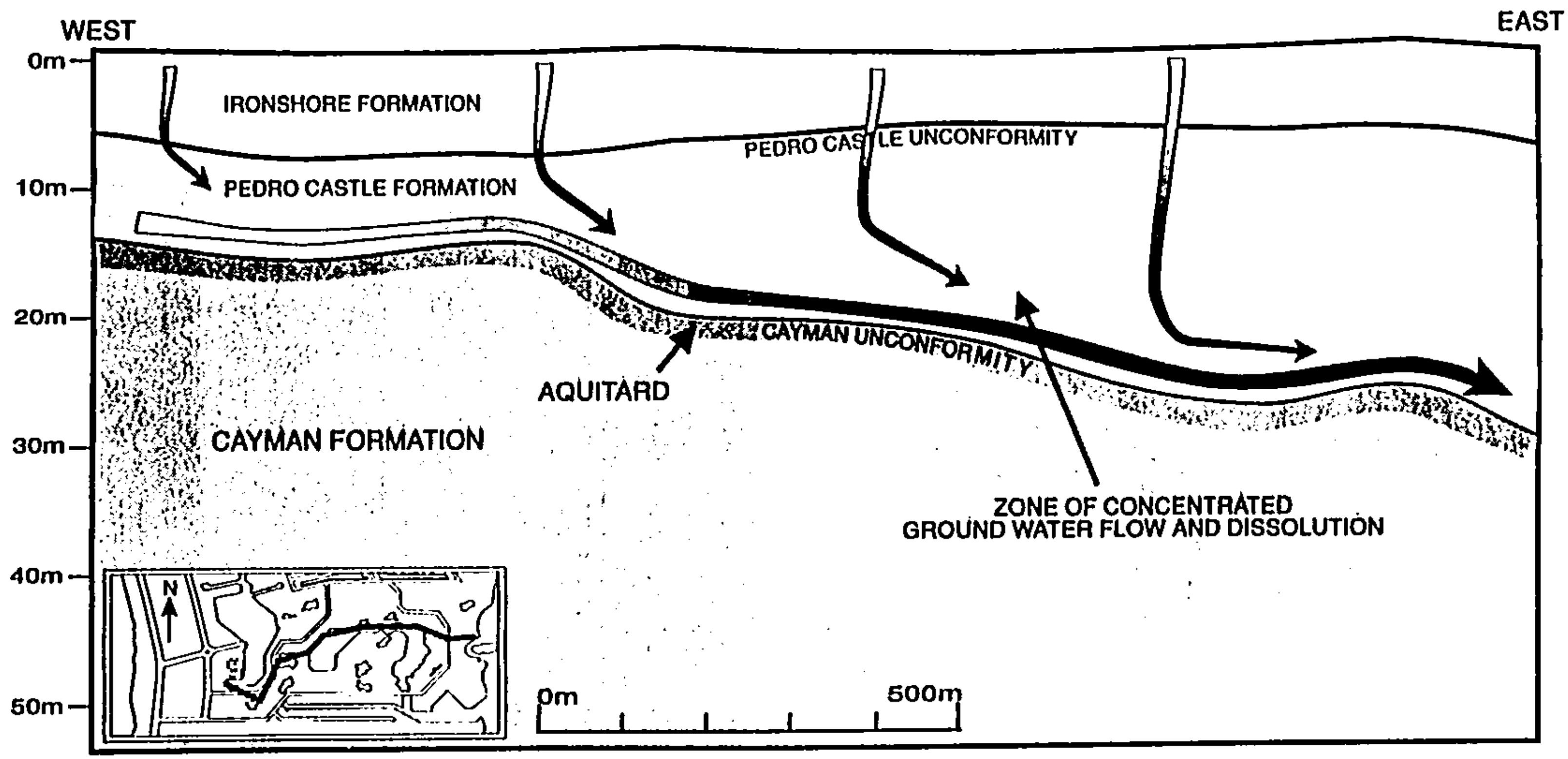

Fig. 24. Development of the zone of dissolution above the Cayman Unconformity
Meteoric fluid percolating down into the Tertiary strata of the Pedro Castle Formation was diverted and forced to flow laterally along the Cayman Unconformity by relatively impermeable strata at the top of the Cayman Formation. A zone of dissolution developed in the Pedro Castle Formation as a result of this concentrated ground water flow.

precipitation of the first two generations of isopachous cements and deposition of the marine cavity-filling sediments (Fig. 25). The isopachous cements may be recrystallized marine cements (cf. Pleydell, 1987). That these cements are overlain by marine cavity-filling sediments supports this assessment. The peloidal cavity fill may also be a marine cement (Pleydell, 1987). Certainly, the fact that it is overlain by an isopachous cement identical to the first generation pore-lining cement indicates the peloidal cavity-fill was marine in origin. Alternatively, the cements and sediments were emplaced after the Messinian sea level drop. Even were this the case, the fact that these cements and sediments are not associated with the extensive secondary porosity dissolution formed by karsting indicates a mixed-water phreatic, rather than vadose, environment.

The Messinian (terminal Miocene) sea level drop marked the transition of the Safe Haven area from a marine to terrestrial setting (Jones and Hunter, 1994a). The Cayman Unconformity developed during this period of exposure (Jones and Hunter, 1994a). Karsting, cementation, dissolution and internal sedimentation in the Safe Haven area were associated with this exposure. Additionally, the sea level lowstand brought much of the strata of the Cayman Formation into contact with fresh and mixed water chemistries, resulting in dissolution and cementation. The 40 m bsl dissolution zone probably developed at this time.

The first period of dolomitization postdates the Messinian sea level fall, and may be linked instead with the subsequent transgression. Emplacement of the caymanite sediments predated dolomitization (Jones, 1991). Therefore, karsting and weathering associated with the lowstand predates dolomitization. The Cayman Formation may not

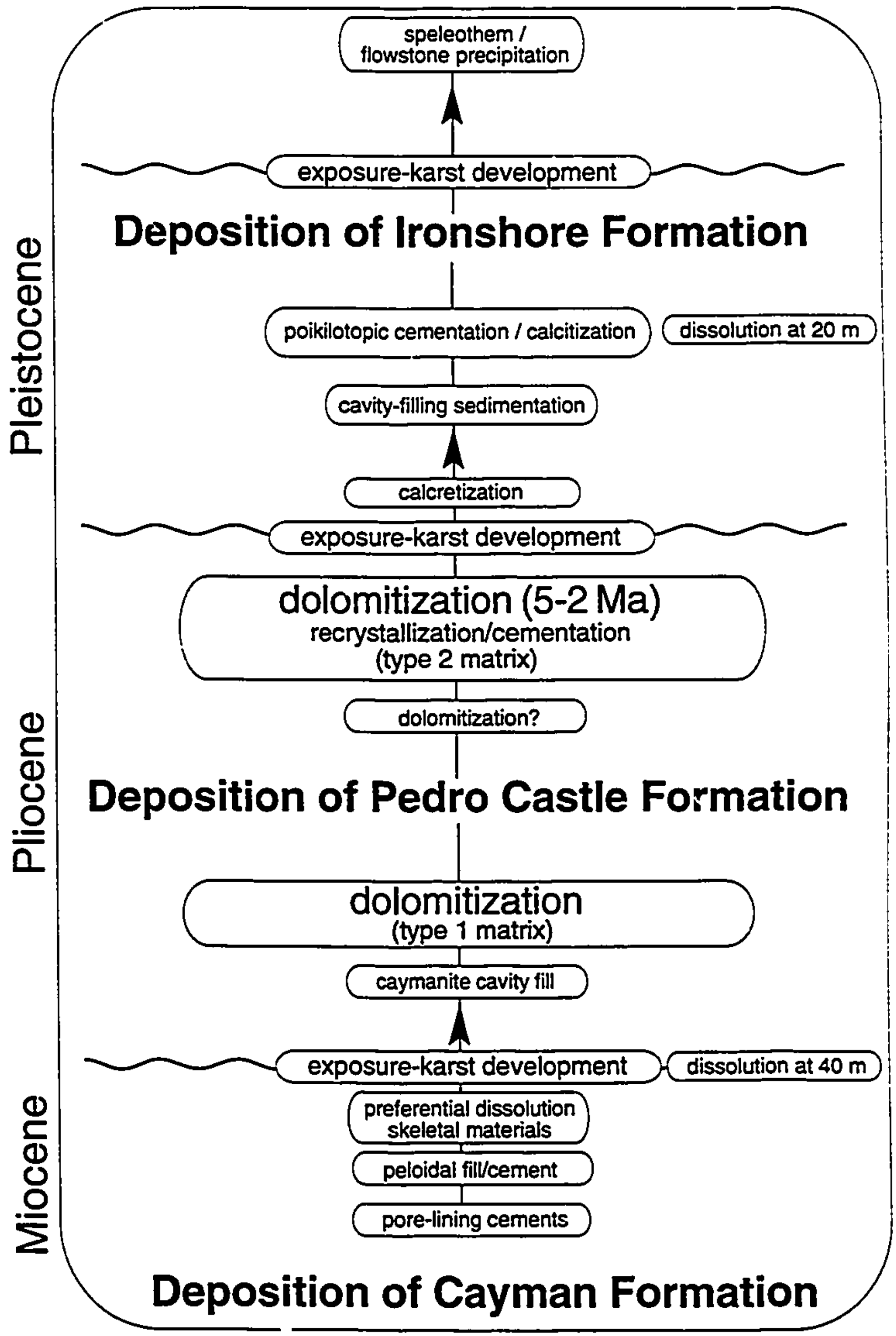

Fig. 25. Paragenetic history of the Safe Haven area.

have undergone dolomitization until the transgression that led to the deposition of the Pedro Castle.

Although all available $^{87}Sr/^{86}Sr$ isotope data points to dolomitization between 2-5 Ma (Pleydell, 1987; Pleydell *et al.*, 1990), the initial period of dolomitization did not post-date deposition of the Pedro Castle Formation. Dolomitization of the Pedro Castle Formation is incomplete, whereas the Cayman Formation has been completely dolomitized. Given this, if dolomitization post-dated deposition of the Pedro Castle Formation, the Pliocene strata must have been isolated from dolomitizing fluids. Interpretation of carbon-oxygen isotope data indicates normal marine (Pleydell, 1987) to slightly brackish (Ng, 1990) dolomitizing waters. Pervasive dolomitization of the Cayman Formation resulted in the finely crystalline type 1 matrix dolomite. This suggests that the entire formation was exposed to the same dolomitizing fluids. This would require that the entire island be: a) submerged, or b) subject to a gradually changing sea level and mixing zone associated with the water table. It would be unlikely in either case that the dolomitizing fluids could fail to affect the Pedro Castle Formation. The fact that Grand Cayman was in an open ocean setting means that it would have been impossible to isolate the Pedro Castle Formation from marine waters. Breaks in the ridge surrounding the North Sound depression would have allowed sea water to reach the Pliocene sediments during sea level lowstands, and during highstands the western end of Grand Cayman would have been completely inundated. It is inconceivable that a dolomitization event that pervasively dolomitized the Cayman Formation would dolomitize only small parts of the Pedro Castle Formation.

On the basis of petrographic textures, the first dolomitization event is probably represented by the type I matrix dolomite of the Cayman Formation. The coarser type II matrix dolomite is related to a later dolomitizing event that may have affected the Pedro Castle Formation and reset $^{87}Sr/^{86}Sr$ isotope values. This is suggested by the fact that the type II dolomite is: a) not postdated by any other dolomites, and b) morphologically akin to dolomites in the Pedro Castle Formation.

The next period of dolomitization took place after deposition of the Pedro Castle Formation, between 2-5 Ma. This second period of dolomitization may have been in two stages. The Pedro Castle Formation records two types of matrix dolomite. The type A dolomite is potentially an earlier generation of dolomite, whereas the type B dolomite is morphologically akin to the recrystallized type II matrix dolomite in the Cayman Formation. Type B dolomite in the Pedro Castle Formation thus formed during the later 2-5 Ma dolomitizing episode.

The exact timing of this second period of dolomitization is open to debate, despite the 2-5 Ma age bracket. In the Safe Haven area, what little caymanite is present in the Pedro Castle Formation is undolomitized, suggesting it was emplaced after dolomitization. Cavity fill sediments and caymanite in Pliocene strata at Pedro Castle, however, are dolomitized (Jones, 1992a). In well SH#2 poorly preserved, dolomitized calcrete textures attest to dolomitization post-dating calcretization, and hence exposure, of the Pedro Castle Formation. It is possible that this second period dolomitization was associated with the exposure of the Pedro Castle Formation some time in the early to middle Pliocene. Calcretes at the top of the Pedro Castle Formation, however, are not associated with dolomitization or dolomite cements. The Pedro Castle Unconformity is a surface that has been modified by fluctuating sea levels, and the well-preserved calcretes and caymanite-type deposits at the top of the formation are probably a result of a regression(s) that postdated any dolomitization.

Poikilotopic calcites clearly postdate dolomitization of the Cayman and Pedro Castle formations, as does the associated zone of dissolution 20 m bsl. Poikilotopic calcite incorporates the calcrete textures at the top of the Pedro Castle Formation. Development of the overgrowths must therefore postdate the unconformity surface. That the poikilotopic calcites predate the Ironshore Formation is uncertain, although they have not been described in Pleistocene or modern strata on Grand Cayman.

Final exposure of the Pedro Castle Formation was followed by a sea level transgression 130 000-125 000 years ago that allowed the deposition of the Ironshore Formation on top of the Tertiary strata (Jones and Hunter, 1990). Speleothem and flowstone deposition appears to have been the most recent addition to the paragenetic fabrics of the Cayman and Pedro Castle formations, and were due to fluctuating late Pleistocene sea levels (Smith, 1987).

SYNOPSIS

The paragenetic history of the Safe Haven area has been governed by changes in relative sea level since the deposition of the Cayman Formation. Rather than a static system subjected to progressive and gradual change, the Tertiary strata in the Safe Haven area experienced diagenetic imprinting that took place over relatively short periods, and was typically restricted in its focus. These diagenetic regimes were not only temporally and spatially restricted, but also subject to retrogression as pore fluids and rock chemistries changed. Despite differences in age, mineralogy and textures, the two formations share many paragenetic features in common. These paragenetic features developed in marine, mixed and freshwater regimes, and are still forming today

CONCLUSIONS

The recovery of the sixteen cores from the Safe Haven area has allowed a detailed look at the complex sedimentological and diagenetic architecture of an isolated carbonate bank. This has been previously impossible on Grand Cayman, and new information encompasses depositional environments, diagenesis, and paleo sea levels, leading to the following findings:

1. The Cayman Formation at Safe Haven was deposited in moderate to high energy conditions in water depths of 10-30 m on an isolated oceanic bank.
2. An energy barrier existed to the east of the Safe Haven area that allowed sediments to accumulate on the leeward edge of the bank during deposition of the Cayman Formation.
3. The Cayman Unconformity is a karsted surface that was modified by marine processes during a stepped sea level rise in the late Miocene or early Pliocene.
4. Topographical highs on the Cayman Unconformity are the remains of marine planation terraces, and record sea level stillstands at 16m and 28m bsl.
5. The Cayman Unconformity acted as an aquitard to meteoric waters during sea level lowstands in the late Pliocene and Pleistocene. Percolating fluids were forced to flow laterally along the unconformity surface and dissolved the Pedro Castle strata immediately overlying the unconformity.
6. The Pedro Castle Formation at Safe Haven was deposited in low to moderate energy conditions in water depths greater than 10 m. A gradual fining of sediment and the presence of pelagic foraminifera upsection atests to deepening water in latter stages

of deposition.

7. The Pedro Castle Formation was deposited in the period 4.8-2.5 Ma.

8. Deposition of the Pedro Castle Formation was initially controlled by the morphology of the Cayman Unconformity, but sea level rise eventually cancelled the effect of the unconformity surface.

9. Sea level during deposition of the Pedro Castle Formation reached 15 m above present day sea level, and may have been higher. This suggests that the Pedro Castle Formation originally covered much of Grand Cayman, and was removed by later weathering.

10. The Pedro Castle Unconformity developed at 2.5 Ma, and was modified during subsequent transgression and regressions until the deposition of the Ironshore Formation 130 000 years ago.

11. The Pedro Castle Unconformity does not record the same well-developed topography as the Cayman unconformity because sea level constantly fluctuated and did not allow extended periods of karst development.

12. The Cayman Formation was 100% dolomitizated before deposition of the Pedro Castle Formation. A later period of dolomization altered part of the Pedro Castle Formation, and recrystallized much of the Cayman Formation. This later dolomitization reset Sr^{87}/Sr^{86} values.

13. The paragenetic architecture of the Tertiary strata at Safe Haven reflects paleo-sea level positions from the late Miocene to present. A zone of dissolution at ≈ 40 m bsl developed during the terminal Miocene sea level lowstand. Another zone of dissolution at ≈ 20 m bsl, may be linked to a sea level lowstand at 7 ka.

Speleothemic accumulations are concentrated between 10-17 m bsl, and were precipitated during Pleistocene sea level lowstands.

14. Lateral variations in diagenetic textures were due to changes in mixing zone water chemistry, and different regimes existed in close proximity to each other.

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