Petrophysical Characterization of Pliocene - Pleistocene Reefal Carbonates, Southern Dominican Republic

Albertus Ditya
University of Miami, aditya@rsmas.miami.edu

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PETROPHYSICAL CHARACTERIZATION OF PLIOCENE - PLEISTOCENE REEFAL CARBONATES, SOUTHERN DOMINICAN REPUBLIC

By

Albertus Ditya

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the requirements for the degree of
Master of Science

PETROPHYSICAL CHARACTERIZATION OF PLIOCENE - PLEISTOCENE
REEFAL CARBONATES, SOUTHERN DOMINICAN REPUBLIC

Albertus Ditya

Approved:

Gregor P. Eberli, Ph.D.
Professor of Marine Geology
and Geophysics

Dean of the Graduate
School

Donald F. McNeill, Ph.D. P.G.
Scientist of Marine Geology
and Geophysics

Ralf J. Weger, Ph.D.
Assistant Scientist of Marine
Geology and Geophysics

James S. Klaus, Ph.D.
Assistant Professor of
Geological Sciences Department
DITYA, ALBERTUS  
(M.S., Marine Geology and Geophysics)

Petrophysical Characterization of 
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Laboratory measurements of petrophysical properties, including porosity, 
permeability, acoustic velocity, and electrical resistivity, were performed on over 
150 plugs of Pliocene-Pleistocene reefal successions in the southern Dominican 
Republic. These reefal successions are intensively altered by multiple episodes 
of meteoric diagenesis. The petrophysical measurements can be related to their 
diagenetic overprint and the pore structure, which is quantified by digital image 
analysis.

The inherent depositional heterogeneity in reefs combined with the 
dynamic meteoric diagenesis processes (cementation and dissolution) produce 
abundant heterogeneity in the petrophysical properties. Reservoir properties 
such as porosity and permeability range from 0.07 to 0.54 (porosity) and up to six 
orders of magnitudes from 0.01 milidarcy up to 2 darcy in permeability. Although 
permeability shows a weak positive correlation to porosity, the variation at any 
given porosity can be as high as 4 orders of magnitude. This variation is caused 
by the different pore types created during deposition and diagenesis. Samples 
altered in the meteoric vadose zone have higher permeability due to occurrence 
of connected vug porosity.
The P-velocity (Vp) at 5Mpa effective pressure ranges from 2900 to 6137 m/s with deviations up to + 2000 m/s from Wyllie time average curve of calcite at any given porosity. The positive deviation is related to intense cementation during deposition and multiple episodes of meteoric diagenesis. The influence of these processes on the pore structure and Vp can be quantified by digital image analysis (DIA). At the same porosity, samples with larger (higher DomSize) and simpler (lower PoA) pore structure have a higher velocity than samples with a smaller (lower DomSize) and more intricate pore network (higher PoA). By assigning the pore structure parameters to velocity-porosity estimations, the prediction of porosity from acoustic data can be significantly improved to a $R^2$ of 0.91. It can be concluded that the porosity in combination with pore size and complexity of the rocks are the most important controlling factors for the acoustic velocity in these reefal carbonates.

Electrical resistivity is assessed by the formation factor and the cementation factor ($m$). The cementation factor shows a significant range with values between 2.1 to 5.3. It has a very weak correlation to permeability ($R^2=0.15$), implying that a) permeability is not well correlated to electrical resistivity and b) permeability estimates from resistivity logs contain large uncertainties. Furthermore, no good correlation exists between electrical properties and depositional environments, diagenesis, pore types, or rock textures. However, a higher amount of microporosity correlates to lower resistivity corroborating previous findings that an increased number of pores decreases resistivity.
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CHAPTER 1

INTRODUCTION

Reefal deposits consist of mainly calcium carbonate secreting marine organisms, growing as a rigid body in shallow-water seas. Reefal carbonates have been studied for decades because of their scientific and economic importance. Economically, ancient reef deposits contain disproportionately large amount of hydrocarbon reserves compared to any other types of sedimentary rocks (Longman, 1993). However, reservoir properties characterization in reef system using geophysical methods can be challenging due to their complex petrophysical variability (Jordan and Wilson, 1998).

Because reef constituents are largely of organic origin they have various grain shapes and sizes (James, 1983). As a result of the biological factors reef systems have a complex 3-D depositional geometry. In addition, these reef bodies are highly susceptible to major diagenetic alteration and often contain some degree of early, in situ cementation. In general, diagenesis occurs more quickly than compaction causing transformation in rock physical properties that effect acoustic velocity in carbonates (Anselmetti and Eberli, 1993). The petrophysical complexity or variations are often below the resolution of geophysical tools and thus, the prediction of petrophysical properties from seismic or well data relies on complementary high-resolution laboratory petrophysical study integrated with geological analysis.
In this study, robust laboratory petrophysical measurements are combined with thorough core-based lithologic, diagenesis, and digital-image analysis from subaerially exposed Pliocene-Pleistocene reefal carbonates from the Southern Dominican Republic. The geological interpretations and pore parameters are correlated with porosity, permeability, acoustic velocity, and electrical resistivity variations to characterize the petrophysical properties in these sub-aerially exposed reefal carbonates.

1.1 Objectives

The goal of this research is to characterize petrophysical complexity of a reefal succession based on a dataset from outcrops and cores in Pliocene-Pleistocene reefal deposits along the south coast of the Dominican Republic. The research seeks to accomplish the following objectives:

1. To identify the influences of depositional lithofacies and meteoric diagenesis on the petrophysical properties;
2. To investigate the effect of pore structure on the acoustic velocity, electrical resistivity, and permeability.

1.2 Working Hypothesis

In order to achieve the above-mentioned research objectives, four hypotheses are to be tested:

1. The depositional lithofacies and early diagenesis can significantly influence the petrophysical properties of reefal carbonates, thus
producing a wide range of values in acoustic velocity, electrical resistivity, and permeability.

Several studies show the correlation of petrophysical properties in association with the depositional settings and diagenesis in carbonate rocks (Enos and Sawatsky, 1981; Anselmetti and Eberli, 1993). Early diagenesis, especially meteoric diagenesis, results in a rapid change in petrophysical properties of the carbonates due to pervasive dissolution, recrystallization from aragonite to calcite or dolomite, and cementation (Inzce, 1998). The correlation of petrophysical properties with depositional lithofacies and meteoric diagenesis zones enable assessment of petrophysical characteristics for each depositional environment and diagenesis.

2. **Pore structures control the acoustic velocities variation in the reefal system.**

Acoustic velocities in porous media depend on porosity, mineralogy, saturation, pressure, temperature, density, and frequency (Mavko and Mukerji 1998; Wang 2001; King 2005). Numerous studies have shown influence of pore geometry/structure on acoustic velocities (Wyllie, 1958; Anselmetti and Eberli, 1993, 1997; Wang, 1997; Eberli et al., 2003; Lonoy, 2006; Weger et al., 2009). These latest afore-mentioned references reveals a strong correlation between pore structure and acoustic velocity variation at any given porosity. I will test that the pore structure, from from 2-D thin sections, will show a correlation with the measured acoustic velocities of this study samples.
3. Pore structure controls the permeability variation in the reef system.

The various pore structures in carbonate rocks make permeability prediction considerably more difficult (Anselmetti et al., 1998). Several studies reported a correlation of pore structure to permeability in certain carbonate lithofacies (Lucia, 1995; Anselmetti et al., 1998; Weger et al., 2009). According to Weger et al (2009), a carbonate rock with larger pores and a simple pore system has better permeability than a rock with smaller and a complex pore system. It is hypothesized that permeability variation in the studied reef system will be controlled by the pore structure with different characteristic since it has different depositional setting and diagenesis with Weger et al. (2009) data.

4. Electrical resistivity is not significantly related to permeability in the reefal carbonates.

Archie (1947) notes the dissimilarity between electrical flow and fluid flow. In other words, permeability and resistivity are not correlated. However, electrical resistivity log has been used to predict permeability in carbonate rocks (Lucia and Conti, 1997; Smith et al, 2003). Verwer et al. (2011) find that the total number of pore connections strongly correlate with electrical resistivity, but is not necessarily correlated to permeability. They show that microporosity can be a pathway for electron conduction. This effectively produces a low resistivity rock with low permeability, which is somewhat counter intuitive to the common interpretation of resistivity. Verwer et al. (2011) hypothesize the importance of porosity, pore structure, and total amount of pores in predicting permeability from resistivity log. In this study, electrical
resistivity and permeability data will be linked to depositional environment, diagenesis, and pore structure to test investigate a correlation between electrical resistivity and permeability.

1.3 Problem Statement

Understanding the control on reefal petrophysical properties of carbonate is often key to proper interpretation of reservoir properties (porosity, permeability) from either seismic or well-log data (Anselmetti and Eberli, 1993). Petrophysical properties of unconsolidated carbonate sediment exhibit considerable spatial homogeneity based on grain size, texture, and packing (Enos and Sawatsky, 1981; Inzce, 1998). However, in carbonates, diagenesis alters the original fabric and rock properties shortly after deposition invoking mineralogic changes and inversion of pore distribution (Lucia, 1999; Moore, 2001; Eberli et al, 2003). Thus, petrophysical properties in carbonates can have a wide range of values even at a similar porosity value, i.e acoustic properties and electrical properties (Rafavich et al., 1984; Wang et al., 1991; Anselmetti and Eberli, 1993; Marion and Jizba, 1997; Weger et al, 2009; Verwer et al, 2011).

Velocity is strongly dependant on porosity (Wang et al, 1991). In carbonate rocks, velocity can vary about up to 2500 m/s at any given porosity (Anselmetti and Eberli, 1993; 2001; Kenter et al, 2002; Weger et al, 2009). Several studies attribute the velocity variations to differences in depositional fabric and specific diagenesis affects (Anselmeti and Eberli, 1993, 2003; Incze, 1998). Typically, platform deposits have higher diagenetic alteration potential.
than those sediment deposited on the platform margin slope (Anselmetti and Eberli, 1993). Thus, platform-top carbonates have high average velocity and a large range in sonic velocity due to the differences of rock textures and diagenesis.

Several studies recognize the influence of pore structure, the final product of depositional lithofacies and diagenesis, on the resultant acoustic velocity (Anselmetti and Eberli, 1993, 1997; Kenter et al, 1995; Wang, 1997; Baechle et al, 2004; Weger et al, 2009). Weger et al. (2009) explain velocity variations in carbonate as being dependent upon the size and complexity of pore structures and quantify this relationship with pore structure parameters derived from digital image analysis from a thin-section image. Simple and large pores have higher acoustic velocity than complex and small pores at a given porosity (see Weger et al, 2009, their figure 2).

Applying the same technique, Verwer et al (2011) document the relationship between sizes, complexity, and number of pores to electrical properties of carbonate rocks. Rocks dominated by small pores and intricate pore network have low cementation factor at a given porosity, compared to the large and simple pore structure (see Verwer et al, 2011, their figure 5). In addition, they note the importance of pore counts and pore connections to electrical resistivity.

Studies of Weger et al. (2009) and Verwer et al. (2011) use samples from various ages, depositional settings, and localities. This thesis addresses pore structure correlation with petrophysical properties specifically in the Plio-Pleistocene shallow-water reefal carbonates of the southern coast of the
Dominican Republic. In addition, this thesis also examines the petrophysical signatures of early meteoric diagenesis in reefal carbonates.

1.4 Study Area

1.4.1 Geology of Hispaniola Island

The Dominican Republic shares the eastern side of the island of Hispaniola, with Haiti on the western part of the island. Tectonically, Hispaniola lies on the northern side of the Caribbean plate where it interacts with the North American plate (Figure 1.1A). The island lies on the Greater Antilles orogenic belt geologic province (Draper et al., 1994a) and is considered mature island-arc formed in an intra oceanic setting (Bowin, 1966). The island of Hispaniola was formed and shaped by four main tectonic phases; Early Cretaceous – Middle Eocene arc construction phase, Middle Eocene arc collision phase, Late Eocene – Early Miocene strike slip phase and Early Miocene to Recent transpressional phase (Draper et al., 1994b). The latest phase is responsible for the ongoing island uplift and therefore the reef terraces in the study area.

The island has experienced major orogenic events due to sinistral transpression caused by eastward motion of the Caribbean plate relative to the North American plate. These transform movements have produced a series of strike-slip related siliciclastic-filled basins on the northern part of the island. Seismic reflection data suggest that the offshore margin south of Dominican Republic is an active margin with oceanic crust under thrusting the island-arc (Duval et al., 1982). In adjacent areas, tectonics coupled with eustatic sea level
changes produced carbonate build-up (Draper et al., 1994a). The long-term regional tectonic uplift has produced a series of reef terraces in such that the oldest terrace has higher elevation than the youngest terrace.

Figure 1.1. Maps of study area. A. Present day tectonic map of the Caribbean showing study location in pink, which located at sinistral transpression zone caused by eastward motion of the Caribbean plate relative to the North America (redrawn from Mann, 1999). B. Geologic map of the Southern Dominican Republic showing the Pleistocene terraces belt in blue and study location is highlighted by the pink square. The study area is tectonically located in front of Los Muertos subduction zone, between the island-arc and San Pedro Forearc Basin. C. Digital Elevation Model showing traceable reefs terraces elevation. The image was colored to represent different altitude from yellow (6m), green (15m), orange (30m), blue (45m), and red (60m). The Boca Chica core transect (red dots) is oriented perpendicular to the terraces strike.

1.4.2 Geology of Study Area

A core transect perpendicular to the coastline was drilled on the reef terraces near the town of Boca Chica, Dominican Republic (Figure 1.1C) and about 50 outcrops were sampled from rock-mining quarries around Boca Chica and ground excavations in Santo Domingo.
Outcrops of fringing reef carbonates form a series of terraces along the southern coast of the Dominican Republic. These terraces extend for about 150 km, with a general east-west orientation (Figure 1.1B). Based on digital elevation model (DEM) images, four major terraces elevations are observed: 6 m, 15 m, 30 m, and >50 m (Figure 1.1C) (Barrett, 1962). These reef terraces are predominantly grain- or mud-supported skeletal carbonate (wackstone, packstone, grainstone), skeletal reef debris deposits (floatstone, rudstone), and in-situ coral-algal framework (boundstone). The reefs grew in a tropical climate and a humid climate (Haggerty, 1989) with depositional environments that include backreef, reef crest, reef front, and fore reef. The oldest terrace is ~2 million years old and the youngest terrace is about ~125 thousand years old, measured from isotope dating of aragonitic corals (Schubert and Cowart, 1980; Mann et al, 1995). The age of the youngest terrace most likely represents Marine Isotope Stage 5e (MIS 5e), indicating the reef terraces was formed during the last interglacial sea level highstand.

The coupling of the tectonic uplifting and sea level fluctuations drove the deposition and post-depositional alteration of these reefs. The change of depositional environments vertically observed in the outcrops and the cores is evidence of sea level fluctuations through time. Exposure-related features are common; distinct elevations of reef terraces, common dissolution vugs and moldic porosity, calcrete, and soil breccia caps on each reef terrace (Figure 1.2)
1.4.3 Reefal Depositional Environment

Klaus et al. (2011) documented four major depositional environments (backreef, reef crest, reef front, and fore reef) based on coral taxonomic composition from a series of material recovered in five core borings. The determination of depositional environment considers the relative abundance of environment indicative coral species, coral species richness, percentage of reef crest indicator coral (*Acropora palmata*), coral growth form, and the general
texture of the matrix sediments. Backreef is dominated by columnar and massive colony shapes, including *Montastrea annularis* s.s. organ-pipe variance *Montastrea* and *Siderastrea siderea*. Reef crest is composed of a mixture of branching size and massive forms, and is dominated by *Acropora palmata*. Reef front is dominated by extremely large colonies of columnar and massive, wall thick- forms, which are primarily *M. annularis* s.s or pipe *Montastrea* and branching form, *Acropora cervicornis* and platy-like form (*Agaricia sp.*) (Klaus and Budd, 2003). Fore reef consist of largely grains of coralline red algae packstone to grainstone, foraminifera, and the marked decrease in coral of any form. A schematic depositional facies zonation of the reef from backreef to fore reef facies illustrates these major depositional settings (Figure 1.3).

### 1.4.4 Meteoric Diagenesis Environment

The reefal terraces have been subaerially exposed due to the regional uplift and the fluctuation of eustatic sea level. Meteoric diagenesis involves under-saturated (acidic) water as the alteration agent, mainly in the form of rainwater. The meteoric water percolates downward through the carbonates and can dissolve grains and matrix until the dissolution potential of the fluid is reached, this dissolution creates secondary porosity, and once saturated these fluids precipitate secondary carbonate minerals and cements. The meteoric environment is divided into two zones based on the position relative to water table: vadose and phreatic zone (Figure 1.4). Hernawati (2011) synthesize the criteria to distinguish vadose and phreatic zone using petrographic and
geochemistry analysis. Vadose zone is characterized by smaller and meniscus calcite cement, preservation of aragonite, wide range of $\delta^{13}$C and $\delta^{18}$O, and variable strontium concentration. Phreatic zone is characterized by larger and better distribution of calcite cement around grains, pervasive low-Mg calcite mineralogy, a narrow range and positive covariance of $\delta^{13}$C and $\delta^{18}$O, and significant decrease of strontium concentration in sediments.

![Diagram of fringing reef depositional environments](image)

**Figure 1.3.** Schematic fringing reef depositional environments of southern Dominican Republic. The colors in description header correspond to colors in the reef profile. Typical rock examples are given for each depositional environment with the red line pointing to its relative position or depth in the profile. Bar scale for each picture is 2mm (modified from Klaus et al, 2011).
Figure 1.4. Meteoric diagenesis profile and typical cement associated with meteoric diagenesis (from James and Choquette, 1983).
CHAPTER 2

METHODS

2.1 Sample Collection and Preparation

This study uses core plugs from five cores of 20 - 60m length, fourteen 1 m cores, and several outcrop samples to characterize the petrophysical properties of the reefs. These samples were taken from the various lithologies, depositional environments, and diagenetic features in the downstepping reefal successions (Figure 2.1).

Figure 2.1. Schematic cross-section of the studied Pliocene - Pleistocene reefal successions that form the terraces on the south coast of the Dominican Republic. For this petrophysical study 170 samples (1 inch cylinders) were cut from outcrop samples, short 1-m cores and the 5 longer cores. For the location of the transect see Figure 1.1. (Figure from Klaus et al., 2011).

One hundred and seventy of one-inch diameter cylindrical plugs with variable lengths were drilled for petrophysical measurements. Plugs were sampled from the cores and outcrop samples using a water-cooled diamond drill bit with vertical and horizontal orientation. The ends of the plugs were cut off and
then polished within 0.01 mm precision (measured with a micrometer gauge) to create flat surface for optimizing contact area between sample and sonic or electric transducers. Samples were dried at 60°C for 48 hours and then stored in a desiccators box for approximately 24 hours. The dry-mass of the samples were measured to the microgram using a Thomas Scientific T200S electronic scale. Chips from one end of each plug were sent to the University of Iowa’s Geology Department for thin section preparation.

The labeling systems of samples from cores are based on the following format: core name, sampling orientation, and depth. For example BC1V5; core Boca Chica 1, vertically sampled, depth: 5 meter from core top. Thin sections and petrophysical measurements are consistent with sample labels. All the samples and measurement result are stored in CSL-Center for Carbonate Research at University of Miami.

### 2.2 Petrophysical Measurements

Petrophysical measurements include electrical resistivity, ultrasonic velocity, porosity, permeability, and density. Figure 2.2 shows the workflow of the measurements performed. Samples from the cores were selected to represent various reef depositional lithofacies. Textures of carbonates were described according to the Dunham (1962) and Embry & Klovan (1971) classifications. Stratigraphic and diagenetic studies were conducted using the same dataset by other authors (Klaus et al., 2011; Hernawati et al., 2011) as part of the Dominican Republic Drilling Project by the CSL- Center for Carbonate Research at the University of Miami.
Porosity (phi) was calculated for the 170 samples using the following formula:

\[
\text{Porosity} = \frac{\text{Bulk Sample Volume} - \text{Grain Volume}}{\text{Bulk Sample Volume}}
\]

The volume of the sample, length and diameter of the plugs were measured using a digital caliper to within 0.01 mm precision. These parameters were measured on three different angles to reduce any error caused by imperfections in plug shape. The average values from three measurements were then used for the bulk sample volume calculation. The grain volume was measured using Micromeritic Accupyc 1330 helium pycnometer, with error of 1%. Error in the porosity measurements can be attributed to error in the length measurements (± 0.01 mm) and the standard deviation of the pycnometer (± 0.04 cm³).
Density

Grain density, dry bulk density, and wet bulk density of all the samples were measured using the following formula.

\[ Rhog = \frac{\text{Mass}(g)}{\text{Grain volumes}(cm^3)}; \]
\[ Rhob_{\text{dry}} = \frac{\text{Mass}(g)}{\text{Dry bulk volume}(cm^3)}; \quad Rhob_{\text{wet}} = (1.02 \times \phi) + Rhob_{\text{dry}} \]

Grain density (Rhog) is defined as the mass of the sample per volume of grains. Dry bulk density (Rhob\text{dry}) is the rock mass divided by its total dry volume. Wet bulk density (Rhob\text{wet}) is calculated with the assumption that the pores are 98% saturated with a 35 ppt solution of NaCl (sea water) and density of the pore fluid is 1.02 g/cm³.

Permeability

Seventy samples were selected for permeability measurement to represent the porosity range. The samples were selected based on porosity, ranging from 0.09 to 0.54. Permeability measurement was performed by TerraTek-Schlumberger (Salt Lake City, Utah) using the Klinkenberg - corrected air permeability method (Klinkenberg, 1941).

Electrical Resistivity

Electrical resistivity measurement was performed for the same 70 samples that were used for permeability measurement. The methodology is described in detail by Verwer et al. (2011). Complex electrical resistivity was measured using...
Figure 2.3. A. Schematic diagram of the resistivity system. B. Schematic cross section of the resistivity meter. (Modified from NER Autolab 1000 manual).
a four-electrode technique (Figure 2.3A), and measured over a range of frequencies (0.01 Hz to 100 KHz) created by a function generator at 3 MPa effective pressure (5 MPa confining pressure and 2 MPa pore pressure) using a New England Research (NER) Autolab 1000 system (Figure 2.3B). Before measurements, the samples were saturated with 35 ppt NaCl, placed under a vacuum for 48 hours, mounted in the transducer, jacketed by a rubber sleeve, and eventually placed in the pressure vessel. The voltage (signal) across the reference resistor and sample was recorded by a digital oscilloscope. The electrical resistivity of the sample was determined using the amplitude ratio and the phase shift between signals from the reference resistor and sample.

To avoid sample damage, the velocity measurement was conducted at 3 Mpa. Ten samples with permeability lower than 0.01 md were excluded from this measurement because the pore fluid could not fully saturate the pores. Therefore, only 60 pairs of permeability and electrical resistivity data are available.

**Ultrasonic Velocity**

Ultrasonic velocity was measured on 155 samples using a pulse transmission technique (Birch, 1960) with a NER Autolab System 1000 in the CSL Petrophysics Laboratory at University of Miami (Figure 2.4). Before the ultrasonic velocity measurement, the samples were saturated with degassed water in a vacuum chamber for 48 hours (~98% saturation). The amount of saturation was calculated by comparing dry and wet bulk density. For the measurement, the samples were jacketed in a rubber sleeve to seal the sample
from confining oil in the pressure vessel and placed between transducers. The transducers were then mounted in the pressure vessel to be measured for the velocity.

An ultrasonic pulse with a center frequency of 1 MHz, was propagated along the sample axis by a source transducer and recorded by a receiver transducer. The velocity was calculated as the ratio between the length of a sample and one-way travel time. Ultrasonic P-wave velocity \((V_p)\) and two orthogonally polarized independent S-wave velocities \((V_{s1}, V_{s2})\) were measured as a function of pressure and the shear wave velocity \((V_s)\), which was reported as the average of \(V_{s1}\) and \(V_{s2}\).

Measurements were conducted at four confining stresses \((P_c)\): 5, 7, 10, and 12 MPa with a constant pore pressure of 2 MPa. Fifty samples from the outcrops were measured with a \(P_c\) of up to 22 Mpa. The velocity of the first arriving waveforms, traveling one way, were measured and recorded. As confining pressure was increased, the velocity evolution was checked to ensure if there was any sample breakage during measurement. Acoustic velocities at 5 Mpa effective pressure were reported. Error in the velocity measurements is estimated to be approximately 3%, caused by sample length variations and the precision of the first arrival picking. Porosity measurement was performed again after the velocity measurements to check for any changes in porosity.
2.3 Petrographic Analysis

Petrographic analysis of the thin sections were performed using Olympus BH2 petrographic microscope with the following features being qualitatively determined: carbonate rock textures (Dunham, 1960 and Embry & Klovan, 1971),
pore types (Choquette & Pray, 1980), and diagenetic features such as cementation, micritization, dissolution, and recrystallization. The results reveal relationships between textures, pore types, and diagenetic fabrics to the petrophysical properties. Particular diagenetic features, such as micritic rims, syntaxial overgrowth, dogtooth spar, and meniscus cement, were also documented to distinguish zones within the meteoric diagenesis realm.

2.4 Digital Image Analysis

Digital image analysis (DIA) of 138 thin sections was performed using the methodology developed by Weger (2006). The method allows for quantification of pore space parameters from digital images of thin sections. In two studies by Weger et al. (2009) and Verwer et al. (2011), these DIA pore space parameters reveal an excellent correlation to acoustic velocity, electrical resistivity, and permeability. DIA consists of three basic steps: (1) image acquisition, (2) image segmentation, and (3) calculation of pore geometry parameters.

Full area images of thin sections (1-inch diameter) were acquired using an Olympus C-4040 digital camera attached to an Olympus BH2 petrographic microscope. The images were acquired using plane and cross-polarized light at 6.6-µm horizontal resolution. The software package “Erica” was used to separate pores from matrix (image segmentation) and to calculate the pore parameters. Thirty different pore parameters are given as the output. The following table is a description of several significant pore parameters Weger (2006) for this study.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Formula</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma ($\gamma$)</td>
<td>$\frac{Perimeter}{2\sqrt{\pi Area}}$</td>
<td>Gamma is defined as ratio between pore perimeter and pore area of an individual pore normalized to circle (Anselmetti et al., 1998). Gamma ($\gamma$) describes roundness of the pore, with a perfect circle having a gamma equal to one.</td>
</tr>
<tr>
<td>Dominant pores size (DomSize)</td>
<td></td>
<td>Dominant pore size (DomSize) is determined as the upper boundary of pore sizes of which 50% of the porosity on a thin section is composed. Half of the pore space of an area is composed of pores as big as or smaller than the DomSize.</td>
</tr>
<tr>
<td>Total pore perimeter over total pore area (PoA)</td>
<td>$\frac{\sum Perimeter}{\sum Area}$</td>
<td>Perimeter over area (PoA) is the ratio of the sum of total perimeter of the pores and total pore area identified in the thin section. It can be regarded as 2D equivalent to specific surface, which is ratio between the pore surface and pore volume. At the same porosity, the smaller the PoA, the simpler the pore geometry is and the larger the number, the more intricate the pore geometry.</td>
</tr>
</tbody>
</table>

*Table 2.1 Description of pore parameters as given by Weger (2006).*

**2.5 Multivariate Linear Regression Analysis**

Multivariate linear regression was performed to quantify trends among the petrophysical properties and the DIA parameters. The following formula was used.
\[ y = C_0 + \sum_i c_{i+1} x_i + e = y_{est} + e \]

\( y \) represents the measured petrophysical property (i.e. acoustic velocity, permeability, electrical resistivity). \( x_i \) represents measured independent variable/s (i.e. porosity, DIA parameters). \( c_0 \) and \( c_i \) are constants to be determined during regression. \( y_{est} \) represents the estimated value of \( y \). \( e \) is the estimation error of the analysis.

The \( e \) would contain any unknown influences on the \( y \). The goal of the regression analysis is to minimize \( e \) by finding the best constant or combination of constants so that the estimate best fit the originally observed data. The coefficient of determination (\( R^2 \)) was used to evaluate whether the addition of the DIA parameter improved the prediction or not. This analysis was conducted to examine the relationship between porosity - acoustic velocity - DIA parameters and porosity - permeability - DIA parameters.
CHAPTER 3

PETROPHYSICAL PROPERTIES OF PLIO-PLEISTOCENE REEFAL CARBONATES OF THE DOMINICAN REPUBLIC

Overview

Core and outcrop samples of the southern Dominican Republic reefal carbonates provide an opportunity to characterize the petrophysical properties and to analyze their relationships with the sedimentological and diagenetic properties. Laboratory measurements document a wide range of petrophysical properties, which include: porosity, permeability, acoustic velocity, and electrical resistivity. The sedimentology and diagenesis analyses describe the complexity and heterogeneity of the reefal carbonates fabric in each environment (Klaus et al., 2011; Hernawati, 2011). Petrographic analyses are conducted in the regards to the sedimentology and diagenesis previously described. The petrophysical properties are compared to assess their relation to each other and for external comparison, for instances: porosity-permeability, porosity-acoustic velocity. The petrophysical properties are then analyzed based on petrographic observations in order to assess a correlation between petrophysical properties and depositional / diagenetic environments.
3.1. Depositional Lithofacies and Diagenesis of the Reefal Carbonates

3.1.1 Depositional Lithofacies Description

The reefal carbonates in the study area are divided into four depositional environments; backreef, reef crest, reef front, and fore reef based on the coral species occurrences (Klaus et al., 2011). To complement the coral faunal analyses, a description of the carbonate textures and fabrics within each facies is also included. The following paragraphs describe the basic textures and fabrics of sediments within each depositional environment. The vertical successions of these facies are depicted in stratigraphic columns (Appendix 1).

**Backreef facies**

Backreef environment is an area in between the shoreline and reef crest. Backreef samples were recovered from core-1 and several outcrop localities. The textures of the backreef lithofacies are branching coral boundstone, coral floatstone, mollusk rudstone, and laminated grainstone (Table 3.1). The matrix in the floatstones samples are generally wackestone to packstone. Wackestone to packstone are also observed around the coral boundstone. Skeletal grains, including mollusk fragments (abundant), benthic foraminifera (miliolidae), red algae, *Halimeda*, and peloids are the major constituents of the backreef. Sand size siliciclastic minerals and lithoclasts are observed as minor constituent (<10%). Bioturbation fabrics are the dominant sedimentary structure. Lamination and fenestral pore structure are observed in the grainstone facies. The textures of the backreef lithofacies are branching coral boundstone, coral floatstone, mollusk rudstone, and laminated grainstone (Table 3.1).
Coral growth is patchy and consists mostly finger or branching morphologies. The abundance of micrite and intense bioturbation indicates the environment had a calm wave action and less bottom agitation, allowing bottom dweller organism to flourish (James, 1983). The mollusk rudstone with abundant cerithids gastropods is a clear indicator of restricted marine environments (Bergman et al., 2010). The presence of fenestral pores and unidirectional low angle cross lamination in bioclastic grainstone facies indicates an existence of a wave action in the backreef at certain periods. These sedimentary structures are indicators of the upper shoreface in the intertidal zone (James, 1979; Shinn, 1983). In conclusion, backreef environments in the study area predominate by mud-rich textures with patchy corals. However, spatial variations are evident with the deposition of coarser grain textures (Figure 3.1).

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Components and Sedimentary structures</th>
<th>Matrix</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branching coral boundstone</td>
<td>Branching coral (<em>A. cervicornis, Porites porites</em>). Heavily bioturbated</td>
<td>Wackestone to packstone (abundant red algae and <em>Halimeda</em>)</td>
<td>Core-1 &amp; outcrop (O)</td>
</tr>
<tr>
<td>Coral Floatstone</td>
<td>Coral rubble (<em>A. Palmata</em>). Bioturbation .</td>
<td>Packstone</td>
<td>Core-1, 3, &amp; O</td>
</tr>
<tr>
<td>Mollusk rudstone</td>
<td>Mollusk (gastropod and bivalve).</td>
<td>Packstone to grainstone (peloid rich)</td>
<td>Core-1 &amp; O</td>
</tr>
<tr>
<td>Laminated grainstone</td>
<td>Red algae, <em>Halimeda</em> &amp; mollusk fragments. Parallel lamination to low - angle cross lamination, fenestrae.</td>
<td>(-)</td>
<td>Core-1 &amp; O</td>
</tr>
</tbody>
</table>

*Table 3.1. Summary of the backreef lithofacies, their main components, and sedimentary structures.*
Reef crest facies

The reef crest is the highest part of the reef that receives the most energy from wind and wave (Geister, 1980; James, 1983). Reef crest samples were recovered from all the cores except core-1. Reef crest in the study area is indicated by the presence of corals *A. palmata* or *Stylophora* sp. (40-50 m terraces and core-2) and branching coral species (*Acropora cervicornis*) preserved in growth position and encrusted by calcareous algae. The matrix in this environment is comprised of skeletal packstone to rudstone with grain sizes...
ranging from 100 µm up to about 2.5 mm. Coral in growth position and skeletal fragments are the major constituents in the reef crest. The lithofacies in reef crest are branching coral boundstone, coralgal boundstone, coral rudstone, and skeletal packstone to grainstone.

The absence of mud in the reef crest lithofacies reflects a depositional environment where the water energy is strong enough to winnow out the mud. Due to favorable condition to support coral growth and associated encrusting red algae, the lithofacies in the reef crest are largely composed of boundstone (Figure 3.2), with variation in coral shape from massive to branching, intercalated with coarse skeletal packstone to grainstone. Open vugs in this environment are common that presumably due to a diagenesis or bioerosion (Figure 3.2).

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Components and sedimentary structure</th>
<th>Matrix</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branching coral boundstone</td>
<td>Branching coral (<em>A. cervicormis</em>, <em>P. porites</em>). Massive</td>
<td>Packstone to grainstone. Skeletal grains and fragments of coral, mollusk, algae, echinoid, worm tubes. Massive</td>
<td>Core-2,3,4 &amp; O</td>
</tr>
<tr>
<td>Coralgal boundstone</td>
<td>Dense coral spacing, various shape and species coated by encrusting algae. Massive</td>
<td>Grainstone to rudstone. <em>Halimeda</em>, red algae, mollusk and coral fragment, echinoid spines.</td>
<td>Core-2,3,4,5 &amp; O</td>
</tr>
<tr>
<td>Skeletal packstone to grainstone</td>
<td>Skeletal grains or fragments of mollusk, <em>Halimeda</em>, red algae, echinoid spines, and benthic foraminifera. Massive.</td>
<td>(-)</td>
<td>Core-2 &amp; 4</td>
</tr>
</tbody>
</table>

*Table 3.2. Summary of the reef crest lithofacies, their main components, and sedimentary structures.*
Figure 3.2. Photomicrograph of the reef crest matrix showing skeletal components interactions in the reef crest cemented together with microbial and meteoric cements. There is abundance of encrusting organisms: red algae, foraminifera. The open vug possibly resulted from bioturbation. Co: coral, EA: encrusting algae, MC: meteoric cement, EF: encrusting foram, SM: skeletal matrix. Plane polarized. Blue epoxy dyed. Scale bar: 5 mm.
Reef front facies

Reef front is a transition zone from the reef crest to the fore reef. It extends from the surf zone and ends where the skeletal/coral growth is more limited (James, 1983). The reef front samples were recovered from the cores and outcrop samples. Reef front samples are characterized by the abundance of branching coral growth morphologies. The matrix is predominantly packstone consisting of skeletal fragments and minor silt to coarse sand silicilastic grains (Figure 3.3). The appearance of muddier matrix implies the decrease in wave action in this environment allowing mud to settle. The matrix constituents are red algae (abundant) and echinoid spines, Halimeda, and mollusk molds. Generally, the matrix and larger skeletal grains in the reef front are more micritized than the reef crest (Figure 3.3). Sedimentary structures in the reef front include geopetals and bioturbation (Figure 3.3C). Bioturbation structures may be an indicator of calmer water energy. Summary of lithofacies in the reef front is given in Table 3.3.

<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Components and sedimentary structure</th>
<th>Matrix</th>
<th>Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td>Branching coral boundstone</td>
<td>Branching coral (A. cervicornis, Porites p.), coral skeleton mostly preserved.</td>
<td>Packstone to grainstone Skeletal grains and fragments of coral, mollusk, benthic foraminifera, echinoid, algae. Red algae commonly preserved.</td>
<td>Core-1,2,3,4,5 &amp; O</td>
</tr>
<tr>
<td>Branching to platy coral boundstone</td>
<td>Branching to platy coral form.</td>
<td>Packstone with red algae rich and mollusk molds, and minor silicilastic grains and lithoclasts.</td>
<td>Core-2,3,4 &amp; O</td>
</tr>
<tr>
<td>Skeletal wackestone-grainstone</td>
<td>Mostly skeletal fragments; Red algae (abundant and preserved), benthic foraminifera, echinoid spines, mollusk fragments, silicilastic grains, and lithoclasts (silt to sand).</td>
<td>(-)</td>
<td>Core--1,2,3,4,5 &amp; O</td>
</tr>
</tbody>
</table>

Table 3.3. Summary of the reef front lithofacies, their main components, and sedimentary structures.
Fore reef facies

Fore reef deposits were only recovered from the subsurface (core-3) due to its position at the toe of reef clinoform. This environment consists of medium to coarse-grained packstone to grainstone lithofacies with an abundance of skeletal fragments, predominated by coralline red algae, larger benthic foraminifera (Amphistegina sp.), and planktonic foraminifera (Figure 3.4). Most of the skeletal constituents are similar to those reef crest and reef front, but are broken apart, except planktonic foraminifera. This implies the skeletal grains in the fore reef
were transported from the shallower environments. The common occurrence of planktonic foraminifera indicates lower water energy that allows the planktonic foraminifera to settle from suspension. Other minor constituents are segmented peloids, Halimeda, corals, and mollusks (Figure 3.4). *Halimeda* grains, which usually dissolved away in other environments, occur in this particular environment as calcified grains (Figure 3.4 A & D). No sedimentary structures are observed. Moldic and interparticle porosity is common to abundant in the fore reef (Figure 3.4 B). Well-cemented intervals occur at 64-65m and 67-69.5m within core-3 (Figure 3.4 C).

**Figure 3.4.** Photomicrographs of representative fore reef lithofacies samples. A. Skeletal packstone with *Halimeda*, planktonic foraminifera, and peloids. B Porous samples with most of the bioclasts are leached away, leaving moldic and interparticle porosity. C. Well-cemented interval in fore reef facies. D. Micritized grains are abundant in the fore reef facies. Plane polarized; scale bar A-C: 1mm, D: 500 µm.
3.1.2 Reefs Stratigraphic Architecture

The architecture of the prograding reefs of southern coast of Hispaniola was constructed by Klaus et al. (2011) using radiometric dating as the age constraint and the correlation of possible subaerial exposure surfaces (Figure 3.5A). At the surface, the exposed terraces form low-angle (5-7° foreslope, ~1° topset) sigmoidal clinoform. The depositional environment vertical successions from the cores (Figure 3.5B) and the stacking pattern of each reef sigmoid through time were interpreted by Klaus et al. (2011).

Figure 3.5. Preliminary stratigraphic cross-sections of the Dominican Republic reef terraces based on the lithologies recovered in the 5 cores. A. The geometry of prograding reef clinoforms with the exposure surface correlation (dashed line) and shallowing upward cycle (triangles) interpreted from each well. B. Klaus et al. (2010) interpretation of the depositional clinoform stacking pattern of the prograding reefs. Pale blue: backreef, yellow: reef crest, green: reef front, and dark blue: fore reef.
3.1.3 Diagenetic Features

The reefal carbonates bear the mark of two major diagenetic environments; early marine and meteoric. Bulk sample mineralogy from X-ray Diffraction (XRD) show mostly Low-Mg Calcite (LMC), except in the upper portion of core-4 and 5. Dolomite occurs in core-3 (42m-70 m) and core-4 (38-60 m). Dolomite rhombs (10-15 µm) fill pores and micron sized dolomite replaces pre-existing bioclasts (Hernawati, 2011). Other diagenetic features include: sub-aerial exposure surfaces, micritization, dissolution, and cementation. They are all observed in thin sections as well as in the outcrops. The general paragenesis of the reef succession described by Hernawati (2011) is summarized in Table 3.4.

<table>
<thead>
<tr>
<th>Diagenetic Event</th>
<th>Marine</th>
<th>Meteoric</th>
<th>Un-known</th>
</tr>
</thead>
<tbody>
<tr>
<td>a. Micritic rims</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b. Micritic cement network</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c. Isopachous cementation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(fibrous to bladed aragonite)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Aragonite dissolution and calcitization</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) Paleosol and calcrete development</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) Meniscus or droplet cementation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5) Dog-tooth cementation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6) Blocky calcite cementation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7) Matrix and bioclast dissolution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8) Matrix neomorphism (microspar replacement of micrite)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9) Dolomite precipitation</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.4. General paragenetic trends observed in thin section samples (modified from Hernawati, 2011).

Sub-aerial exposure features can be observed in the outcrops as calcrete, soil breccia, dissolution vugs, root cracks, paleosols, and speleothems. Petrographic analysis shows the occurrence of soil related structures such as:
soil breccias, oncoids, and alveolar structures. These features mainly occur in and adjacent to sub-aerial exposure surfaces.

Micrite occurs in the sample in four modes: micritic envelope, cement, matrix, and grains. A micrite envelope is a micrometer dark rim surrounding the grain, and is observed in a majority of the samples (Bathurst, 1974) (Figure 3.6C). In some samples, a micritic envelope occurs that is associated with calcrete and paleosols. In this occurrences, the envelope has a reddish color and thicker than normal, and has irregular thickness. Micrite also forms as cement with a structure that looks like filaments connecting two grains. This is also called alveolar structure (Tucker and Wright, 1990) or micritic filaments (Hillgärtner et al., 2001) (Figure 3.6 G and H).

Cementation occurs more significantly in the coarser grain facies. In the backreef wackestone, cementation is very limited. Cementation occurred in three successive stages and the complete sequence can be observed in the deeper fore reef facies. The earliest cements consist of isopachous coatings of fibrous aragonite cement or radiaxial bladed calcite lining the surface of the original interparticle pore system (Figure 3.6D). These early coatings are commonly very thin to absent and followed by either thicker meniscus calcite cements or dogtooth like cements (Figure 3.6 A, B, E, F, and G). The last step of cementation is a blocky calcite cement infilling the interparticle or intraparticle pore system. In the oldest reefal clinoform (core-2 and 45-60 m terrace), the cements overprint each other and the sequence abovementioned of cementation is difficult to recognize (Figure 3.6C).
Dissolution of carbonate minerals occurs selectively. Original aragonite bioclasts, such as mollusks and *Halimeda*, are generally observed as molds rimmed by micrite or completely filled by granular or blocky calcite. Calcite bioclasts such as red algae or foraminifera only suffer partial dissolutions. In the muddy facies, the dissolution is limited to the bioclast, whereas in the grain-dominated fabrics, dissolution occurs on both the grains and matrix, creating moldic and vuggy pore types. Vuggy porosity intensifies with the occurrence of calcrete adjacent to sub-aerial exposure surfaces.

*Figure 3.6. Photomicrographs of diagenetic features in the reefal carbonates. A. Skeletal grainstone with meniscus cement in the vadose zone (plane polarized, scale 250 μm). B. Skeletal packstone cemented by circum-granular cement in the phreatic zone (xpl, scale 250 μm). C. Tightly cemented skeletal grainstone. The skeletal grains are leached away and occluded with blocky calcite (bc). The resemblance of skeletal grains is created by the preserved micrite envelopes (plane polarized, 250 μm). D. Isopachous fibrous cement (iso) as a sign of early marine diagenesis (plane polarized, 1 mm).*
3.1.4 Diagenesis Interpretation

A meteoric diagenetic overprint is clearly indicated by the co-existence of subaerial exposure features in the outcrop, for instance; calcrete, soil breccia, dissolution vugs, root marks, paleosol, and speleothems (Esteban and Klappa, 1983). The bulk-sediment stable-isotope compositions of the outcrop and core samples (Hernawati, 2011) are notable for their strongly depleted carbon values, which are commonly associated with meteoric diagenesis (Allan and Mathews, 1982; Immenhauser et al., 2000).
The majority of modern shallow-water reef mineralogy is aragonite and high magnesium calcite (HMC). Stabilization to low magnesium calcite was likely driven by subaerial exposure processes. The role of meteoric diagenesis in carbonate mineral stabilization is common, as reported in several other pioneering studies (Matthews, 1974; James and Choquette, 1984).

A micritic envelope is the result of carbonates precipitating in microbial borings (Bathurst, 1966). It commonly occurs in marine settings (Longman, 1980). Micritized grains could also be the result of recrystallization that common in shallow-water seas (Reid and McIntyre, 1998). The occurrence of micritic envelopes and micritized grains implies that most of the samples experienced marine diagenesis during deposition. An exception to this is the irregular reddish micritic envelope that occurs in the paleosols.

The cementation stages in the thin sections indicate two diagenetic sequences: marine and meteoric. The marine diagenesis is evident by filling of isopachous and fibrous aragonite-like cements in between particles, similar to those in other studies (Ginsburg and James, 1976; James et al, 1976). Although the current mineralogy is LMC, the isopachous and fibrous shape of the calcite cement can be a good indication of an original aragonite mineralogy, and therefore marine diagenesis (Folk, 1976).

Meteoric cement types are as follows; meniscus spar cement (Dunham, 1971) and circum-granular cement (Moore, 1989). The meniscus spar cement indicates the meteoric vadose zone (Dunham, 1971). The circum-granular cement has two forms; equant and dogtooth, and indicates the meteoric phreatic
zone. Based on the occurrence of these two types of cements, the meteoric environment is divided into two zones: vadose (red) and phreatic (blue) (Appendix 2). The final stage of cementation is the pore-filling blocky cements, which can form in either the vadose or phreatic zone.

Bioclastic dissolution is not a diagnostic of either marine or meteoric realm (Melim et al., 2001). However, this dissolution occurs in most of the samples, producing large amounts of moldic and vuggy porosity. Most of the molds are skeletal grains with aragonite and HMC original mineralogy, such as bivalves, mollusks, and Halimeda. The abundance of vuggy porosity near the subaerial exposure surfaces could be the result of root activities and/or the preferential pathway of percolating meteoric water.

Pervasive dolomite found in core-3 and core-4 occludes the once open pores. The mechanism of dolomite formation in the study area was studied by Hernawati (2011). The study suggested dolomite was formed in near normal marine conditions. The general summary of depositional environments, carbonate fabrics, matrix, and diagenetic features is given in Table 3.5.

<table>
<thead>
<tr>
<th>Depositional Environment</th>
<th>Fabrics</th>
<th>Matrix</th>
<th>First Cement</th>
<th>Overprint</th>
<th>Diagenesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>backreef</td>
<td>mud to grain supported</td>
<td>mudstone-wackstone</td>
<td>Vadose</td>
<td>Microporosity, Moldic</td>
<td></td>
</tr>
<tr>
<td>reefcrest</td>
<td>coral framework</td>
<td>packstone-grainstone-floatstone-rudstone</td>
<td>Vadose &amp; Phreatic</td>
<td>Moldic, Intraframe, vuggy</td>
<td></td>
</tr>
<tr>
<td>reefront</td>
<td>coral framework</td>
<td>packstone-grainstone-floatstone-rudstone</td>
<td>Vadose &amp; Phreatic</td>
<td>Microporosity, Moldic, Intraframe</td>
<td></td>
</tr>
<tr>
<td>forereef</td>
<td>grain supported</td>
<td>packstone</td>
<td>Phreatic</td>
<td>Interparticle, moldic</td>
<td></td>
</tr>
</tbody>
</table>

*Table 3.5 Summary of the depositional fabrics and diagenesis features of the reefs.*
3.2. Petrophysical Properties of the Reefal Carbonates

3.2.1 Petrophysical Properties

The petrophysical properties of the reefs show a remarkably wide range of values (Table 3.6). Reservoir properties such as porosity and permeability have outstanding characteristics with porosity ranging from 0.07 to 0.54 and permeability ranging 6 magnitudes from 0.01 milidarcy (md) up to 2 darcy (d). The velocity of the compressional wave, p-velocity (Vp) at 5Mpa effective pressure, ranges from 2900 to 6137 m/s with departures up to + 2000 m/s from Wyllie time average curve of calcite at any given porosity. Electrical properties such as the cementation factor also show a significant range with values between 2.1 to 5.3.

<table>
<thead>
<tr>
<th>Property</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity (fraction)</td>
<td>0.07</td>
<td>0.54</td>
<td>0.2879</td>
<td>0.1002</td>
</tr>
<tr>
<td>Permeability (md)</td>
<td>0.01</td>
<td>1.94x10^4</td>
<td>763.1</td>
<td>2806</td>
</tr>
<tr>
<td>Vp (m/s)</td>
<td>2898</td>
<td>6137</td>
<td>4538</td>
<td>705.5</td>
</tr>
<tr>
<td>Vs (m/s)</td>
<td>1506</td>
<td>3069</td>
<td>2364</td>
<td>363.5</td>
</tr>
<tr>
<td>Grain Density (g/cm^3)</td>
<td>2.56</td>
<td>2.91</td>
<td>2.73</td>
<td>0.05</td>
</tr>
<tr>
<td>Cementation factor</td>
<td>2.109</td>
<td>5.29</td>
<td>3.199</td>
<td>0.5448</td>
</tr>
<tr>
<td>Formation factor</td>
<td>8.174</td>
<td>308.1</td>
<td>71.49</td>
<td>59.89</td>
</tr>
<tr>
<td>Vp/Vs</td>
<td>1.521</td>
<td>2.578</td>
<td>1.923</td>
<td>0.1204</td>
</tr>
<tr>
<td>Impedance x 10^7 (kg/m^3)(m/s)</td>
<td>0.53</td>
<td>1.50</td>
<td>1.02</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Table 3.6. Petrophysical property ranges of the reefal carbonates.

3.2.2 Porosity and Permeability

3.2.2.1 Result

The porosity of plug samples is normally distributed with an average of 0.29 ± 0.1. The porosity ranges from 0.07 to 0.54. Average values for the
depositional facies are: backreef (0.27 ± 0.08), reef crest (0.27 ± 0.1), reef front (0.3 ± 0.09), and fore reef (0.33 ± 0.08) with a 0.22 minimum porosity (Figure 3.7).

Figure 3.7. Porosity histogram of the depositional environment with a bin frequency of 0.05. These histograms show that porosity range is not unique to the depositional environments in the study area. Fore reef environments have the best porosity ranges among the depositional environments.

Porosity is notably different in the outcrop samples and the core samples (Figure 3.8). The surface samples (black histogram) have lower porosity than the core samples (grey histogram), regardless of the environment. The outcrop samples are taken at the present exposure surface. Petrographic analysis
indicates that cement is more abundant in the surface samples than core samples.

![Figure 3.8. Porosity histogram for outcrop samples (black) and core samples (grey). Samples from the outcrop have a lower porosity than core samples.](image)

Permeability ranges from 0.01 md to 19400 md. This wide range of permeability exists at all porosity values. For example, at 0.18 porosity permeability has a range of $10^5$ md; at 0.42 porosity it also has a range of $10^4$ md (Figure 3.9). The relationship of porosity-permeability and depositional environment is shown in Figure 3.10. Permeability varies significantly in all environments: backreef (0.04-6760 md; mean: 4.23 md), reef crest (0.01-19364 md; mean: 17.5 md), and reef front (0.02-5800 md; mean: 4.32 md)). The fore reef environment has the narrowest range (0.8-333 md; mean: 23 md) (Figure 3.10A).
Figure 3.9. Porosity (X axis) vs. permeability (Y axis) log scale cross-plot. Permeability varies up to 5 orders of magnitude at any given porosity.

Figure 3.10. The porosity (X axis) vs. permeability (Y axis) cross-plots. A. Porosity-permeability plot color-coded by depositional environments. Permeability in reef front environments is lower than in reef crest environments. B. Porosity-permeability plot color-coded by diagenetic overprint. The samples with phreatic (blue) overprint have less permeability than the samples altered in the vadose zone.
A trend exists in the porosity-permeability relationship in regards to the diagenetic zones (Figure 3.10B). Samples with mostly meteoric phreatic diagenesis generally have a lower permeability but are higher in porosity than those with a vadose overprint. The reason for this difference is in the more effective pore throat occlusion with circumgranular cements in the meteoric phreatic zone, compared to the meniscus cements forming in the vadose zone.

### 3.2.2.2 Discussion and Interpretation

Permeability in carbonate rocks is predominantly affected by pore type and their connectivity, rather than by the total amount of porosity (Lucia, 1987). The poor porosity-permeability correlation in these reefal samples highlights the difficulty of predicting permeability solely from porosity (Figure 3.10). In general, a combination of the depositional textures and diagenesis analysis can be used to investigate the porosity-permeability trend in the analyzed samples (Figure 3.10).

The wide range of porosities in all depositional environments from the backreef, reef crest, and reef front is related to the wide range of primary textures and the multiple episodes of diagenetic overprint. The facies of the studies reefal successions vary from wackestone to boundstone. After deposition, multiple episodes of meteoric vadose and phreatic diagenesis occluded and created pore spaces through cementation and dissolution. As a result, a variety of pore types such as, moldic, interparticle, intraparticle, intraframe, vuggy, and microporosity
can be observed in the samples. The combination of heterogeneous depositional textures and diagenesis led to the wide range of porosity in these environments.

Porosity in the fore reef environment has a higher and narrower range than in the other reef environments. This narrow range of porosity is a reflection of a less heterogeneous depositional facies and fewer diagenetic overprints. The fore reef samples consist of packstone to grainstone with early marine cementation but a strong meteoric phreatic overprint. Moldic and interparticle pores are the only two pore types that occur in this particular environment. In all other environments, the pore types are more varied and consequently the porosity and permeability are more variable.

The porosity - permeability relationship in the reefal dataset shows an inverse correlation with significant scatter (Figure 3.9). A combination of original depositional lithologies and post-depositional meteoric diagenesis can explain some of the porosity and permeability trend. The coarse-grained fabric in the reefal environments is often altered by meteoric vadose diagenesis. This alteration results in rocks with high permeability at any given porosity. The fine-grained fabrics are mostly altered by meteoric phreatic diagenesis. This alteration creates moldic rocks with small pore sizes (<300 µm) and occluded interparticle pores with circum-granular cement. In several of the wackestone samples cementation is absent and micropores are predominant. As the result, most of phreatic samples have lower permeability than the vadose.

The reef front and fore reef facies has an abundance of muddier and finer grained samples that have undergone meteoric phreatic diagenesis. These
samples have lower permeability at any given porosity than the coarser grained samples that have undergone vadose diagenesis. The lower permeability at any given porosity can be attributed to an abundance of microporosity and small moldic pores. The backreef and reef crest samples with meteoric vadose diagenesis, show a wide range of permeability at any given porosity. For the vadose samples, the highest permeability at any given porosity belongs to the samples with occurrence of connected vugs. These pore types provide a connectivity for fluids to percolate through sample. The lowest permeability is in well-cemented rocks with isolated moldic or vuggy pores. These tight, well-cemented samples (porosity < 0.2 and permeability <10 md) are found in all environments and diagenetic zones.

As described in Subchapter 3.1, the backreef consists of a variety of original rock fabrics. In the backreef, porosity and permeability vary due to cementation and original rock textures. The backreef samples show strong meteoric vadose diagenesis. As in all environments the permeability varies widely based on the combination of original textures and the subsequent diagenetic overprint. Figure 3.11 gives representative samples for the high (A, B, C) and low permeability samples (D, E, F) and their respective texture, diagenetic overprint and resulting pore structure. Samples with high permeability (>10 md) are those with grainstone textures and interparticle pore types. Samples with low permeability (<10 md) are predominately wackestone to packstone samples with microporosity and cemented grainstones.
Figure 3.11. Photomicrographs of backreef samples comparing samples with different porosities and permeabilities. The sample index corresponds to data points in the cross-plot below the pictures. A. Tightly cemented skeletal grainstone with moldic pores. B. Skeletal wackestone-packstone with small moldic porosity and micropores. C. Skeletal packstone. D. Skeletal grainstone with predominant interparticle pores. E. Coral with the highest permeability in the backreef. F. Mollusk rudstone with interparticle porosity. Scale bar 2mm.
Mud-dominated samples (Figure 3.11 B) have more microporosity and show less diagenesis features than grain-dominated samples (Figure 3.11 A, C, D, F). Microporosity (here defined a pore with <30 µm, following Baechle et al. 2008), provides a narrow pathway for the fluid to travel and therefore lowers the permeability. The grain-dominated samples show variations in cementation that is reflected in the petrophysical properties. The high porosity and permeability samples show less cementation (Figure 3.11 D, E, F), whereas the low permeability samples are more tightly cemented (Figure 3.11 A).

The reef crest samples also show a strong overprint of meteoric vadose diagenesis (Figure 3.12). They are comprised mostly of grain-dominated textures or coral fragments. The highest permeability for any given porosity was found in the samples with “touching vug” pore types (Lucia, 1995). These pores are associated with either intense dissolution or calcrete in the vadose zone (Figure 3.12 D, E, F). Samples with lower permeability for a given porosity consist of highly cemented samples and/or those with moldic pore types (Figure 3.12 A, B, C). The samples with meteoric phreatic overprint show an abundance of moldic pore types (Figure 3.12 C, F).

The permeability in the reef front is generally lower than the reef crest at any given porosity. The matrix texture is muddier than the reef crest because its position relatively in the upper slope of a fringing reefs body. Most of the samples are constructed by packstone and overprinted in the meteoric phreatic zone (Figure 3.13). Small moldic pores (<300 µm) and microporosity occur as the
Figure 3.12. Photomicrographs of reef crest samples with different porosity and permeability. The sample index corresponds to data points in the cross-plot below the pictures. A. A well-cemented skeletal grainstone with moldic pores. B. Skeletal packstone with isolated vuggy pores. C. Skeletal packstone (phreatic samples) with abundant small moldic pores. D. Packstone with some interparticle pore types. E. Skeletal packstone with molds and connected vugs. F. Skeletal grainstone that is intensely leached in the meteoric phreatic zone. Scale bar 2mm.
predominant pores. Fine circum-granular (< 100 µm) cements also fill the original interparticle porosity. These combinations of pore type, matrix, - and cement type create isolated moldic pores. The isolated moldic pores do not contribute to permeability although it can create variations in porosity (Lucia, 1995). Therefore, the permeability in this reef front environment with meteoric phreatic overprint is generally low at any given porosity.

Figure 3.13. Photomicrographs of reef front samples, comparing samples with different porosity and permeability. The sample index corresponds to data points in the cross-plot below the pictures. A. Skeletal packstone with abundant moldic pore types. B. Skeletal packstone with moldic pores and abundant circum-granular cementation. C. Skeletal packstone with interparticle and moldic pore types. Scale bar 2 mm.
The fore reef samples have the most uniform textures and diagenesis. They are comprised of bioclastic packstone to grainstones and altered by meteoric phreatic diagenesis. In the fore reef environment with strong phreatic overprint, the porosity and permeability number is a function of the cements and pores (Figure 3.14).

Figure 3.14. Photomicrographs of fore reef samples, comparing samples with different porosity and permeability. The sample index corresponds to data points in the cross-plot below the pictures. A. Skeletal grainstone that is well cemented and has the lowest porosity. B. Skeletal grainstone that is partially leached and thus has a higher porosity than the sample A. C. Skeletal grainstone that is more dissolved and less cemented than A and B has the highest permeability. Scale bar 2 mm.
Vertically in the cores, skeletal packstones and grainstones have a differential cementation (see Appendix 1 core-3 interval 44.2 - 69.5m). In this environment, the permeability depends upon the amount of cement and porosity (Figure 3.14, A, B, and C). The cemented samples have lower porosity and the leached samples have higher porosity.

A linear regression in the fore reef samples between porosity and log$_{10}$ permeability, using equation: Log$_{10}$ (k) =10 x (porosity) - 2.3, results in an excellent correlation ($R^2 = 0.88$). The simple textures and diagenesis leads to a high correlation between porosity and permeability.

3.2.3 Acoustic Velocity

3.2.3.1 Result

Velocities measured under a confining pressure of 7 Mpa and a pore fluid pressure of 2 Mpa are used for the following correlations. The effective pressure of 5 Mpa is high enough for a good signal transmission without fracturing the samples. Compressional wave velocity ($V_p$) varies from 2898 m/s to 6137 m/s. Shear wave velocity ($V_s$) varies from 1500 m/s to 3070 m/s.

Acoustic velocities for the reeval samples have a broad range at any given porosity despite that fact that most of the samples are pure limestones (Figure 3.15). Generally, $V_p$ is high in all samples and shows an inverse correlation with porosity. All samples have $V_p$ values that are significantly higher than velocities calculated at a given porosity with Wyllie’s time average equation. The time average equation of Wyllie et al. (1958) calculates the velocity in a saturated rock as an average between the velocity of the solid, in this case calcite, and the
velocity in the fluid, in this case water. The proportion of the solid versus the fluid phase is given by the porosity, whereby a complete saturation of the pore space with fluid is assumed (Wyllie et al., 1958).

\[
\frac{1}{V_p} = \frac{1 - \phi}{V_{ps}} + \frac{\phi}{V_{pf}}
\]

\(V_p = \) measured p-wave velocity
\(\phi = \) porosity,
\(V_{ps} = \) p-wave velocity of solid phase; \(V_{pf} = \) p-wave velocity of fluid phase

Figure 3.15 Velocity as a function of porosity for the reefal carbonate samples. \(V_p\) and \(V_s\) show an inverse correlation with porosity. \(V_p\) varies up to 1500m/s at any porosity. \(V_s\) has narrower range at porosities lower than 0.25 and a broader range above 0.25.
The velocities are at least 500 m/s higher than Wyllie’s time average curve and can be up to 2000 m/s above the curve (Figure 3.16). Shear velocity shows a narrow range of deviation of less than 500 m/s at porosities lower than 0.25 and a greater range of deviation of up to 1500 m/s at porosities above 0.25.

![Figure 3.16](image)

*Figure 3.16. Vp is high in the reef system with values being at least 500 m/s faster than the Wyllie time average prediction for calcite. At any given porosity, the departure from the Wyllie’s is about +2000m/s. WTC = Wyllie time average curve.*

The effect of increasing pressure (up to 10 MPa) on the velocity evolution is negligible (Figure 3.17). Most the samples exhibit little response in acoustic velocity to increasing effective pressures from 3 to up to 10 Mpa. However, some of the plugs consisting of more friable reef front and fore reef lithofacies disintegrated after 5 Mpa.
Figure 3.17. The velocity evolution of the core samples with increasing effective pressures. Each trace represents the velocities for one sample as the effective pressure changes from 3 to 10 MPa.

In the following, the Vp values at 5 MPa effective pressure are related to the depositional environment and diagenetic overprint (Figure 3.18). The depositional environments do not cause a good separation of velocities but some trends can be observed. At porosities greater than 0.2, the reef crest shows a higher velocity than the reef front and fore reef environment. The textures of the slower reef front and fore reef facies are generally packstone to grainstone with moldic and interparticle pore types. The diagenetic environment has a strong influence on the velocity in the measured reefal carbonates (Figure 3.18). In this data set, samples are grouped
into meteoric phreatic and vadose, assuming all the samples experienced marine diagenesis prior to meteoric diagenesis. Samples with a predominantly vadose meteoric diagenetic overprint tend, at a given porosity, to be faster than samples with a digenetic overprint from the meteoric phreatic zone.

![Figure 3.18. Porosity (X axis) and Vp (Y axis) cross-plots. A. Porosity-Vp plot color-coded by the depositional environment. Reef front and fore reef samples (green and blue dots) have a slightly lower velocity than reef crest samples (yellow dots) at the same porosity. B. Porosity-Vp plots color-coded by the diagenetic environment. The phreatic samples (blue dots) show a higher porosity range and lower Vp values than the vadose samples (red dots) at a given porosity. These two cross-plots emphasize the influence of original depositional facies and diagenetic processes on the acoustic velocity of reefal carbonates. WTC = Wyllie time average curve.]

3.2.3.2 Control on Acoustic Velocity of the Reefal Carbonates

Most of the samples in this data set are calcitic limestones. Thus, the mineralogy is not a factor in the wide range of velocities. In addition, most samples are Pleistocene in age with a few samples of Late Pliocene. Thus velocity variations can not be related to age. Likewise, the burial depth of the measured samples are all within a 100 m and consequently compaction is not a controlling factor in the acoustic velocity variations of these reefal carbonates.
Compressional velocity (Vp) and shear velocity (Vs) are inversely correlated with porosity. Porosity is the main control on velocity of carbonates, as previous studies have reported (e.g., Wyllie et al., 1958; Rafavich et al., 1984; Wang et al., 1991; Anselmetti and Eberli, 1993). Comparison of measured Vp and the theoretical Wyllie’s equation shows that the reefal carbonates are significantly faster than Wyllie’s prediction, at any given porosity (Figure 3.16).

Ansellmetti and Eberli (1999) define term “velocity deviation” as the difference between measured velocity and the theoretical Wyllie’s equation. They refer high acoustic velocity in regards to porosity as positive velocity deviation. The positive deviation is associated with a stiff frame-like fabric in rocks with pore types such as moldic and intraparticle. This stiff frame also resists compaction and results in very small velocity changes when pressures increase (Anselmetti and Eberli, 1993). The reefal carbonates in this data set corroborate these findings (Figure 3.17). What is impressive in this data set is the consistent positive velocity deviation whereby every sample is at least 500 m/s faster than what is predicted by Wyllie’s time average equation. The positive velocity deviation in this study data is caused by two factors. First, the reefal environment has abundant framestone and boundstones with a stiff original framework. In addition, in the high-energy reefal environment pervasive early cementation stiffen the frame and secondary dissolution and cementation add to the stiffening process by creating rigid pore types such as moldic, intraframe, vuggy porosity.

Syn- and post-depositonal cementation, as described in subchapter 3.1, transforms the sediments into rocks. Grain contact cements, circum-granular
cement, and micritic networks cements occur in almost all samples as the product of marine and multiple meteoric diagenesis. These cementation processes fuse the grains together into a rigid framework, creating a fast rock. As reported by Inzce (1998), the pervasive cementation of meteoric diagenesis in Pleistocene reefal samples creates a rock with high acoustic velocity. In addition to cementation, petrographic analysis shows that most micrite matrix in the wackestones or packstones is transformed and recrystallized into sparry calcite.

Figure 3.19. Photomicrograph of rocks with high porosity and high acoustic velocity. A. Skeletal grainstone with grains and a micritic envelope framework has a high porosity of 0.54 but has a fast velocity of 3000 m/s (Sample BC3V27). B. Close-up of fast coral sample displaying coral septa with interlocking aragonite crystals and intraframe porosity (porosity: 0.48, Vp: 3.8 km/s, Sample BC5H2.3).

The occurrence of moldic and intraframe pore types create a stiff framework resulting in fast rock with even with little cement (Anselmetti and Eberli, 2001). The most porous sample of this study (porosity = 0.54) is supported only by a micritic envelope framework around molds. It still has a compressional velocity that is 500 m/s above the Wyllie’s time average curve (Figure 3.19A). This indicates that the micritic envelopes produce a rigid framework for acoustic waves to travel through the rock. Corals consist of a solid
framework with internal structure of interlocking calcite or aragonite crystals (Figure 3.19B). This internal structure has a high elastic rigidity, and thus creates rocks with a positive velocity departure from the Wyllie’s curve.

### 3.2.3.3 Diagenesis and Acoustic Velocity

Another unique characteristic of this data set is the significant variation of velocity at equal porosities (Figure 3.16). The depositional lithologies and diagenesis can explain this variation largely. The lithology of the carbonate sediments at the time of deposition has a strong influence on the diagenetic potential. Therefore, the acoustic velocity evolves as the carbonate sediments transform into rock (Anselmetti and Eberli, 1993).

In the data, rocks have positive velocity deviation due to intense early diagenesis that includes marine and meteoric. The carbonates can have stiff frame in relatively short period and without undergoing burial. The fusing of grains by cement is the most important factor in changing rock elastic behavior (Inzce 1998, Eberli et al., 2003). Different types of cement in the different diagenetic environments can create different effect on acoustic velocity.

In this data set, samples altered in the meteoric phreatic environment have a lower Vp at any given porosity than the samples from the vadose diagenetic environment (Figure 3.18B). This is somewhat unexpected because typically the meteoric environment causes more cementation than the vadose one (Harris 1979, Halley and Harris, 1979). However, the vadose cement is concentrated at grain contacts often as meniscus cement. The phreatic cement is distributed around the grains or around molds (circum-granular cement).
Meniscus cement in the vadose rocks effectively welds the grains together, stiffens the rocks, and increases the elastic moduli of the rocks. Circum-granular cement is not necessarily creating grain-to-grain contact. More often cement faces against each other, leaving small gaps between the crystals. As a result, the vadose generally has a higher velocity than the majority of the phreatic samples at any given porosity.

In addition, the phreatic samples are predominated by smaller moldic pores (<300 µm) compared to the mostly larger moldic and vuggy pores in the vadose zone. Skeletal grains with original aragonite mineralogy are mostly dissolved away, and all that remains are moldic pores. Since the reef crest and backreef samples are dominated by coarser-grained, skeletal materials, the moldic pores in the vadose samples are larger than the finer-grained phreatic samples. Wyllie et al. (1958) reported that the acoustic wave can be transmitted effectively in vuggy rocks, regardless the porosity. Samples with larger moldic pores have been reported to have a faster velocity than samples with smaller moldic pores (Anselmetti and Eberli, 1993). Over a decade later, Weger (2006) confirms that larger and simpler pore structures have faster velocity than smaller and more complicated pore systems.

3.2.3.4 Permeability and Acoustic Velocity

In a data set with highly variable pore types and ages, a positive velocity deviation has been related to rocks with low permeability by Anselmetti and Eberli (1999). In this study data, all samples have positive deviations but can
have both low and high permeability up to 2 darcy. The variability of permeability is interpreted to be a function of the meteoric diagenesis that simultaneously produces cementation and dissolution, enabling reefal carbonates to have high velocity as well as permeability. In addition, meteoric vadose and meteoric phreatic diagenesis have distinctive velocity and permeability characters. Vadose samples tend to have a higher velocity and permeability than phreatic samples with the same porosity. Petrographic analysis confirms that this difference is caused by the difference in dissolution and cementation in the two zones.

In the vadose zone, preservation of interparticle pores and the occurrence of “touching” vugs enhance the permeability. At the same time, meniscus and micritic network cements create the stiff frame. As the result, these rocks can have high velocity and high permeability (Figure 3.20A).

The overprints of the phreatic diagenesis mostly coincide with reef front and fore reef lithofacies, where often the matrix is finer-grained. In the phreatic zone, abundance of the small moldic pores lower the velocity and the permeability. In the phreatic, the circum-granular cements are not necessarily fuse grain together leaving mostly small moldic pores and even smaller interparticle pores that don’t contribute to permeability (Figure 3.20B). As the result, the samples in the phreatic have less stiff frame, lower in velocity, and lower in permeability.
Table 3.20. Photomicrographs showing representative fabrics and petrophysical values for the meteoric vadose and phreatic zones in samples with similar porosity: A. Vadose rock (sample BC1V 42.6) with predominantly meniscus cement that has high velocity and permeability. B. Phreatic rock (sample BC5H 9.5) with circum-granular cements and small moldic pores. Both, velocity and permeability are lower than in the vadose sample.

<table>
<thead>
<tr>
<th></th>
<th>Porosity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.26</td>
<td>Vp</td>
<td>0.27</td>
</tr>
<tr>
<td>4607 m/s</td>
<td></td>
<td>4244 m/s</td>
</tr>
<tr>
<td>291 md</td>
<td>K</td>
<td>10 md</td>
</tr>
</tbody>
</table>

3.2.4. Electrical Resistivity

Electrical resistivity on the reefal carbonates is measured in the laboratory to provide a better understanding in interpretation of electric log data. Archie (1942) established the relationship of measured electrical resistivity and certain characteristic physical properties of reservoir rocks. Generally, for brine-saturated sandstones, the electrical resistivity follows the empirical Archie's formula:

$$FF = \frac{R_o}{R_w} \quad FF = \phi^{-m}$$

Where FF: formation resistivity factor (unitless), $R_o$: measured resistivity of brine saturated rocks, $R_w$: resistivity of the brine used in experiment, $\phi$: fractional
porosity, and m: cementation factor (unitless). In this study, the electrical resistivity for measured samples is reported as formation resistivity factor (FF) and cementation factor (m). Cross-plots of FF and m to porosity, permeability, rock texture, depositional environments, and diagenesis are used to evaluate the relationship among electrical resistivity and rock physical properties.

3.2.4.1 Result

The formation resistivity factor ranges from 8 to 830 and has an average of 71.5 for the samples analyzed. Porosity is inversely correlated with FF (Figure 3.21A). The linear regression coefficient correlation ($R^2$) for porosity and $\log_{10}$ FF is 0.59. The correlation of FF to permeability is weak (Figure 3.21B). The linear regression coefficient correlation ($R^2$) for $\log_{10}$ permeability and $\log_{10}$ FF is 0.3.

*Figure 3.21. Left). Cross-plots between formation resistivity factor (in log scale on the Y axis) and porosity. The cementation factor (m) lines are drawn in the cross-plot. It ranges from 2 up to 5. Right). Cross-plot between formation resistivity factor (in log scale on the Y axis) and permeability, showing a weak correlation to permeability.*
The variations of electrical resistivity have been empirically determined due to several factors, such as: tortuosity, pore structure, and porosity. The variation of FF at any given porosity is not related to the depositional environments, diagenesis, rock texture, or pore types (Figure 3.22). Samples with diagenetic overprint in the meteoric vadose or meteoric phreatic zones have a similar range of values at any given porosities. Likewise, no trend can be detected if the samples are color-coded in regards to texture, the depositional environment, or pore type (Figure 3.22).

Figure 3.22. Cross-plots of formation resistivity factor and porosity (semi-log scale) color-coded by several geological parameters. A. Meteoric diagenesis zonation. B. Dunham’s classification of carbonate textures. C. Depositional environments. D. Choquette and Pray’s pore classification. The formation resistivity factor is not correlated to the geological parameters.
The cementation factor (m) quantifies electrical resistivity variations at a constant porosity (and pore fluid conductivity). The cementation factor is the slope of the average trend line representing the relationship of FF and porosity on log-log scale. It is dependent on the shape and type of the grains, shape, and types of the pores, specific surface area, tortuosity, anisotropy, and compaction (Salem and Chilingarian, 1999).

In carbonate rocks, the cementation factor (m) has a range of values instead of a single value. In this study, m ranges from 2.1 (at a porosity of 0.15) to 5.4 (at a porosity of 0.48). Cementation factor shows a very weak correlation with permeability ($R^2=0.15$) (Figure 3.23).

The cementation factor (m) measured in this study is compared to two previous studies in Table 3.7. The range of m in this data set exceeds both ranges reported by Lucia (1983) and Verver et al. (2011), respectively. In addition, m is shifted to higher values. The lowest value by Verver et al. (2011) are 1.7 and by Lucia 1.8, whereas in this data set the lowest m is at 2.1. Likewise, the upper end of m is 5.3 in this data set whereas it is 4 and 4.1, respectively, in the previous studies.

<table>
<thead>
<tr>
<th>Study</th>
<th>m value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lucia, 1983</td>
<td>1.8 to 4</td>
</tr>
<tr>
<td>Verwer et al., 2011</td>
<td>1.7 to 4.1</td>
</tr>
<tr>
<td><strong>This study</strong></td>
<td><strong>2.1 to 5.3</strong></td>
</tr>
</tbody>
</table>

*Table 3.7. Comparison of cementation factor in this study with several previous studies.*
Figure 3.23. Cross-plot of permeability log scale (X axis) with cementation factor (Y axis). Permeability varies widely at any value of the cementation factor (m, indicating that little correlation exists between permeability and electrical resistivity in this data set. This implies that direct use of electrical resistivity log to predict permeability in reefal carbonates may be inaccurate.

### 3.2.4.2 Interpretation and Discussion

The measured formation resistivity factor (FF) of the analyzed samples shows an inverse correlation to porosity, although there is some significant scatter. In 1942, Archie’s laboratory experiments established a relationship that shows inverse correlation between formation resistivity factor and porosity. In comparison to Archie’s sandstone samples, the reefal carbonates have more heterogeneity in pore structure. This pore structure heterogeneity leads to a
weaker correlation between FF and porosity, as several electrical resistivity studies in carbonate rocks have demonstrated (Hilchie, 1982; Lucia, 1983; Verwer et al., 2011).

The formation resistivity factor is weakly correlated to permeability ($R^2=0.3$). This has been originally noticed by Archie (1947) in his carbonate samples. In the paper, he wrote that" fluid flow and electric flow are therefore not strictly analogous…” . Recently, Verwer et al. (2011) proposed that pore structure and pore number control electrical resistivity in carbonate instead pore throat (permeability).

In this study, there is no correlation between depositional environment and diagenesis to electrical resistivity (Figure 3.22A and C). This is presumably due to the heterogeneity in the rock texture and pore types in carbonate (Figure 3.22B and D). The importance of pore structure or fabric heterogeneity has been investigated by several researches (Hilchie, 1982; Lucia, 1983; Focke and Munn, 1987; Ramakrishan et al., 1998). Most of them suggest that electrical resistivity can be assigned to certain rock texture and pore types. These findings cannot be corroborated in the complex heterogeneity of the analyzed samples; neither pore type or rock texture is correlated with the electrical properties. Even Archie (1947) anticipated the effect of complex reservoir heterogeneity of the reservoir pore structure on electrical resistivity, particularly in his carbonate samples.

The cementation factor is a slope of the regression line relationship of formation resistivity factor on log-log scale. The cementation factor ($m$) is a major
factor in the calculation of water or hydrocarbon saturations. Typically for clean formation, the following formula is used to calculate water saturation.

$$Sw = \left[ \left( \frac{a}{\varphi^m} \right) \times \left( \frac{R_w}{R_i} \right) \right]^{(1/n)}$$

Where $Sw$: Water saturation, $a$: constant, $\varphi$: porosity, $m$: cementation factor, $R_w$: resistivity brine, $R_i$: resistivity measured, $n$: saturation exponent.

The measured cementation factor ($m$) shows a wide range of values, even wider than in the studies by Lucia (1983) and Verwer et al. (2011). Verwer et al. (2011) calculated that changes in the cementation factor from 2 to 3 (the other parameters are constant) result in changes of the water saturation from 27% to 60%. The average $m$ is $3.2 \pm 0.54$ in this study. The use of average value of $m$, or the conventional usage of $m = 2$, to calculate water saturation in reefal carbonates may lead to large inaccuracy of water saturation calculation.
CHAPTER 4

PORE STRUCTURES AND PETROPHYSICAL PROPERTIES OF THE DOMINICAN REPUBLIC PLIO-PLEISTOCENE REEFAL CARBONATES

Overview

Pore structure has been proven as one of the factors influencing petrophysical properties of carbonate rocks, in particular acoustic velocity, and electrical resistivity (Blair et al., 1996; Anselmetti and Eberli, 1993; Saleh and Castagna, 2004; Baechle et al., 2004, Weger, 2006, Weger et al., 2009; Abousrafa et al., 2009; Verwer et al., 2011). Weger (2006) developed a Digital Image Analysis (DIA) method to quantify pore structure parameters from thin sections. This method has been successfully applied to explain variations in acoustic velocity, permeability, and electrical resistivity (Weger et al., 2009; Verwer et al., 2011). The studies aforementioned measured carbonate samples from different ages and localities. This study applies DIA to explain petrophysical variations in the Pliocene-Pleistocene reefal carbonate rocks in the Dominican Republic. In this study, the correlation DIA parameters to petrophysical properties reveal pore structure influences on the petrophysical properties. The DIA parameters that best correlate to the petrophysical properties are size (dominant pore size), complexity (perimeter over area), and roundness (γ). These parameters explain most of the variations at a given porosity in acoustic velocity, permeability, and electrical resistivity.
4.1. Choquette and Pray Pore Classifications in the Reefal Carbonates

Anselmetti and Eberli (1993) show how each pore type, using the Choquette and Pray classification, corresponds to a different deviation of acoustic velocity from the Wyllie's time average. The characteristics of each individual pore type can help explain the acoustic behavior of porous media like carbonates with a variety of pore sizes and shapes. Likewise taking pore types into account enhances the porosity - permeability relationship (Anselmetti and Eberli 1997, Lucia, 1995).

In this study, samples were grouped based on Choquette and Pray classification (1970) with the petrographic analyses. Cross-plots of velocity - porosity and porosity - permeability with the predominant pore types superimposed in color are shown in Figures 4.1 and 4.2, respectively. Both cross-plots show that incorporating the predominant pore types into the velocity-porosity or porosity-permeability plots does not yield a better separation or a trend in our data set. One reason for this poor separation in velocity - porosity or permeability - porosity is due to the difficulty of assigning one dominant pore type to each sample since more than one pore type coexists in each sample.

However, intraframe porosity is the fastest among the pore types. This is due to interlocking of carbonate minerals that create rigid body of coral. Some of coral skeleton were leached by meteoric diagenesis. The dissolution creates vuggy pore in coral body. This weakens the coral stiffness, which results in lower velocity of intraframe pore.
The presence of several pore types in a single sample is common in the reefal carbonates (Figure 4.3). Moldic, interparticle, intraframe, vuggy, and microporosity can all be observed in varying proportions in a single sample. Assigning a predominant pore type then becomes subject to interpretation, qualitative assessment, and inconsistency. Because of the challenges during pore classification, this study uses Digital Image Analysis, following the methodology of Weger (2006) as a quantitative method to analyze pore structures.

Figure 4.1. Porosity and Vp cross-plot color-coded by pore types using the Choquette and Pray pore classification. All samples deviates positively from the time average equation. The pore type assignment does not produce pattern to explain these deviations but individual pore types are overlapping each other at any given porosity.
Figure 4.2. Porosity-permeability cross-plot color-coded by pore types using the Choquette and Pray classification. Pore typing is not showing substantial separation of permeability at any given porosity.

Figure 4.3. Photomicrograph of a floatstone, illustrating the occurrence of various pore types in one sample, which can lead to difficulties in assigning a predominant pore type. Mo = moldic, IF = intraframe, IP = interparticle.
4.2. Digital Image Analysis

Digital image analysis offers an objective means for the analysis of thin section photomicrographs and has, thus, been utilized in other studies to determine size, shape and distributions of grains, cements and porosity (Erlich et al., 1984; Fortey, 1995; Lindqvist and Åkesson, 2001) and to explain petrophysical variations in carbonate rocks (Anselmetti et al., 1998). Weger (2006) advanced the digital image analysis method of digital photographs of thin sections using a computerized method for both image acquisition and analysis.

Prior studies in carbonate petrophysics report a relationship between pore shape parameters and acoustic velocity (Wyllie, 1958, Anselmetti and Eberli, 1993, Wang, 2001, Weger et al., 2009). Using samples from carbonate rocks of different localities and ages, these studies show a strong correlation between pore structure and acoustic velocity variations. This study applies the DIA methodology used by Weger et al. (2009) to analyze acoustic velocity characteristics in reefal carbonates. The software package is Matlab based. A detailed description of the DIA performed in this study is given in Weger (2006).

Digital Image Analysis Parameters Selection

A linear regression analysis was performed to determine which parameters are most useful for improving correlations among petrophysical properties. The formula used is given in the chapter 2. The $R^2$ coefficient provides information how well the addition of a DIA parameter improves the estimation of the petrophysical properties. Table 4.1, shows the highest $R^2$
values of the correlated petrophysical properties. The description and meaning of each pore parameters below is explained in Weger (2006). The linear regression analysis $R^2$ shows the three DIA parameters best correlate with the petrophysical properties of: Dominant pore size, Perimeter over area, and Gamma. The DIA parameters will be used in the following discussion to explain the relationship among petrophysical properties.

<table>
<thead>
<tr>
<th>Pore Parameter</th>
<th>$R^2$</th>
<th>Pore Parameter</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant pore size</td>
<td>0.86493</td>
<td>Gamma</td>
<td>0.51031</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pore Parameter</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perimeter over Area</td>
<td>0.69</td>
</tr>
<tr>
<td>Dominant pore size</td>
<td>0.3411</td>
</tr>
</tbody>
</table>

*Table 4.1 Summary of the coefficient of determination ($R^2$) of each correlated petrophysical properties, include: Porosity-Velocity, Porosity-$\log_{10}$ Permeability, Porosity-$\log_{10}$ Formation Factor, and $\log_{10}$ Permeability and $\log_{10}$ Formation Factor.*

**Dominant Pore Size**

The Dominant pore size indicates the pore size range that dominates the sample and is defined as the upper boundary of the pore sizes, of which 50% of the porosity on a thin section can be composed (Weger, 2006; Weger et al, 2009). In this data set, the dominant pore size ranges from 30 $\mu$m to 2900 $\mu$m (Figure 4.3). Dominant pore size is plotted on a log scale in the following subchapters.
Perimeter Over Area

Perimeter over area (PoA) is the ratio between the total perimeter of the pore spaces and the total pore area of a thin section. It can be regarded as the 2-D equivalent to a specific surface, the ratio between the volume of pores and area of the surface area that encloses them. The PoA ranges from 20 to 250 mm$^{-1}$ (distribution shown in Figure 4.5). Similarly to dominant pore size, the PoA is also plotted on a log scale in the following subchapters.

Figure 4.4 Histogram showing the distribution of the dominant pore size in the data set. n: 138, f: 100.
Gamma

Gamma ($\gamma$) is defined by Anselmetti et al., (1998) as the perimeter over area of an individual pore normalized to a circle. It describes the roundness of a pore. Gamma reported in this study is weighted with area ($\tilde{\gamma}$) to be consistent with Anselmetti et al., (1998). The gamma weighted area ranges from 1.75 to more than 7 with the distribution given in Figure 4.6.
In addition to pore shape parameters, microporosity is used in the analysis to explain variations in permeability. Microporosity here is defined as the difference between porosity measured in the laboratory and the porosity from digital image analysis (thin section). The average thickness of a thin section is around 30 µm and, thus, pores smaller than 30 µm cannot be seen in the microscope. Thus, the micropore size includes pores smaller than 30 µm.

4.3. Pore Structure in the Reef System and Its Effect on Acoustic Velocity

Two main velocity characteristics can be observed in the data of the Dominican Republic reefal carbonates. First, the compressional velocity (Vp) in the dataset is high, as previously described in the Chapter 3. Second, the Vp correlates inversely with porosity. However, the Vp varies from the Wyllie time average with a range of up to 2000 m/s for any given porosity. These characteristics of the porosity-velocity relationship can be explained by analyzing the samples pore structures.
Figure 4.7. Cross plot of Perimeter over Area (PoA) and Dominant Pore Size (Dom Size). Pores are simple and variable in size. This plot compares data from this study (red circles) with the data set of Weger et al. (2009) (black dots).

PoA and DomSize from samples in this study (red circles in Figure 4.7) are compared with the data of Weger et al. (2009) (black points) in Figure 4.7. The pores of the reefal samples are larger and simpler than most of the samples in the Weger et al. (2009) data set. The analyzed reefal carbonate samples pore structures are simple with the PoA <100 mm⁻¹. The variation of Vp at any given porosity can be related to both pore parameters. At similar porosities, samples with complex pore structure (reddish color in the Figure 4.8A) have lower a Vp than those with simpler pores (blue colors in the Figure 4.8A). Larger pore size (red colors in Figure 4.8B) has higher Vp than smaller pore size (blue colors in...
Figure 4.8B). In general, samples with large, simple pores have a higher Vp than samples with small, complicated pores. In other words, in summary, the velocity-porosity relationship in reefal carbonates is strongly influenced by pore size and pore network complexity (Figure 4.8).

![Diagram](image)

*Figure 4.8 Cross-plots of porosity and Vp color coded by log scale of the DIA parameters Perimeter over Area (left) and Dominant Pore Size (right). Both parameters show a gradient separating relatively low and high velocities in the plots, indicating that rocks with simple pores (low Perimeter over Area) and large Dominant Pore Size have a higher acoustic velocity at a given porosity than small-complicated pores.*

The link between PoA and DomSize to Vp (in color) is illustrated in Figure 4.9. As the Vp changes, the pore complexity and size changes gradually, which is shown by four representative thin section photomicrographs from samples with similar porosity (0.23 to 0.25) and texture (except for the coral boundstone). Samples with lower PoA and higher DomSize have a higher velocity than those with a higher PoA and lower DomSize. The simple pore structure in the analyzed reefal samples are well-cemented, mud-lean, and coarse-grained textures. These finding corroborates the findings by Weger et al. (2009), stating that PoA
and DomSize are the most important parameters after porosity influencing acoustic velocity.

Figure 4.9. Cross-plot of perimeter over area vs. dominant pore size for samples with porosity between 23 – 25% color-coded with Vp. The enlarged points with A to D labels are the corresponding samples with thin sections pictures that are shown below the graph. Photomicrographs A to D, are given to show a representation of the samples and their petrophysical values.
4.3.1 Quantification of the Influence of the Pore Structure

After porosity pore structure has the second largest influence on the acoustic velocity-porosity relationship, if the other parameters (temperature, pressure, saturation, mineralogy, etc) are equal (Weger et al. 1998). In this dataset the pore structure is simple with variation in size.

To quantify the influence of DIA parameters on the velocity-porosity prediction, $V_p$ is estimated using a multivariate linear regression from a combination of porosity and DIA parameters. The $R^2$ values are then compared with the estimation determined from porosity alone (Table 4.2). The formula is given in Chapter 2.

<table>
<thead>
<tr>
<th>Estimator Used for Velocity Linear Regression</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.765</td>
</tr>
<tr>
<td>Porosity and Aspect Ratio</td>
<td>0.781</td>
</tr>
<tr>
<td>Porosity and Gamma</td>
<td>0.810</td>
</tr>
<tr>
<td>Porosity and % Microporosity</td>
<td>0.789</td>
</tr>
<tr>
<td>Porosity and PoA</td>
<td>0.862</td>
</tr>
<tr>
<td>Porosity and DomSize</td>
<td>0.871</td>
</tr>
<tr>
<td>Porosity and $\log_{10}$ PoA</td>
<td>0.900</td>
</tr>
<tr>
<td>Porosity and $\log_{10}$ DomSize</td>
<td>0.910</td>
</tr>
<tr>
<td>Porosity and PoA and DomSize</td>
<td>0.896</td>
</tr>
<tr>
<td><strong>Porosity and $\log_{10}$ PoA and $\log_{10}$ DomSize</strong></td>
<td><strong>0.913</strong></td>
</tr>
</tbody>
</table>

Table 4.2. Coefficients of determination ($R^2$) from the calculations between measured and estimated velocity from regressions using pore parameters as input (n=137).

The velocity estimation from porosity alone results in a extremely high coefficient correlation ($R^2=0.765$). The high $R^2$ value emphasizes the significant control porosity on the velocity. Even with such a good correlation as a starting point, the addition of various pore parameters from DIA into the estimation procedures still improves the result by 10% to 15% improvement. Even better,
PoA or DomSize alone can improve the correlation by 10%. The best correlation is given by combining porosity, log_{10} PoA, and log_{10} DomSize (R^2=0.913).

Given that log_{10} PoA and log_{10} DomSize are the DIA parameters that explain best the velocity deviations at a given porosity, the two parameters are plotted with the velocity deviation in Figure 4.10. The R^2 value for log_{10} PoA and log_{10} DomSize are 0.42 and 0.49, respectively. The numbers show that these two pore parameter able to explain 42% to 49%, respectively, of velocity deviations from the Wyllie’s time average trend line.

Figure 4.10. Cross-plots of the velocity deviation versus DIA parameters. A). Log_{10} PoA. B. Log_{10} DomSize vs deviation. The red lines are the linear regression lines. The equation and R^2 values are shown on the plots.

4.4. Permeability and Pore Structure in the Reefal Carbonates

The relationship between permeability to pore type or pore geometry of carbonate rocks has been studied for decades (e.g. Enos and Sawatsky, 1981; Lucia, 1995; Anselmetti et al., 1998; Weger et al., 2009). Aforementioned studies show that the heterogenous pore systems in carbonate rocks makes predictions
of permeability from porosity difficult. Anselmetti et al. (1998) show a control of connectivity of macropores (gamma) and microporosity. Weger et al. (2009) show a link between porosity-velocity-permeability to digital image parameters: perimeter over area and dominant pore size. In this study, pore parameters from digital image analysis largely explain permeability variations at any given porosity.

4.4.1 Result

![Figure 4.11. Cross-plot of porosity-permeability color-coded with γ. At any given porosity, low γ (dark blue color) correlates to low permeability.](image)

Anselmetti et al. (1998) report the importance of macropore shape to permeability whereby Gamma is related to the complexity and connectivity of
pores. Simple pores like isolated round vugs with a low $\gamma$ are usually not well connected and thus have a low permeability. In contrast high $\gamma$ that measures the complexity of pore structure with many potential connections correlates with high permeability in Anselmetti et al. (1998). This finding corroborates Anselmetti et al. (1998) as a higher $\gamma$ relates to samples with higher permeability at equal porosity (Figure 4.11).

In contrast Weger et al. (2009) found that PoA and DomSize explains porosity - permeability variation better than $\gamma$. The influence of PoA and DomSize on the porosity - permeability relationship in our data set is shown in Figure 4.12. Both parameters show a weak correlation to porosity - permeability.

![Figure 4.12. Cross-plot of porosity and permeability color coded by A) PoA And B.) DomSize. Both pore parameters show a weak correlation to permeability variations at any given porosity. Size and complexity of the pores are not the best parameters to explain permeability in reefal carbonates.](image)
4.4.2 Discussion and Interpretation

In this study data, permeability trend is affected by the pore structure and the total porosity. There is a porosity dependence on permeability (Figure 4.13A) and to pore structure (Figure 4.13B). Higher γ values indicate samples with higher permeability similar as in the data set of Anselmetti et al. (1998).

γ is the ratio between perimeter over pore area of and individual pore, normalized to a perfect circle so that a γ of one corresponds to a perfect circle. The circularity of pores captures the pores connectivity. A sample with connected vuggy porosity has higher ratio of γ than a sample with isolated moldic pores at the same porosity. The edge of an individual vuggy pore is rougher (longer perimeter) than the moldic pores with the same pore area. As the result, samples with vuggy pores typically have higher gamma value (Figure 4.14).

\[ \text{Figure 4.13. Cross-plots of (A) permeability (log scale) vs. porosity and (B) permeability (log scale) vs. } \gamma. \text{ The coefficient of determination (} R^2 \text{) suggests that permeability is controlled by both of porosity and pore shape.} \]
Figure 4.14. Photomicrographs of two samples with the same porosity: A) Skeletal packstone with moldic pores, and B) Skeletal grainstone with vuggy pores. The skeletal packstone has low lower $\gamma$ values and lower permeability. Sample B has vuggy pores, which, when connected, contributes significantly to permeability, has higher $\gamma$ values. Scale bar: 500 µm.

The occurrence of corals in a floatstone texture makes the assessment of connectivity with DIA difficult. Because corals and the matrix will generate different $\gamma$ values. This limits the use of the $\gamma$-permeability correlation. The higher $\gamma$ value in the floatstone samples is due to the presence of coral chambers rather than the occurrence of connected vuggy pores. In a coral fragment, the perimeter can be too long for its pore area (Figure 4.15). By excluding samples with floatstone texture the $R^2$ of $\gamma$ to permeability improves from 0.21 to 0.40.

PoA and DomSize are not sufficient to explain the porosity - permeability relationship. Most of the samples have a simple pore network, and the size of pores is not necessarily correlated to permeability in this data set. For example,
samples A and B in Figure 4.14 have similar value of the DomSize and PoA, but their permeability is very different. Sample B is dominated by moldic and interparticle porosity connected by vugs. Sample A is dominated by isolated moldic pores, which are not connected with each other. As the result, although the pore size is relatively similar, the permeability is different by nearly 4 orders of magnitude.

Figure 4.15. Floatstone with coral fragments. \( \gamma = 2.67, K= 0.07 \text{ md}, \) porosity = 0.25. The \( \gamma \) value is high but the permeability is low. Cora growth structures produce complicated but isolated pores that increases gamma but inhibits flow. Scale bar: 1mm

A multivariate linear regression analysis was performed to predict permeability using porosity and pore parameters as constants. The \( R^2 \) values are
compared to illustrate the prediction improvement. By incorporating gamma into the calculation, the $R^2$ improves from 0.40 to 0.57 (Table 4.3).

<table>
<thead>
<tr>
<th>Estimator Used for $\log_{10}$ permeability Linear Regression</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>0.40</td>
</tr>
<tr>
<td>Gamma</td>
<td>0.40</td>
</tr>
<tr>
<td>$\log_{10}$ PoA</td>
<td>0.07</td>
</tr>
<tr>
<td>$\log_{10}$ DomSize</td>
<td>0.1</td>
</tr>
<tr>
<td><strong>Porosity and Gamma</strong></td>
<td>0.57</td>
</tr>
<tr>
<td>Porosity and $\log_{10}$ PoA</td>
<td>0.44</td>
</tr>
<tr>
<td>Porosity and $\log_{10}$ DomSize</td>
<td>0.44</td>
</tr>
<tr>
<td>Porosity and Gamma and $\log_{10}$ PoA</td>
<td>0.58</td>
</tr>
<tr>
<td>Porosity and Gamma and $\log_{10}$ PoA $\log_{10}$ DomSize</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Table 4.3. Coefficients of correlation from the calculations between measured and estimated permeability from regressions using pore parameters as input.

As discussed in the subchapter 4.2, samples with simple and large pores are faster than samples with smaller and more intricate pore structures. The cross plot of porosity-velocity color coded with permeability reveals that there is potential of finding high permeability sample in the samples that deviate more than 500 m/s from the Wyllie time average trend line (Figure 4.16). This finding implies that the high impedance interval in the seismic data not only represent well-cemented rocks or separate-vug porosity but in reefal carbonates with presumably similar diagenesis and depositional setting, the high impedance intervals can also potentially have high porosity and permeability, and thus are high-quality reservoir rocks. High permeability is possible in high impedance rocks due to grain contact cements (meniscus and micritic network), which preserves interparticle pores without significantly occluding pores and connecting vuggy pores.
Figure 4.16. Cross-plot of porosity and permeability color-coded with permeability. The enlarged data points and label A to D are the samples of which the photomicrographs and petrophysical properties are given below the cross-plot. The photomicrographs and cross-plot illustrate that the relatively fast velocity reefal carbonates have high permeability. Scale bar: 1mm. $dVp$ = deviation of $Vp$ measured from $Vp_{\text{Wyllie}}$. 
4.5. Pore Structure and Electrical Resistivity

Electrical resistivity logs have been widely used for decades to calculate hydrocarbon or water saturation of carbonate rocks (Schlumberger, 1974; Doveton, 1994). Several publications report on the application of electrical resistivity log analysis to distinguish between effective and ineffective porosity (Lucia and Conti, 1987, Smith et al., 2003). Recently, Verwer et al. (2011) reported the control of pore structure and absolute number of pores on the electrical resistivity in carbonates. Using the Verwer et al. (2011) methodology, this study investigates the influence of pore structure on the electrical resistivity.

4.5.1 Result

The relationship of porosity, formation factor, and cementation factor (m) in the analyzed samples is shown in Figure 4.17A. In these reefal carbonates, the cementation factor is above 2 in samples with a porosity range of 0.15 to 0.46. At any given porosity, the cementation factor varies by 2. The variation of the cementation factor is not related to permeability (Figure 4.17B). The cementation factor changes gradually as the formation factor increases or decreases (Fig. 4.17A). Permeability is weakly correlated to the formation factor and cementation factor (Fig. 4.17B). This implies that the use of the conventional value of m= 2 to calculate water saturation is not possible in reefal carbonates.
The cementation factor is not a sufficient indicator of permeability variations at any given porosity (Figure 4.18). Samples with similar cementation factors can have permeabilities with ranges up two 4 orders of magnitude. The highest cementation factor in this data set is a coral sample with intraframe pore structure. The lowest cementation factor is in a skeletal wackestone with a preponderance in microporosity. Both samples are low in permeability for their given porosity. The rest of the samples have textures that are more heterogeneous and usually more pore types occur in one sample.

Figure 4.17. Cross-plots of porosity and formation factor color-coded: A). by cementation factor The lines of theoretical equal cementation factor are also plotted. This plot shows that the cementation factor is not a single number but rather a range of values. B) Porosity and formation factor color-coded with permeability. Permeability is weakly correlated to the formation factor and cementation factor.
Figure 4.18. Cross-plot of porosity and $\log_{10}$ permeability color coded by the cementation factor (m). There is no clear relationship between permeability and cementation factor. Samples with similar cementation factors can have permeability that ranges up to 4 orders of magnitude.

Verwer et al. (2011) reported a high correlation between pore parameters and the absolute pore number to cementation factor. The correlation coefficient for the linear regression in their data is higher than 0.5. In this data set, cross-plots between the cementation factor and $\log_{10}$ PoA (Figure 4.19A) and $\log_{10}$ DomSize (Figure 4.19B) show inverse correlation between the PoA and the cementation factor and a positive correlation between DomSize and the cementation factor. However, the relationship is weak (R<0.5). The cross-plot
between the cementation factor and the absolute number of pores shows an even weaker correlation (Figure 4.19C).

*Figure 4.19. Cross-plots of the cementation factor to A) $\log_{10} Po_a$. B) $\log_{10} DomSize$. C) $\log_{10}$ absolute pore numbers. The linear regression equation and R-values are given on the cross-plots. The cementation factor has the highest correlation to pore complexity (PoA).*

The DIA parameters exhibit indistinct trends within the porosity - formation factor space (Figure 4.20). The DomSize and PoA show the following subtle trend. In general, some high values of DomSize correlate with higher values of the formation factor at equal porosity (Figure 4.20A). Although there are some samples with higher DomSize but lower in formation factor. PoA shows a clearer trend with most of the simple pore structure have a higher formation factor at similar porosity (Figure 4.20B). As it was shown before in Figure 4.19, the pore number is not correlated to variation of formation factor at any given porosity (Figure 4.20C). In general, samples with more microporosity have a lower formation factor at a given porosity (Figure 4.20D).
Figure 4.20. Cross-plots of porosity and formation resistivity factor, color-coded by A) \(\log_{10}\) DomSize, B) \(\log_{10}\) PoA, C) \(\log_{10}\) number of pores, and D) microporosity. The pore parameters (DomSize and PoA) show a weak correlation to the variation of the formation factor at any given porosity. Increases in microporosity decreases the formation factor (lower resistivity).

4.5.2 Discussion and Interpretation

Porosity influences the electrical resistivity. This relationship has been originally investigated by Archie (1942) and later tested in carbonate rocks by several studies (Lucia, 1983; Focke and Munn, 1987, Ramakrishan et al., 1998, Verwer et al., 2011). In the analyzed samples, porosity is the most influential physical factor for electrical resistivity \((R^2 =0.59)\). The formation resistivity factor
decreases with increasing porosity, but a significant scatter exists from the general trend.

The DIA pore parameters, DomSize and PoA, show a weak correlation to variations of electrical resistivity at any given porosity. Verwer et al. (2011) suggested that sample with high DomSize and low PoA have a high resistivity, whereas samples dominated by low DomSize and high PoA have a low resistivity. In this study data, such trend does not exist because of the coexistence of multimodal pore types in one sample.

Samples with single pore type display a better correlation to DIA parameters (Figure 4.21). When the samples have more than one pore type, especially if the separate vug/moldic and other pore types co-exist, the relationship between electrical resistivity and DIA parameters is weak. Size and complexity of the pores structures from 2-D thin section presumably is not sufficient to explain the coexistence of bimodal or multimodal pore types in the analyzed samples. However in one point the findings of this study corroborate the findings of Verwer et al. (2011). Rocks with a lot of microporosity have a lower resistivity at a given porosity indicating that the high number of pore numbers and pore connections decreases resistivity as (Verwer et al. (2011) postulated.
Figure 4.21. Cross-plots of porosity and log10 formation factor color-coded by perimeter over area (left) and dominant pore size (right) in samples with moldic pores. These two cross-plots show the effect of pore structure on electrical resistivity variations. Samples with large and simple pores have a higher formation factor (resistivity) than samples with small and intricate pore structures. In this moldic samples the amount of micropores become important for the electric charge.

Pore connection is an important factor controlling electric resistivity (Verwer et al., 2011). As such, resistivity is used for estimation of permeability from well logs. In this data set, the cementation factor does not correlate well to permeability (Figure 4.16). Archie (1947) pointed to the difference between fluid flow and electrical flow, stating that they are not analogous with his uniform samples. In less uniform carbonate samples, several studies proposed the importance of grouping pore types (such as: separate vugs, interparticle, and microporosity) for permeability estimation from electrical resistivity data (Lucia, 1983; Focke and Munn 1983). In this data set, it is not possible to group pore types due to heterogeneity of pore types.
4.5.3 Comparison to Previous Study

Figure 4.22. Cross plot of porosity and log$_{10}$ formation factor of the combined data sets of Verwer et al (2011) and this data set color-coded with A) the cementation factor, B) microporosity, C) dominant pore size, and D) perimeter over area.

For a general interpretation, the data of this study is compared with the data of Verwer et al. (2011). Once both data sets are plotted together, the trends of electrical resistivity to pore geometry are more obvious (Figure 4.22). This study's data have a higher formation factor than the Verwer et al. data (2011). It is interpreted to be the result of the larger and simpler pore structures of this study data compared to the Verwer et al. (2011) data set. Such large and simple
pore structures samples have less pore connections and as a result a higher resistivity.

Figure 4.23. Cross-plot of porosity and log_{10} permeability color coded by cementation factor (m) with data from Verwer et al. (2011) and this study. This study’s data generally has lower permeability than Verwer et al. (2011).

Figure 4.23 illustrates the relationship of porosity-permeability with the cementation factor in this study data (circles) and the Verwer et al. (2011) (squares). This study data set displays generally higher cementation factors than the ones in the Verwer et al. (2011) data set and generally a lower permeability.
The samples with the highest cementation factor have a low permeability because they contain unconnected simple and large pores (vuggy, intraframe, moldic). The samples with an intermediate cementation factor have simple and large pores structures that facilitate fluid flow (high permeability) but reduce the number of pore connections, causing a high cementation factor.
CHAPTER 5
CONCLUSIONS AND IMPLICATIONS

5.1 Conclusions

Integration of petrophysical laboratory measurements, thorough core-based lithologic description, thin-section petrography, diagenetic analysis, and digital-image analysis allows for a robust characterization of the sub-aerially exposed Pliocene-Pleistocene reefal carbonates successions of the Southern Dominican Republic. Core description and petrographic analysis enable a comparison of the geological interpretation (rock textures, pore types, depositional environments, and diagenetic environments) and measured petrophysical properties. Whereas, digital image analysis from thin sections provide pore parameters and allow a quantitative correlation of pore structure to petrophysical properties.

Depositional environments and diagenesis of the reefs

The Plio-Pleistocene reefal successions of the study area form a series of stacked prograding sigmoidal clinoforms. Each reefal clinoform consists of four depositional environments: backreef, reef crest, reef front, and fore reef. Backreef environments contain mud-rich textures with patchy corals, but spatial variations exist with coarser grain textures. Reef crest and reef front facies are marked by boundstones with a slightly muddier matrix in the reef front. The fore reef facies contains of grain-supported (packstone-grainstone) rock textures with an abundance of transported skeletal fragments from upper part of the clinoform. The reefal carbonates bear the mark of two major diagenetic environments; early
marine and meteoric settings. Meteoric environments are divided into two zones: vadose and phreatic, based on petrographic and geochemical analysis (Hernawati, 2011). Cementation and dissolution features are a common result of meteoric diagenesis.

**Porosity and permeability**

The reefal carbonates of the southern Dominican Republic exhibit a wide range of porosity (0.07 to 0.54 fraction) and permeability (0.01 to 19400 md). The porosity-permeability data show an inverse correlation with 4 to 5 orders of magnitude variations at any given porosity. These variations make permeability prediction from porosity difficult.

**Depositional environment and diagenesis relationship to porosity-permeability**

In the analyzed samples, permeability varies because of the diagenetic alteration. Different diagenetic zone shows a different porosity-permeability characteristic. Generally at any given porosity, the phreatic samples have lower permeability than the vadose samples. Petrographic analysis confirms that this difference is caused by differences in dissolution, cementation, and original rock textures in the two zones. Phreatic diagenesis mostly altered the lower part of the reefal clinoforms (reef front and forereef facies). This part of the reef is composed of finer-grained or muddier sediment matrix with an abundance of microporosity and small moldic porosity. In phreatic samples, cements form a circum-granular ring and occlude original interparticle porosity. Vadose samples occur mostly in
the upper part of reef clinoform (backreef and reef crest facies). The vadose samples are generally higher in permeability due to the occurrence of connected vugs and preservation of original interparticle porosity. However, some of the vadose samples also have permeability values as low as the phreatic samples due to a muddier texture or cementation of the original interparticle pores.

Pore structure relationship to porosity-permeability
Permeability variations are affected by pore structure as well as porosity (both $R^2 = 0.4$). Anselmetti et al. (1998) notes the importance of macropore shape on permeability. $\gamma$, which quantifies the perimeter-over-pore area (PoA) of individual pores, is used to estimate the pore connectivity (Anselmetti et al. 1998). $\gamma$ can distinguish the occurrence of connected vuggy pore types in the rock matrix. A vug-connecting interparticle or moldic porosity has a higher ratio of perimeter-over-area than an isolated moldic pore at the same porosity, thus a higher $\gamma$ value. In our data set, higher $\gamma$ is found in samples with higher permeability at equal porosity. In the samples, DomSize and complexity (represented by PoA) show less influence on permeability than $\gamma$. Incorporating $\gamma$ into the prediction of permeability from porosity, the $R^2$ can be improved from 0.4 to 0.57 (about 17%).

Acoustic velocity
Acoustic velocities in the reefal carbonates have a broad range at any given porosity. At 5 Mpa effective pressure, compressional wave velocity ($V_p$) varies from 2898 m/s to 6137 m/s and shear wave velocity ($V_s$) varies from 1500 m/s to
3070 m/s. The compressional velocity is inversely related with porosity ($R^2=0.76$). At any given porosity, $V_p$ is significantly higher than the Wyllie’s time average (positive deviation). The deviation is at least 500 m/s higher than the time average curve but can reach as much as 2000 m/s above the curve. The DR samples exhibit a rigid behavior with little or no response in acoustic velocity to increasing effective pressures.

**Depositional environment and diagenesis.**

The positive deviation of the velocity in the analyzed samples is due to pervasive cementation of diagenesis. These reefal carbonates have developed a stiff frame in relatively short geological time (Pleistocene) without having undergone burial. The fusing of grains by cement is the most important factor in changing rock elastic behavior (Eberli et al., 2003).

The diagenesis directly affects the relationship between porosity and velocity. The phreatic and vadose samples show a different velocity characteristic due to different types of cement and pore structure. The vadose cements are concentrated at the grain contacts (meniscus cement). The phreatic cements are distributed around the grains or around molds (circum-granular cement). Meniscus cement in the vadose zone rock effectively welds the grains together, stiffens the rock, and increases the elastic moduli of the rock. However, circum-granular cements are not necessarily creating a better grain-to-grain contact. As a result, at any given porosity samples with vadose meteoric cements have a higher velocity than the phreatic zone samples.
Samples from the phreatic zone are dominated by small moldic pores (<300 µm) compared to the mostly large moldic and vuggy pores of the vadose zone. Because the reef crest and backreef samples are predominantly coarse-grained skeletal rocks, the moldic pores in the vadose samples are mostly larger than the finer-grained phreatic samples. Samples with larger moldic pores are reported to have a higher velocity than smaller moldic pores at the same porosity (Anselmetti and Eberli, 1993).

Control of pore structure on acoustic velocity

After porosity, pore structure has the second greatest influence on the acoustic velocity-porosity relation. Pore structure, derived from digital image analysis, explains most of the variation of Vp at any given porosity. At the same porosity, samples with larger (higher DomSize) and simpler (lower PoA) pore structure have a higher velocity than samples with a smaller (lower DomSize) and more intricate pore network (higher PoA). This size-structure pore relation in Pleistocene reefal carbonates corroborates previous findings by Weger et al. (2009) for other rock types. When the pore size, complexity, and microporosity are used in a multivariate linear regression to estimate Vp, the correlation of determination improves by 15%. from an R² of 0.76 (porosity alone) to an R² of 0.91.
**Electrical resistivity in the reefal carbonates**

The measured formation resistivity factor (FF) of the analyzed samples shows an inverse correlation to porosity ($R^2=0.59$). However, some significant scatter remains. Due to complex heterogeneity of rock fabric and pore structure in the Dominican Republic samples, there is no good correlation between the formation factor and pore type, rock texture, depositional environment, or diagenetic zones.

Pore connection is also an important factor controlling electric resistivity (Verwer et al., 2011). As such, resistivity on borehole logs is used as an estimation of permeability. In our data, the measured electrical resistivity does not correlate well to permeability. Pore parameters from 2-D digital image analysis of the DR samples, where bimodal or multimodal pore types co-exist, are not sufficient to explain pore connectivity.

In the analyzed samples, the correlation between electrical resistivity and DomSize (pore size) and PoA (pore complexity) is weak. However, in the bigger picture, a better correlation exists when the electrical measurement from this study data is compared to the Verwer et al. (2011) data. The weak correlation in this dataset is because the pore structure are simple (low PoA).

**5.2 Implications**

*Implications for estimating porosity and permeability from acoustic log*

In the DR reefal dataset, velocity deviates positively from the Wyllie’s time average curve. Both porosity and permeability show wide ranges. Porosity
ranges from 0.07 to 0.54 (fraction) and permeability ranges from 0.01 to 19400 md. The positive deviation from the Wyllie time average in the data is the result of pervasive cementation during early diagenesis. Meniscus type cements effectively glue grains together and create stiff rocks while at the same time preserving porosity and permeability. This finding implies that positive deviation is not always associated with separate vug porosity.

The estimation of porosity from acoustic velocity in the Dominican Republic samples is difficult. It can be improved by incorporating knowledge of pore structure obtained from digital image analysis of thin sections. The Dominican Republic data indicates that a significant improvement in estimating porosity can be achieved by combining pore structure information with the velocity data. To reliably estimate pore structure from any velocity and porosity, well-log analysis requires more confirmation from laboratory acoustic measurements combined with petrographic or digital image analysis.

**Implications for estimating porosity and permeability from electric log**

Electrical resistivity in carbonate rocks displays a remarkably wide range. At any given porosity, formation factor can vary up to and exceeding one order in magnitude. The formation factor inversely correlates to porosity with a correlation coefficient of 0.59. The estimation of porosity from acoustic velocity has a better correlation ($R^2=0.76$) than from the formation factor. This finding implies that the use of acoustic logs is better to estimate porosity, however, if the acoustic logs is not available, the electric logs can be utilized with precautions. The cementation
factor of the measured samples widely ranges from 2.1 to 5.3. In this study, both formation factor and cementation factor show a weak correlation to permeability. The implies that permeability estimation directly from electrical resistivity logs contains many uncertainties.

Variations of carbonate rock electrical resistivity in with equal porosities are the result of the pore structure (Verwer et al., 2011). Quantitative digital image analysis parameters, perimeter-over-area (PoA) and dominant pore size (DomSize), show a weak correlation to variations in electrical resistivity. This weak correlation is due to complexity in the pore structure. Any attempts to use 2-D thin section analysis to aid electric log interpretation needs to consider the complexity of the pore types/structures. This study also recognizes that the co-existence of multiple pore types in the rocks is a limitation in using Digital Image Analysis.

**Implications for interpreting porous interval in seismic data**

In carbonates, it is known that high impedance interval often have relatively high porosity. However, it is generally considered as reservoirs with separate (non-connected) vug porosity with limited reservoir quality. Weger et al. (2009) have clearly shown that rocks with large simple pore structure have high velocities. Many of these samples also have a high permeability. Thus, high impedance intervals on seismic data can potentially contain high quality reservoir rocks.
In the subaerially exposed reefal rocks from the DR, the acoustic impedance is typically high. Thus, samples from the study area provide very strong evidence that high impedance can exist in high porosity and high permeability intervals. Several samples with porosity higher than 20% and permeability greater than 100 md have velocity higher than the Wyllie time average. These data document that in the DR reefal carbonates, a link between high porosity, high velocity, and high permeability can exist. However, not every rock with high-velocity and high porosity has high permeability. Well-cemented rocks or coral framestone are fast and can have a low permeability. Both modes may exist in the same depositional sequences. In the Dominican Republic samples, the separation between these modes can be analyzed by examining diagenetic environments. The meteoric vadose samples generally have higher permeability for the high velocity and high porosity samples.
References


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Harris, P. M., 1979, Facies anatomy and diagenesis of a Bahamian ooid shoal: University of Miami, Comparative Sedimentology Laboratory, Sedimenta 7, 163 p.


Appendix 1
Stratigraphic Columns
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**Depositional Environment:**
- RC (Reef Coral)
- RF (Reef Framework)

**Diagenetic Zones:**
- MV (Metavolcanic)
- MP (Metapelite)
**Stratigraphic column of core Boca Chica-5**

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**Depositional Environment**
- RC

**Diagenetic Zones**
- MV
- MP
Appendix 2
Stratigraphic Columns and Petrophysical Properties
Petrophysical Properties of core Boca Chica-1

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### Petrophysical Properties of core Boca Chica-4

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