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Paleomagnetism and rock magnetism of the rocks of the Trenton-Black River groups, Dover Field southwestern Ontario.

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Paleomagnetism and Rock Magnetism of the rocks of the Trenton-Black River Groups, Dover Field Southwestern Ontario

By

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Abstract

Paleomagnetic and rock magnetic analyses were conducted on Ordovician specimens collected from two wells in the Dover Field and a reference core (OGS-83) in southwestern Ontario, for comparison to the results of Garner (2006) in the Hillman/ Goldsmith-Lakeshore Fields (HGLF). Single domain (SD) and pseudosingle domain (PSD) magnetite grains were observed in the Dover Field, differing from the SD and PSD pyrrhotite and magnetite with minor hematite content in the HGLF. Inclination-only analysis was used to determine the paleodirections of the wells for the Dover Field and the reference core OGS-83. Well A samples (dolomite) had a mean of I=-1.0° +3.0°/-3.4° (N=3, k=378.3), while two segments from Well B (limestone) had means of I=-15.8° +3.8°/-3.6° (k=83.0) and I=-8.3° +5.0°/-5.4° (k=46.2). The paleolatitudinal arc produced from Well A intercepted the Late Pennsylvanian and Permian sections of the reference apparent polar wander path, while the Well B arc intercepted the Pennsylvanian or the Triassic, and the OGS-83 arc intercepted the Permian. The Dover and HGLF (Garner, 2006) results differed, suggesting that the diagenetic history of the areas were not the same. Isotopic analysis suggested a shallower burial depth and lower temperature of dolomite formation in the Dover Field compared to HGLF.

Rock magnetic properties were examined before and after standard porosity and permeability analysis (PPA) to determine what affect, if any, there was on the magnetic minerals of samples from this study. Due to the inability of partial anhysteretic magnetization (pARM) analysis to remove an induced magnetization which was acquired either outside of the laboratory or during saturation isothermal magnetization (SIRM)

analysis, this technique did not provide useful results. The PPA did have an affect on the SIRM data; the SIRM values and 100/SIRM, 200/SIRM, 300/SIRM and 400/SIRM values increased for nearly all samples suggesting that the PPA increased either the concentration of grain size of the magnetic minerals. No discernable patterns in the pARM and SIRM changes related to lithology or similar factors were established. Further study on a larger number of samples may be required to determine if a consistent pattern exists.

Co-authorship Statement

The following thesis contains materials from two manuscripts that were prepared to be submitted to the Canadian Journal of Earth Science and the Journal of Geophysical Research.

1. Canadian Journal of Earth Science

The manuscript titled, "A Comparison of Paleomagnetism and Rock Magnetism of the Rocks of the Dover Field and the Hillman/Goldsmith-Lakeshore Fields of Southwestern Ontario.", is coauthored by S. A. Cascadden and M.T. Cioppa. Sample collection, laboratory work and data analysis present in this thesis was performed by the author. The submitted version of the manuscript appears in Chapter 2.

2. Journal of Geophysical Research.

The manuscript titled, "The Effects of Whole Core Analysis for Permeability and Porosity on Paleomagnetic and Rock Magnetic Signatures.", is coauthored by S.A. Cascadden and M.T. Cioppa. Sample collection, laboratory work and data analysis present in this thesis was performed by the author. The submitted version of the manuscript appears in Chapter 3.

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Statement of Originality

I certify that this thesis, and the research to which it refers, are the product of my own work, and that any ideas or quotations from the work of other people, published or otherwise, are fully acknowledged in accordance with the standard referencing practices of the discipline. I acknowledge the helpful guidance and support of my advisor, Professor Cioppa.

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

Shelie A. Cascadden

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1.0 INTRODUCTION

1.1 Introduction and Objectives

This paleomagnetic and rock magnetic study aims to determine the extent of fluid flow during the Alleghenian Orogeny. This study will examine the paleomagnetic and rock magnetic signatures of the Ordovician Trenton Group within the Dover Field (Ontario), and comparing those results to those obtained in the study on the Hillman/Goldsmith-Lakeshore Field (Garner, 2006). The Dover Field has been partially dolomitized and contains natural gas while the Hillman/Goldsmith-Lakeshore Fields have been completely dolomitized and contains oil and gas. Paleomagnetic techniques will be used to isolate unique magnetic signatures associated with diagenetic events. Paleomagnetic directions that reveal the age of the diagenetic event can help define fluid migration patterns that can be used to determine the extent of fluid flow.

The specific objectives of this thesis are:

1) To determine the paleomagnetic and rock magnetic signatures of the Trenton Group rocks in the Dover Field.
2) To compare the paleomagnetic and rock magnetic results with the observed variation in carbonate lithologies (dolomite vs. limestone) in order to examine the effects of dolomitization on the magnetic signatures.
3) To compare and contrast results in paleomagnetic and rock magnetic signatures from the Dover Field and non-reservoir reference core OGS-83 to those observed in the Hillman/Goldsmith-Lakeshore Fields to determine if the magnetization in

either or both of the fields can be compared to those observed elsewhere that have been attributed to the fluid flow during the Alleghenian Orogeny.

4) To determine the effects of standard whole core analysis for permeability and porosity on the rock magnetic and paleomagnetic signatures.

This thesis is formatted into four chapters. Chapter 1 provides a general introduction to this thesis and the paleomagnetic principles related to it. Chapter 2 is a paper for submission to the Canadian Journal of Earth Science. Chapter 3 is a paper for submission to the Journal of Geophysical Research. Chapter 4 provides the conclusion of this thesis as well as an integration of papers one and two.

1.2 Geology

1.2.1 Introduction

Since the 1920's, the Michigan Basin has been producing commercial quantities of oil and gas (Montgomery, 1984), mostly from the Middle Ordovician Trenton-Black River Group. The Ordovician sequence contains the greatest hydrocarbon accumulation in southern Ontario, and the rocks of the Trenton-Black River Groups are known to be one of the largest hydrocarbon reservoirs in the Michigan Basin and surrounding areas (Suk et al., 1993). This was proven when in 1956 the Albion-Scipio reservoir trend was discovered. By 1982 it was producing 97% of all oil recovered from the Michigan Basin, and spurred renewed interest in the southwestern margins of the Michigan Basin particularly the Trenton Group formations (Montgomery, 1984). By 2006, the Albion-

Scipio fields had produced more than 250 MM barrels of oil since discovery (Smith, 2006).

1.2.2 Depositional Environment

Southern Ontario is underlain by the Algonquin and Findlay Arches or up lifted zones, which are features of the Precambrian basement. The Algonquin Arch separates the Michigan and Appalachian Basins (Figure 1.1) and is bordered in the north by the Canadian Shield. There is a maximum of approximately 1500 m of Paleozoic strata covering this basement arch that pinch out, thin, or have been partially eroded over the crest of the arch, and thicken into the Michigan and Appalachian Basins (Carter et al., 1996). In southern Ontario the Paleozoic sedimentary rocks range in age from Upper Cambrian to Upper Devonian (Carter et al., 1996).

The focus of this study, the Middle Ordovician Trenton Group, consists of the Coburg, Sherman Fall and Kirkfield formations, and is overlain by the late Ordovician Blue Mountain Formation and underlain by the Cobocunk Formation of the Black River Group (Figure 1.2). Brookfield (1988) states that the Trenton Group consists of shallow to deep shelf sequences of alternating shale and limestone. Whether this sequence was formed in a tropical or cool water environment is unclear to date with arguments supporting both scenarios. Brookfield (1988) describes the Trenton Group's depositional environment as a carbonate ramp. The Trenton Group consists of interbedded calcareous shales and muddy carbonates which are mainly bioclastic (Liberty, 1969; Brookfield, 1988). The Trenton Group can be divided into four main facies that range from inferred shallow shoal to deep shoal and "basinal" facies (Brookfield, 1988) (Figure 1.3). Both the Trenton Group and the Black River Group limestones contain abundant carbonate mud consisting of micrite and recrystallized microspar (Brookfield, 1988). The Trenton Group limestone was deposited on a gentle carbonate ramp with carbonate sedimentation ending when the ramp facies were overstepped by basinal shales (Carter et al., 1988). The Black River Group consists of basal subaerial and tidal flat clastics overlain by supratidal, tidal flat and lagoonal carbonates. Figure 1.4 depicts the depositional facies for the Trenton Group, as determined by Brookfield and Brett (1998). There are three stages of basinal development (Figure 1.5) in the formation of the Trenton and Black River Group. Smosna (1991) described the first stage as a stable carbonate shelf on the passive continental margins where the Black River Group accumulated; the second stage consists of rapid subsidence of the basin and the formation of a carbonate ramp in which the Trenton Limestones were deposited; the third stage involves a major collision of the North American Plate with a volcanic arc system.

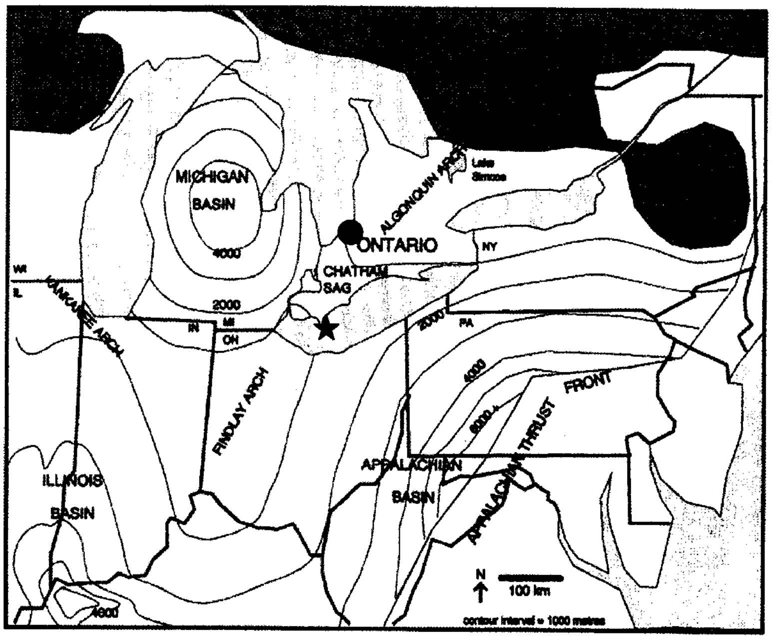

Figure 1.1. Regional structural setting of southern Ontario depicting the Michigan and Appalachian Basins (Carter et al., 1996)
★ Hillman Field ● Dover Field

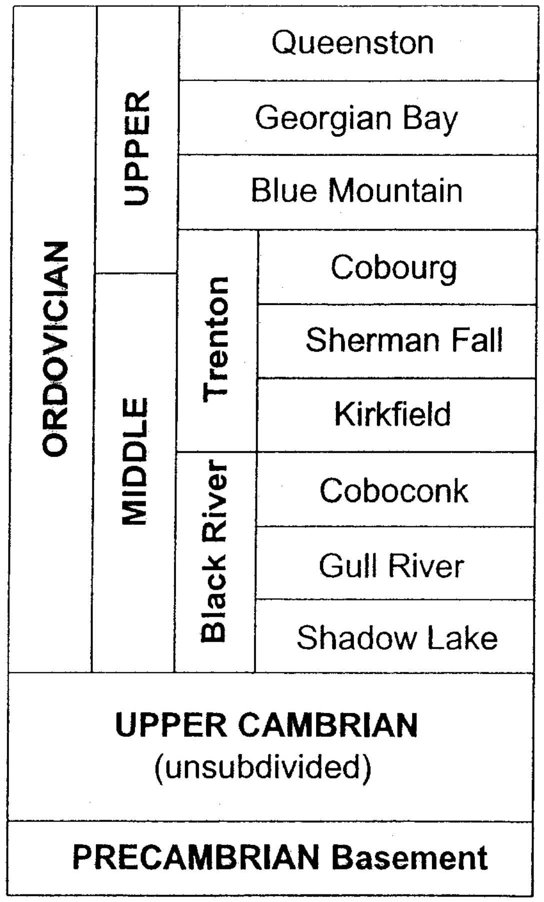

Figure 1.2. Stratigraphic column for Southern Ontario depicting the Upper and Middle Ordovician (Carter et al. (1996)).

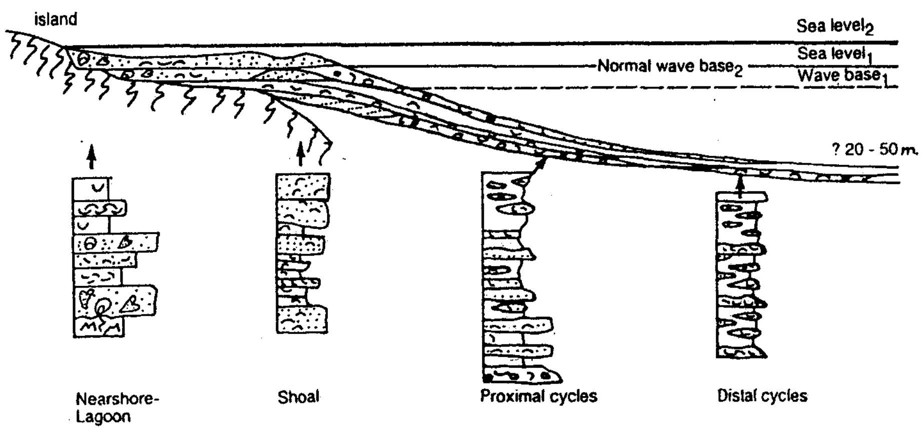

Figure1.3. The four main facies comprising the Trenton Group. (Brookfield and Brett, 1988).

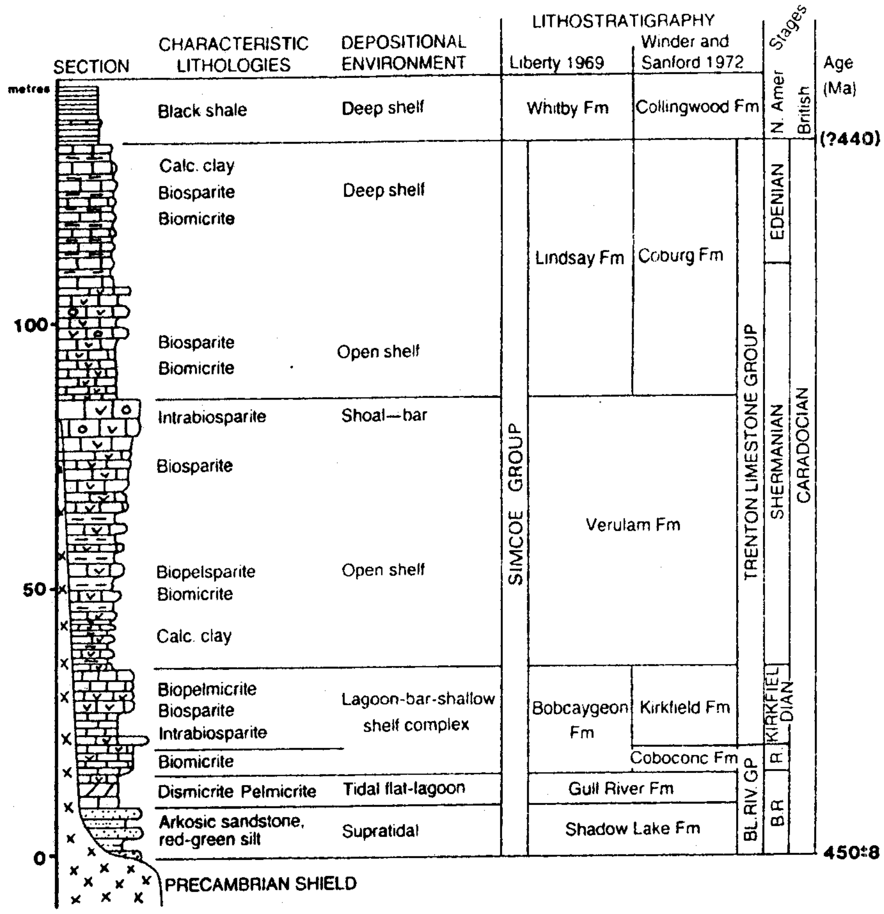

Figure 1.4. General depositional environment and stratigraphic sequence of Ontario Mid-Ordovician (Brookfield and Brett, 1988).

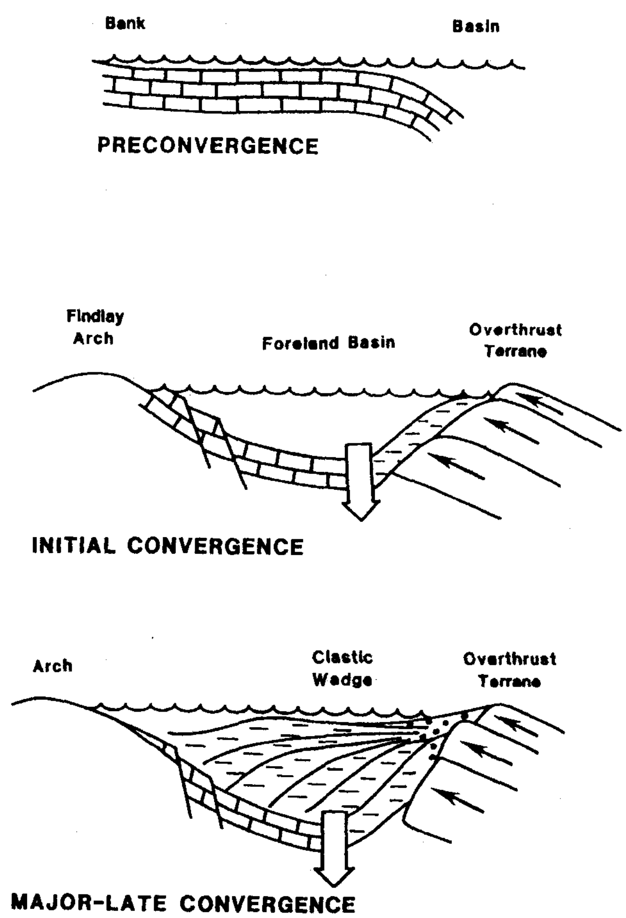

Figure 1.5. Three stages of basinal development related to the Trenton and Black River Groups.(Smasna et al., 1991).

1.2.3 Structure

The Paleozoic rocks of southern Ontario are virtually undeformed, however, tectonic activity has resulted in several major faults and multiple minor faults, which have an important role in the formation and trapping of hydrocarbons (Zeigler and Longstaffe, 1999). At various times in the Paleozoic the Algonquin Arch (Figure 1.1), which is where the study area is located, was tectonically active with periods of uplift of the arches occurring with or without subsidence of the Michigan and Appalachian Basins. The arch is an extension of the Findlay Arch to the southwest, and is separated from it by a major structural depression referred to as the Chatham Sag (Carter et al., 1996). Carter et al. (1996) referenced Johnson et al. (1992) and Sandford (1993a, 1993b), as stating there were several episodes of uplift of the Algonquin Arch and/or coincident subsidence after Cambrian time in the Michigan and Appalachian Basins. Carter et al. (1996) goes on to state that local relief on the buried basement surface is due to post-Precambrian faulting. The Ordovician carbonate rocks in eastern North America were deposited during a period of major tectonic activity coinciding with a large-scale transgression and during a period where there was a significant terriginous influx (Smosna et al, 1991).

It was speculated by Sanford et al. (1985) that the location and orientation of faults and fractures of the Paleozoic strata of Southern Ontario can be attributed to Precambrian basement fractures. Carter et al (1996) and Ziegler and Longstaffe (2000) suggested the faults acted as a conduit for fluid flow and can be responsible for the dolomitization of carbonate strata. However, the fault displacement typically does not extend to units overlying the Trenton (Carter et al, 1996). The faults within the Dover field generally have a westerly trend. The subsurface structural top of the Trenton Group typically has a depression over dolomitized zones (Figure 1.6) (Carter et al, 1996), and such areas of dolomitization commonly contain oil and gas. Smith (2006) suggested the structural depressions and structural sags formed as a result of the formation of negative flower structures (formed in trans-tensional parts of strike-slip fault zones), dissolution of limestone or dolomite, and/or volume reduction associated with the dolomitization of limestone. The majority of data on the structure of the reservoirs to date is derived from gravity, aeromagnetic, facies and isopach mapping (Carter et al, 1996).

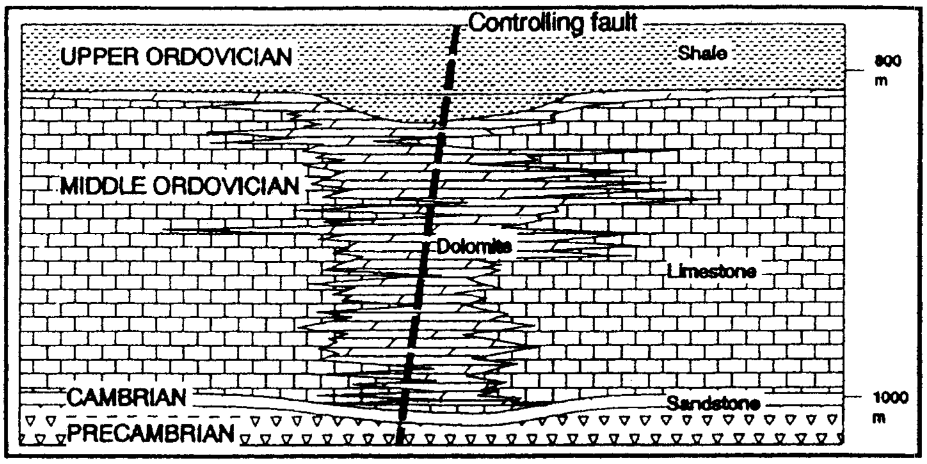

Figure1. 6. Geologic relations of an Ordovician hydrocarbon trap (Carter et al., 1996).

1.2.4 Dolomitization and Fluid Flow

It has been widely accepted that dolomitization of the Trenton and Black River Groups is a result of fluids migrating upwards through faults and fractures (Carter et al. 1996; Ziegler and Longstaffe 2000; and Colquhoun and Trevail 2000). There are various suggestions for the origin of the fluids that resulted in the diagenesis of the study area. Suk et al (1993) suggested that the fluids responsible for the diagenesis of the Trenton and Black River Group are basinal brines mixed with meteoric recharge on the margins of the basin. There is strong evidence of a late stage Paleozoic diagenetic event attributed to the migration of fluids during the Alleghenian Orogeny. Schedl et al., (1992) listed two possible sources of this fluid migration: 1) topographically driven flow of meteoric waters, and 2) basinal brines and hot, over-pressured fluids released by metamorphic reactions deep in the crust. Both of the above could have caused regional diagenesis. However, Suk, et al., (1993) indicated that the several arches bounding the Michigan Basin isolated the basin and probably restricted the influx of tectonically driven fluids from the outside of the basin. From the evidence provided above , it is not clear if the source of the fluids associated with the late Paleozoic diagenetic event can be correlated between this event and the dolomitization associated with the fluid migration through faults and fractures.

Taylor and Sibley (1986) described three types of dolomite in the Trenton Group. These are: 1) cap dolomite, 2) fracture-related dolomite, and 3) regional dolomite. The cap dolomite is found in the upper part of the Trenton and in the perimeter of the basin, however it does not exist in the northern part of the basin. Through petrographic and geochemical analysis it was determined that the cap dolomite formed at relatively shallow depths. The regional dolomite is present only in the western and south-western edges of the basin. Fracture-related dolomite is generally related to fractures, sub-surface faults and structures mostly in the southern part of the basin and post-dates the cap dolomite and formed during deeper burial. Brookfield (1988)/Mukherji (1969) stated the dolomitization of the Black River limestone occurs as early syngenetic replacements and late diagenetic replacements.

1.2.5 Study Location

The study area is located in Dover, Ontario, more specifically in two wells within the Dover Field. The two wells are identified as Well A (PPC/ROMA-#12-7-16-IV) and Well B (PPC/RAM-#12-7-6-IV). An additional non-reservoir reference core Well OGS-83 located in southwestern Ontario was used for comparison. The information gathered from these three cores was compared to four cores from the Hillman/Goldsmith-Lakeshore Fields also located in southwestern Ontario (Colquhoun, 1991; Garner 2006).

As core logging during the sampling phase for this thesis indicated that the extent of dolomitization of the study areas varies, the mechanisms responsible for and variables controlling the extent of dolomitization are of concern. The Dover Field is located within the Chatham Sag and comprises partially dolomitized limestone. The non-reservoir reference core is mostly limestone, and the Hillman and Goldsmith-Lakeshore Fields are almost completely dolomitized, with only one small interval in one of four cores remaining limestone (Colquhoun 1991 and Garner 2006). The extent of dolomitization may be significant when looking for hydrocarbon reservoirs.

1.2.6 Recent Research

General studies on the carbonates of the Trenton-Black River Groups and the carbonate rocks of southwestern Ontario fall into two major categories. Some of the studies such as Carter et al. (1988), Brookfield and Brett (1987), Mukherji (1969) and Brookfield (1988) were concerned with determining the depositional environment of the Trenton Group in southwestern Ontario. Various other studies such as Harper et al. (1995), Duffin (1989), Zeigler and Longstaffe (2000) and Zeigler and Longstaffe (1997) were concerned with the origin of K-feldspar, clay mineral authigenesis and hydrogen isotopes to study K-feldspar alteration respectively. Duffin (1989) and Harper et al. (1995) studied the authigenic K-feldspar alteration that occurs directly below the Cambrian-Precambrian unconformity. The alteration is widespread and gives a date of approximately 549 ± 18 Ma (Early Cambrian). This K-feldspar formed by replacement of primary feldspar, which is thought to be caused by hot brine moving along the Precambrian-Paleozoic unconformity, as the estimated temperatures for the formation of secondary K-feldspar exceed the known burial temperatures in southwestern Ontario. This fluid alteration affected much of the mid-continent North America including the Trenton Group.

Zeigler and Longstaffe (1997) studied the oxygen isotopic composition of various alteration minerals in southwestern Ontario ranging from Upper Cambrian to Middle Ordovician in age. These studies indicate an initial hot brine from evolved Paleozoic seawater and the later mixing of meteoric water with the brines. Subsequently, Zeigler and Longstaffe (2000) examined the chlorite and illite alteration in southern Ontario. The chlorite alteration is consistent with abasinal brine evolved from seawater. Comparatively, the illite alteration is consistent with tepid meteoric water. The introduction of the meteoric water is thought to have resulted from the Taconic Orogeny to the east.

Carter et al. (1996) studied hydrocarbon traps in southern Ontario. This study determined that the traps appear to be associated with faults and fractures in the Paleozoic rocks of southern Ontario. As this theory grew in popularity, a slew of studies were conducted by Ziegler and Longstaffe (2000), Colquhoun and Trevail (2000), Smith (2003), Smith and Nyahay (2004), and Davies and Smith (2006) which confirmed its plausibility. A study by Sagan (2004) used 3-D seismic and structural investigations to add further insight to the fault systems within the Trenton-Black River groups. This theory is important because the formation and migration of hydrocarbons in southern Ontario was not well understood previously.

While there have been several paleomagnetic studies of the Trenton Group as a whole, such studies done on the Trenton dolomites are sparse. Most major studies examined the Trenton Group outcrops in the United States, which usually consist of limestone rather than dolomite. The most recent paleomagnetic work done on the Trenton Group was by Suk et al. (1993) and Garner (2006), with earlier work by Jackson (1990), McCabe et al., (1984) and McElhinney and Opdyke (1973). Suk et al. (1993) confirmed earlier work by

Kent (1979, 1985); McCabe et al. (1983, 1984); Jackson et al. (1988) which demonstrated that the areas sampled in the Michigan Basin had been remagnetized during the late Paleozoic, presumably as a result of the Alleghenian Orogeny. Garner (2006) conducted a paleomagnetic and rock magnetic analysis of the Trenton Group dolomites in the Hillman/Goldsmith-Lakeshore Fields and concluded that the earliest remagnetization event or magnetization age observed in this area was Permian and observed in the single small interval of limestone. A remagnetization associated with the dolomitization occurred in the Late Paleozoic to Early Mesozoic. This study also concluded that a calcite fracture fill event occurred in the Triassic.

It has been suggested that the remagnetization of the Trenton Group occurred during the Kiaman reversed Polarity Superchron (Suk et al. 1993; Kent 1979, 1985; McCabe et al. 1983, 1984; Jackson et al. 1988). The Permo-Carboniferous reversed polarity superchron is an interval of virtually constant reversed polarity lasting for ~70 m.y. from the mid-Carboniferous through the majority of the Permian (Butler, 1992), and is also know as the Kiaman interval. The Alleghenian Orogeny-induced remagnetization occurred during this interval, and is often referred to as the Kiaman overprint or Kiaman remagnetization (McCabe et al. 1995).

Smith (2006) conducted a study on the Trenton-Black River hydrothermal dolomite reservoirs in New York to determine the origin and characteristics of the reservoirs. This study used previous fluid inclusion and CAI studies to determine that all Trenton-Black River dolomites in Ohio, Michigan and Ontario are undoubtedly hydrothermal in origin.

Smith (2006) demonstrated that the dolomite fields in New York, Ohio, Michigan and Ontario are a result of wrench faulting and bottom-up hydrothermal fluid flow, mainly occurring in the Late Ordovician.

1.3 Principles of Paleomagnetism and Paleomagnetic Dating

1.3.1 The GAD model and apparent polar wander

The geocentric axial dipole (GAD) model is an essential concept to many paleomagnetic principles. The model is shown in Figure 1.7 and considers the magnetic field (H) of the Earth to be produced by a single magnetic dipole (M) at the center of the Earth, aligned with the rotation axis with λ representing the geographic latitude, r_e the mean Earth radius and I the inclination of the magnetic field (Butler, 1992). Butler (1992) defines inclination and declination as: inclination is the angle measured from horizontal, ranging from -90° to +90° and defined as positive downward; declination is the angle from geographic north to horizontal, ranging from 0° to 360°, positive clockwise. The model and associated equation for determining inclination are independent of declination, therefore, for a GAD, the declination is approximately zero everywhere. The model relates M, I, λ and H through the dipole equation:

$$H_v = \frac{2M \sin \lambda}{r_e^3} \qquad \text{(equation 1.1)}$$

$$H = \frac{M \sqrt{1 + 3 \sin 2\lambda}}{r_e^3} \qquad \text{(equation 1.2)}$$

with the inclination of the field being determined by:

$$\tan I = \frac{H_v}{H_h} = \frac{2 \sin \lambda}{\cos \lambda} = 2 \tan \lambda \qquad \text{(equation 1.3)}$$

The model allows paleomagnetists to obtain the magnetization age of rocks. The magnetization contained within a rock (or sediment) has two angles relative to the Earth's surface: inclination (I) and declination (D). The declination and inclination are obtained as the magnetic minerals align themselves with the Earth's magnetic field during rock formation. If the inclination and declination of the rock's magnetization do not correspond to the inclination and declination of the current magnetic field, the magnetization must have formed at a different time or place than its current location. Since the inclination is directly related to the latitude at which the rock's magnetization was formed, the magnetization can be used to determine the place on the Earth's surface where it was formed. One can determine the direction of the geomagnetic field at the time when the magnetization was formed by comparison to a set of known reference directions determined for each continent (e.g. van der Voo, 1993; and Besse and Courtillot, 1988, 1991, 1994).

If the rock sampled has not moved since the magnetization was formed, it is possible to calculate a pole position using the declination and inclination obtained from paleomagnetic analysis. The calculated pole for a stationary rock will coincide with the GAD. However, over time, areas and continents move due to plate tectonics, and the movement results in the calculated pole shifting from the GAD. This is known as the apparent polar wander (APW). Specifically, through the geocentric axial dipole method, an apparent polar wander path (APWP) represents the apparent motion of the rotation axis with respect to the continent of observation (Butler, 1992). For simplicity's sake, an APWP is usually displayed with a continental plate in a fixed position, although in reality the magnetic poles remain stationary and the continents are in motion. Paleomagnetists have constructed apparent polar wander paths (APWPs) for various continents, as the movement (drift) of each continent varies. Generally, continental drift can change the observed latitude and longitude of a rock but does not change the induced declination and inclination (Cioppa et al. 2003). Essentially, an APWP plots sequential positions of paleomagnetic poles for a specific continent, with each continent having its own path, and is usually shown on the present geographic grid (Butler, 1998) (Figure 1.8). By comparing the calculated paleopoles to the reference APWP for its continent, a date of magnetization or rock formation can be obtained.

1.3.2 Remanent Magnetizations

The natural remanent magnetization (NRM) is the permanent magnetization in a rock which is present prior to any laboratory treatments (Butler, 1992). Piper (1987) describes NRM as the vector resultant of the primary magnetization (acquired when the rock was formed) and any secondary magnetization (acquired during a subsequent geologic time).

Butler (1992) defines three basic types of primary NRM; 1) chemical remanent magnetization (CRM; 2) detrital remanent magnetization (DRM); and 3) thermoremanent magnetization (TRM). The two types of magnetization important to this study are CRM and DRM since these types of magnetizations are inherent in sedimentary rocks.

Detrital remanent magnetization is acquired during deposition and lithification of sedimentary rocks (Butler, 1992). A depositional DRM occurs when particles are aligned with the magnetic field at the time of deposition. The acquisition of a post-depositional detrital remanent magnetization (pDRM) occurs after deposition but before consolidation, with compaction being an important process. Depositional and post-depositional alignment depends on: 1) grain size; 2) rate of depositionl and 3) bioturbation.

A chemical remanent magnetization (CRM) is acquired by chemical changes that form ferromagnetic minerals, that is minerals with atoms that have a magnetic moment, below their blocking temperatures in a magnetizing field (Butler, 1992). The stability of the magnetic minerals is dependant on grain size. Chemical magnetizations may destroy primary NRM and replace it with the CRM. If the CRM is acquired long after deposition it may be considered secondary. There are two types of chemical reactions involving ferromagnetic minerals that can create a CRM: 1) precipitation or growth of a ferromagnetic mineral from solution, and 2) alteration to a ferromagnetic mineral from a pre-existing mineral. Alternatively, secondary NRM can be the result of chemical changes affecting ferromagnetic minerals, exposure to lightning strikes, or long-term exposure to the geomagnetic field after rock formation (Butler, 1992).

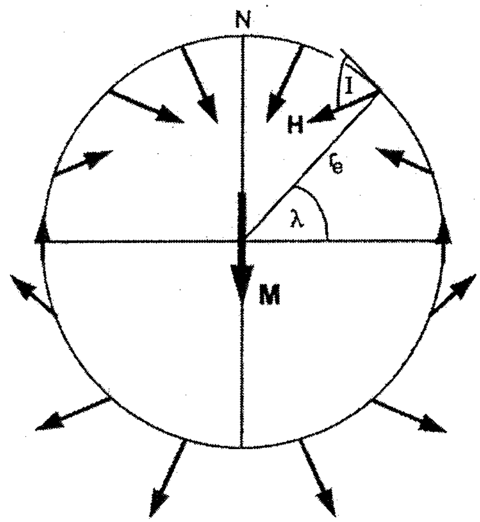

Figure 1.7. Geocentric axial dipole model. The magnetic field direction at the Earth's surface produced by the geocentric axial dipole are shown. M is the magnetic dipole moment, is the geographic latitude, re is the mean Earth radius, I is inclination, N is the north geographic pole and H is the magnetic field vector (Butler, 1992).

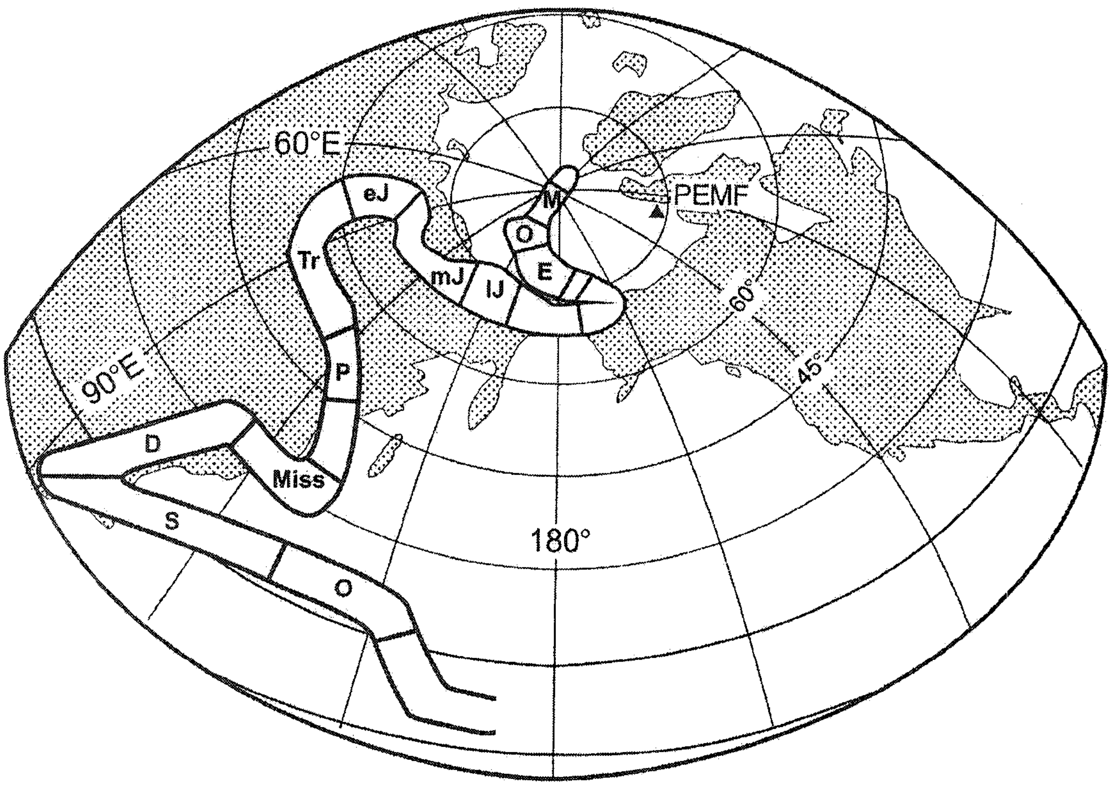

Figure 1.8. Apparent polar wander path for North America (Besse and Courtillot, 1988 and Van der Voo, 1993).

1.3.3 Remagnetization

The natural remanent magnetization is acquired during rock formation and is dependent on the orientation and intensity of the magnetic field at the time of formation, the location of the rock, and geologic processes during rock formation. After formation it is possible to acquire a secondary magnetization. A secondary magnetization results from a chemical change, lightning strike, or long term exposure to the geomagnetic field after rock formation that affects ferromagnetic minerals (Butler, 1998). Over time rocks may be exposed to several events that can produce a secondary magnetization

In this study there are two secondary magnetizations of particular interest: thermoviscous remagnetization and chemical remanent magnetization (CRM). A thermal remagnetization is produced when the temperature is increased above the Curie Temperature either by burial and metamorphism or the introduction of hot fluids and is subsequently cooled in the presence of a magnetic field (Butler, 1998). As mentioned previously, chemical magnetizations occurs when ferromagnetic grains are formed by chemical changes that alter pre-existing ferromagnetic minerals or precipitate new ferromagnetic minerals in a rock (Butler, 1998). If the CRM is produced by fluid migration through the rock, the direction of that CRM can be used to date the fluid migration event – a possibility that has been explored extensively for MVT deposits by Symons et. al. (need a couple of references – look on georef), and has potential for similar use in hydrocarbon migration. Since fluids containing hydrocarbons from the Alleghanian Orogeny are believed to have had some effect on determining reservoir properties and/ or reservoir filling in the study area, dating the timing of fluid migration is potentially an important result of this study.

1.4 Methodology

1.4.1 Sampling

Samples were taken from two vertical wells within the Dover Field in southwestern Ontario; Well A (PPC/ROMA-#12-7-16 IV) and Well B (PPC/RAM-#12-7-6-IV). The two cores are comprised of partially dolomitized limestones. Additional samples were taken from a nearby non-reservoir core (Well OGS-83) which is comprised of limestone. Orientation of cores was done as per Cioppa et al. (2000). An arbitrary master orientation line (MOL) was determined by reassembling the core segments and using the longest segment possible and drawing a line down the middle of the core. With an MOL in place, the plugs are drilled and oriented with respect to this reference line. Plugs from the different facies were drilled perpendicular to the MOL and the azimuths of each plug were measured with reference to the MOL. Oriented specimens from Well OGS-83 were not possible because only fractions of the core were available for sampling. A total of 146 samples were collected from 23 segments from the Dover Field; and a total of 24 samples were collected from the non-reservoir reference core OGS-83.

1.5 Magnetic Methods

1.5.1 Paleomagnetism and Rock Magnetism

Approximately 146 samples were collected from the Trenton Group in the Dover Field from Well A and Well B for paleomagnetic and rock magnetic analysis. Additionally, about 24 samples were collected from the nearby reference well (OGS-83). A series of magnetic analyses were conducted on various specimens.

The natural remanent magnetization (NRM) was measured for all samples prior to analysis on a 2-G Enterprise DC-SQUID cryogenic magnetometer, with a sensitivity of about 2×10^{-6} A/m. Samples were then selected for either thermal or alternating field (AF) demagnetization. The thermal demagnetization was carried out using a MMTD-1 thermal demagnetizer in 17 steps from 80° to 450°. Thermal demagnetization involves exposing a sample in steps of increasing temperatures to identify the main magnetic minerals present. Each magnetic mineral has a unique unblocking temperature, and thus magnetization directions carried by specific minerals can be isolated. In general, the magnetization intensity decreases with increasing temperature, becoming zero at the Curie temperature (Butler, 1992). Alternating field demagnetization was carried out using a Sapphire Instruments SI-4 demagnetizer in 14 steps from 5 to 140 mT. AF demagnetization is useful for isolating the primary magnetization of a specimen containing magnetite or pyrrhotite.

Once AF demagnetization was completed, 10 samples from each of Well A and Well B were selected for partial anhysteretic magnetization (pARM) and then saturation isothermal magnetization (SIRM) analyses to determine grain size and mineralogy. pARM's were imparted by exposing the samples to a small direct magnetic field in the presence of a large, decreasing alternating field which results in a remanent magnetization placed on grains that have coercivites in the range of the biasing field. pARM's were imparted in 10 steps from 10 to 100 mT with a magnitude of 0.05 mT. pARM magnetizes a fraction of the magnetic grains in the corresponding coercivity range (Jackson et al., 1988). As the coercivity is inversely related to the grain size, a decrease in grain size gives greater values of pARM at higher coercivities.

SIRM analysis involved treating specimens in 16 steps from 5 to 1200 mT, increasing the intensity after each step. Following acquisition we demagnetize the sample using AF demagnetization in 9 steps from 5 to 120 mT. Both sets of results were then plotted on a log graph and the curves obtained from these measurements were then compared to the normalized acquisition and decay curves of specific magnetic minerals (Symons and Cioppa, 2000) in order to determine the magnetic minerals and their corresponding grain size.

1.5.2 Component Analysis

Individual sample directions were calculated using principal component analysis (Kirschvinck, 1980). Only components with a maximum angular deviation of $<11^{\circ}$ were considered for this analysis. Additionally, most components were defined over three or more demagnetisation steps. Segment means were calculated using Fisher statistics (1953). Where a DIRM was present a viscous remanent magnetization correction to the present Earth's magnetic field was not possible on these specimens, therefore, an inclination-only mean was calculated (Enkin and Watson, 1996). Results from these segment means were then compared with the APWP (Van der Voo 1993) to determine their approximate age.

1.5.3 Storage

Before the magnetic analysis, specimens were stored in a magnetically shielded room for 2 months in order to remove any laboratory induced remanences due to drilling. Samples are stored in the magnetically shielded room throughout analysis.

1.5.4 Geochemistry and Petrography

Thin sections were made from 20 of the core samples, ten from Well A and ten from Well B. The thin sections were stained with a mixture of Alizarin Red-S and potassium ferricyanide following the procedure outlined by Dickenson (1966). This method of staining can by used to distinguish between carbonates according to their composition.

The staining can also be used to distinguish between ferroan calcite which would stain purple and non-ferroan calcite which would stain red to pink. In the same manner ferroan dolomite would stain a blue colour and non-ferroan dolomite would remain unstained. The thin sections were examined using a standard petrographic microscope.

Using the results of the thin section analysis, 16 samples were chosen for $\delta^{18}O$ and $\delta^{13}C$ isotope extraction and analysis, based on lithology, diagenetic features and cements. The samples were extracted from the core using a microscope mounted drill assembly and were powdered. The samples underwent chemical separation (Al-Aasm et al. 1990). The powdered samples were reacted *in vacuo* with 100% pure phosphoric acid (H_3PO_4) for a minimum of four hours at 50°C for dolomite extraction and 25°C for calcite. During the reaction CO_2 gas was produced which was then analysed for isotopic ratios on a thermo Finnigan DeltaPlus isotope ratio mass spectrometer (IRMS) at the University of Windsor. Oxygen and carbon isotopes are reported in per mil (‰) relative to the VPDB (Vienna PeeDee Belemnite) standard.

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2.0 A Comparison of Paleomagnetism and Rock Magnetism of the Rocks of the Dover Field and the Hillamn/Goldsmith-Lakeshore Fields of Southwestern Ontario

2.1 Introduction

Historically the Trenton-Black River Groups have been major oil and gas producers within the Michigan Basin. Many small and large oil and gas reservoirs have been discovered in the Trenton Group in Ontario, Michigan, Ohio and more recently in south-central New York (Smith, 2006). The carbonate rocks of this formation consist of limestone, partially dolomitized limestone and dolomite. It has been widely accepted that dolomitization is a result of fluids migrating upwards through faults and fractures (Carter et al. 1996, Ziegler and Longstaffe 2000, Colquhoun and Trevail 2000). Harper et al. (1995) proposed that fluids traveling along the Precambrian-Paleozoic unconformity affected porous and permeable rocks above and below it. Ziegler and Longstaffe (2000) studied rocks both above and below the unconformity and confirmed that fluid migration along the Precambrian-Paleozoic unconformity into the overlying Ordovician rocks resulted in authigenic clay mineralization.

Several authors have suggested that the fracture controlled dolomitization of limestone patch reefs led to an increase in porosity within the reef, thus resulting in potential hydrocarbon reservoirs (Ziegler and Longstaffe, 1999). The dolomitization patch reefs pf the Trenton-Black River Group have thus been a major target for hydrocarbon exploration in the Appalachian and Michigan Basins.

The study area is located within the southeastern edges of the Michigan Basin, bordering the Appalachian Basin, and thus providing an excellent test site for investigating the migration of fluids from the Appalachian into the Michigan Basin during the Alleghanian orogeny. The Dover Field is located within the Chatham Sag while the Hillman/Goldsmith-Lakeshore Fields are located on the edge of the Findlay Arch. The Hillman/Goldsmith-Lakeshore Fields contained oil and gas while the Dover Field only contained natural gas.

It has been proposed that the precipitation of authigenic magnetite is related to hydrocarbon migration (McCabe et al., 1987 and Elmore et al., 1987). Studies conducted by McCabe et al. (1984) and Suk et al. (1993) recognize a late Paleozoic remagnetization held in magnetite minerals within the Trenton Group carbonates. This remagnetization has been related to the Alleghenian Orogeny and, more specifically, the late Paleozoic Kiaman Superchron which occurred at the same time which can complicate some studies.

The aims of this study are:

1. To compare the paleomagnetic and rock magnetic characteristics of samples collected from the Dover Field in south-western Ontario, the Hillman and Goldsmith-Lakeshore Field in southwestern Ontario (Garner, 2006) (Figure 1).
2. To compare the reservoir characteristics to those of a non-reservoir reference core located between the two fields.

3. To determine if magnetization ages in the two areas are the same or different in order to investigate the role the migration of fluids generated by the Alleghenian Orogeny played in creating magnetizations.

The study will use traditional geochemical and petrographic analysis in conjunction with paleomagnetic and rock magnetic methods. Recent studies by Cioppa et al. (2000), Cioppa et al. (2001), Cioppa et al. (2002), and Cioppa et al. (2003) have shown that paleomagnetism when combined with geochemical and petrographic analysis can be used to date specific diagenetic events associated with hydrocarbon reservoirs.

2.2 Methods and Well Description

2.2.1 Well Description

The focus of this study, the Trenton-Black River Group, is overlain by the late Ordovician Blue Mountain Formation and is underlain by the Cobocunk Formation of the Black-River Group. The Middle Ordovician Trenton Formation consists of the Coburg, Sherman Fall and Kirkfield formations in descending order (Figure 2.1). The cores examined for this study consist of two cores from vertical wells associated with hydrocarbon reservoirs in the Dover Field; one non-reservoir core OGS-83 and four cores from two oil producing wells from the Hillman and Goldsmith-Lakeshore pools in southwestern Ontario (Garner, 2006). The lithologies studied vary from limestone to partially dolomitized limestone to dolomite.

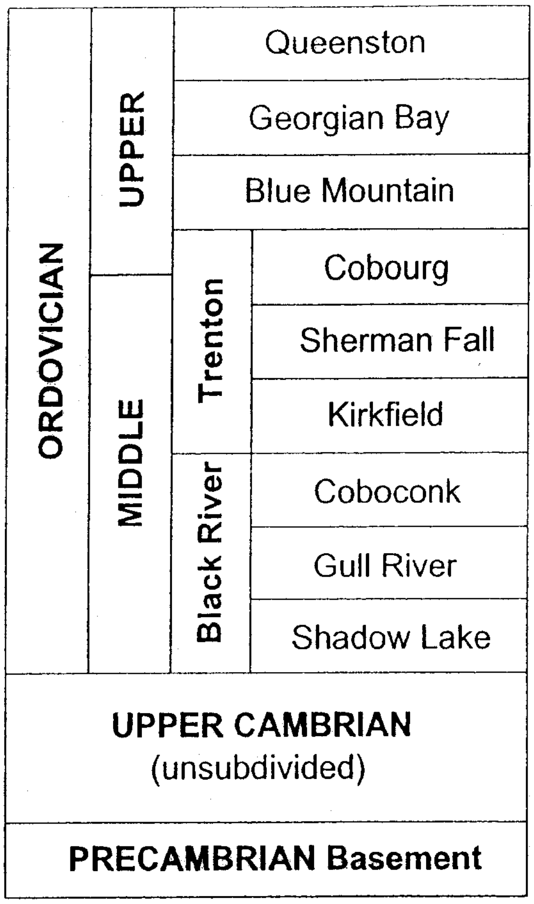


Figure 2.1. Stratigraphic column for Southern Ontario depicting the Upper and Middle Ordovician (Carter et al. (1996)).

2.2.2 Methodology

Sampling techniques and orientation methods are described by Cioppa et al (2000). Two wells were sampled from the Dover Field; Well A (PPC/ROMA-#12-7-16-IV) and Well B (PPC/RAM-#12-7-6-IV). In addition, 24 samples were collected from a non-reservoir reference well (OGS-83). All specimens were stored in a magnetically shielded laboratory at the University of Windsor throughout the testing and analysis. The remanence was measured using a 2-G DC-SQUID cryogenic magnetometer.

Specimens from the Dover Field and OGS-83 were divided into two groups one group undergoing thermal demagnetization in approximately 17 steps from 80^{o} to 450^{o} using a Magnetic Measurements MMTD-1 thermal demagnetizer. Thermal demagnetization was terminated when the measurements suggested chemical alteration had occurred in the samples. The second group was subjected to Alternating Field (AF) demagnetization in 14 steps from 5 to 140 mT using a Sapphire Instruments SI-4 demagnetizer.

Upon completion of AF demagnetization, 10 representative samples were selected to determine magnetic mineralogy and granulometry using various rock magnetic techniques. Partial anhysteretic magnetization (pARM) was used to determine the coercivity range of magnetic minerals in specimens. Saturation isothermal demagnetization (SIRM) was used to determine which magnetic minerals are present and their corresponding grain size.

pARM's were imparted by exposing the samples to a small direct magnetic field in the presence of a large, decreasing alternating field which results in a remanent magnetization placed on grains that have coercivites in the range of the biasing field. pARM's were imparted in 10 steps from 10 to 100 mT with a magnitude of 0.05 mT. pARM magnetizes a fraction of the magnetic grains in the corresponding coercivity range (Jackson et al., 1988). As the coercivity is inversely related to the grain size, a decrease in grain size gives greater values of pARM at higher coercivities.

SIRM analysis involved treating specimens in 16 steps from 5 to 1200 mT, increasing the intensity after each step. Following acquisition we demagnetize the sample using AF demagnetization in 9 steps from 5 to 120 mT. Both sets of results were then plotted on a log graph and the curves obtained from these measurements are then compared to the normalized acquisition and decay curves of specific magnetic minerals (Symons and Cioppa, 2000) in order to determine the magnetic minerals and their corresponding grain size.

Petrographic (thin-section) analysis was conducted on 20 samples from the Dover Field, 10 from Well A and 10 from Well B the selection of samples was based on facies. Thin sections were examined using a standard microscope. Based on the results of the thin section analysis 16 samples were selected for $\delta^{18}O$ and $\delta^{13}C$ stable isotope analysis based on the chemical separation method by Al-Aasm et al. (1990).

2.3 Results

2.3.1 Core Logging

Core A is comprised of limestone with alternating layers of dolomite. There are abundant stylolites with occasional dissolution occurring around the stylolites. Chert nodules, vugs, and fossils are also visible. Core B is comprised predominantly of limestone with occasional wispy shale layers. There are occasional vugs and fossils visible.

2.3.2 Paleomagnetic Directions

Prior to analysis, demagnetization steps below 100°C and 5 mT were discounted due to the probability of these values resulting from a spontaneous viscous remanent magnetization either in the laboratory or during core storage. Thermal and alternating field demagnetization results indicated that approximately 42% of the samples from the cores in the Dover Field had an apparent drilling induced remanent magnetization (DIRM) which was removed by temperatures of approximately < 270°C, while 10% of the reference core OGS-83 had a DIRM. Colquhoun (1991) cited Pinto and McWilliams (1990) as indicated nearly vertical inclinations of >80° are probably acquired during coring. Therefore, samples with a low temperature magnetization component inclination of > 80° were discounted from the analysis. A viscous remanent magnetization correction to the present Earth's magnetic field was not possible on the specimens with these steep inclination values, therefore, an inclination-only mean was calculated (Enkin and Watson, 1996).

The specimens that did not have a DIRM carried two components which can be seen in Figures 2.2, 2.3 and 2.4. The first component represents a viscous remanent magnetization (VRM) which is low temperature / low coercivity and lies between 68° and <80° which is in agreement with the present Earth's magnetic field (PEMF), which has an inclination of 70°, for the locations in the study areas. The second component represents the characteristic remanent magnetization (ChRM) which is high temperature and ranges between ~1° and ~40°.

The two wells in the Dover Field produced different results. Well A is comprised of dolomites and partially dolomitized limestone which were examined as a single segment based on the paleomagnetic results. The core from this well was less affected by a DIRM, however, the samples displayed a non-Fisherian distribution (Figure 2.5) and therefore an inclination-only mean was calculated (Enkin and Watson, 1996). The segment-based inclination only mean for Well A based on lithology was I=-1.0° +3.0°/-3.4° (N=3, k=378.3).

The second well form the Dover Field, Well B, is comprised of limestone. Two segments were fitted together in this well, one with 32 specimens, and one with 30 specimens. Similar to Well A, this well was also affected by a DIRM and also did not produce a Fisherian distribution (Figure 2.6), therefore an inclination-only mean was also calculated for both segments of the well. The inclination-only mean for the two segments was I=-15.8° +3.8°/-3.6° (k=83.0) and I=-8.3° +5.0°/-5.4° (k=46.2).

The non-reservoir reference well OGS-83 is comprised of limestone. Since a non-fisherian distribution was also produced for this well (Figure 2.7) an inclination-only mean was also calculated for this well. The inclination-only mean was I=-6.6° +3.7°/-3.8° (k=48.3).

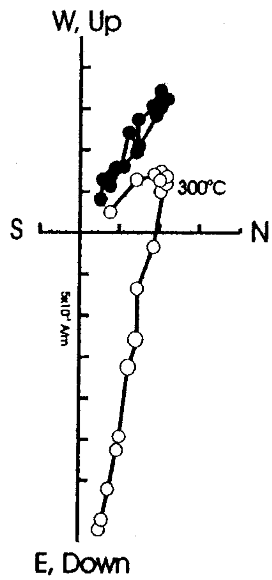
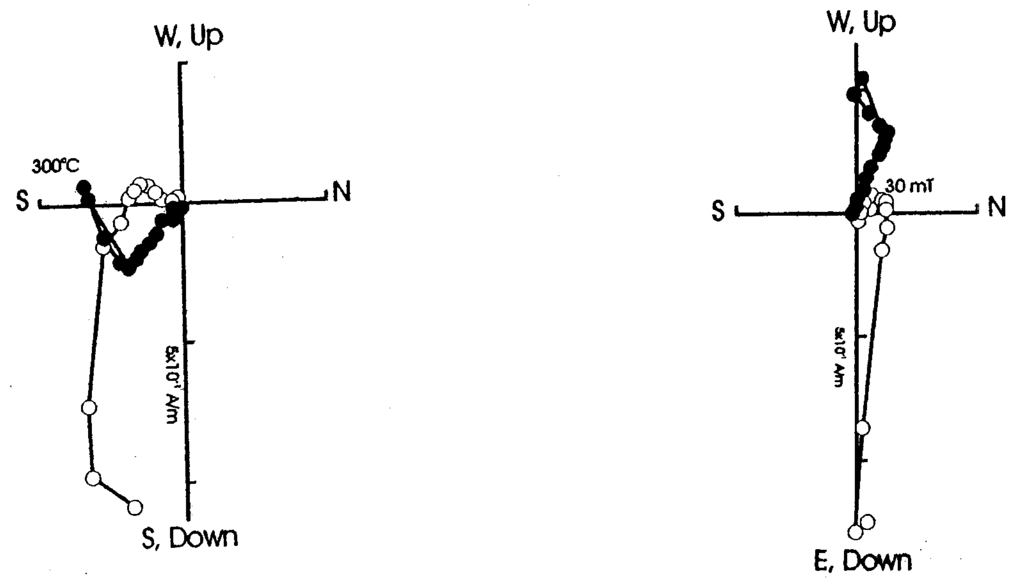


Figure 2.2. Non-azimuthally oriented orthogonal demagnetization (Zijderveld, 1967) for representative specimens from Well A. Thermally demagnetized specimen 011702.



a) **b)**

Figure 2.3. Non-azimuthally oriented orthogonal demagnetization (Zijderveld, 1967) for representative specimens from Well B. (a) Thermally demagnetized specimen 021401. (b) AF demagnetized specimen 025001.

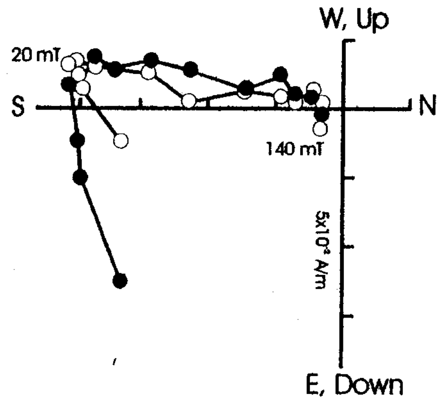


Figure 2.4. Non-azimuthally oriented orthogonal demagnetization (Zijderveld, 1967) for representative specimens from Well OGS-83. AF demagnetized specimen 830105.

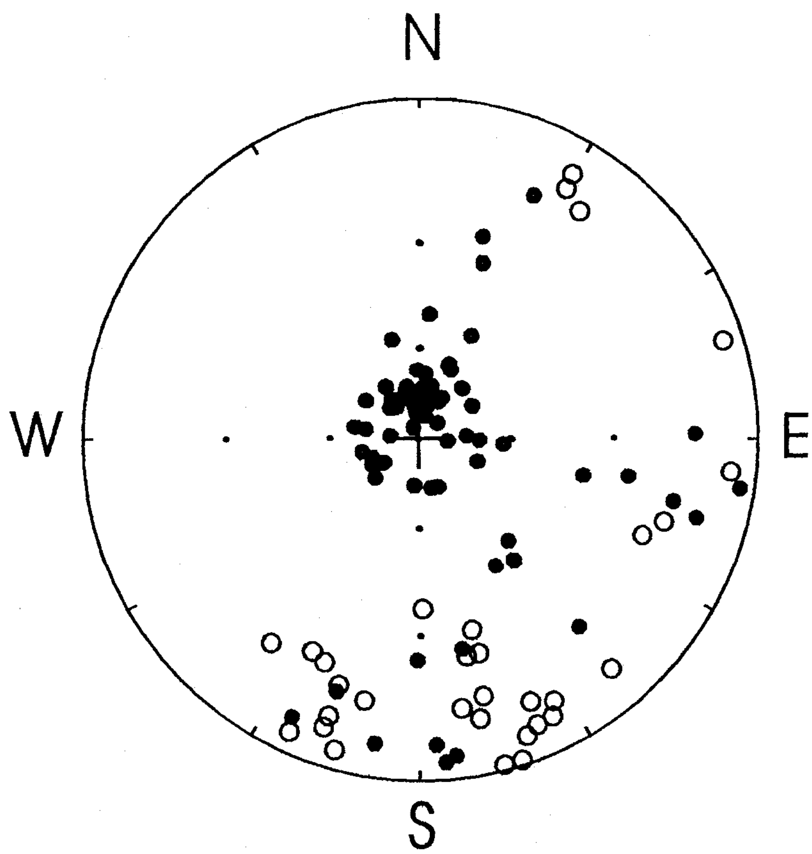
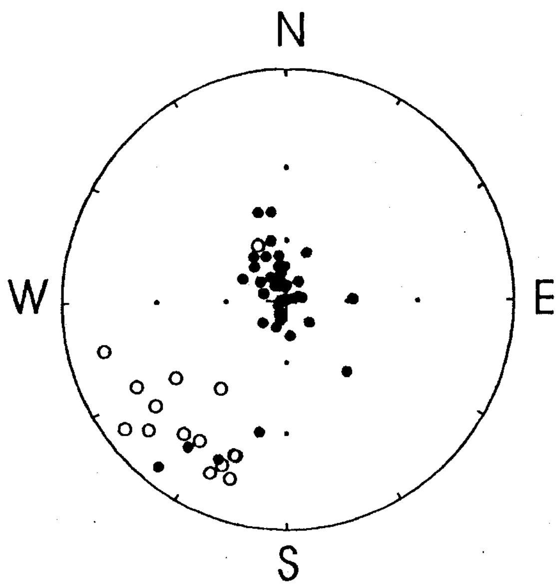
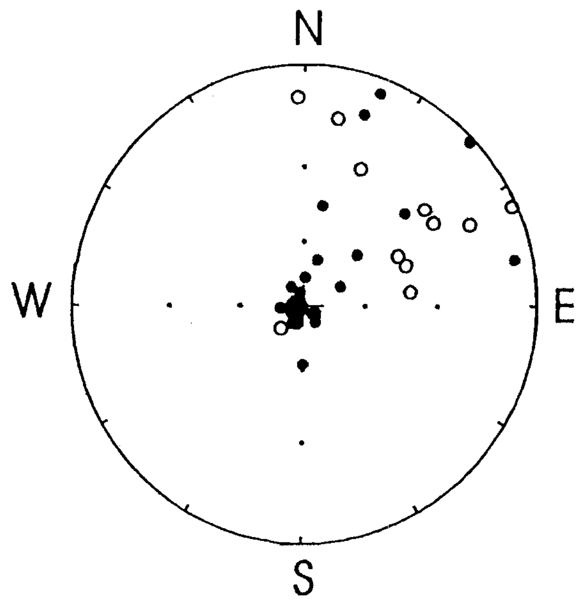


Figure 2.5. Equal-angle stereographs of unoriented segment means ChRMs from Well A. Open circles indicate negative inclinations.



a)



b)

Figure 2.6 (a) Equal-angle stereographs of unoriented segment mean ChRMs from Well B segment 1. (b) Equal-angle stereographs of unoriented segment mean ChRMs from Well B segment 2. Open circles indicate negative inclinations.

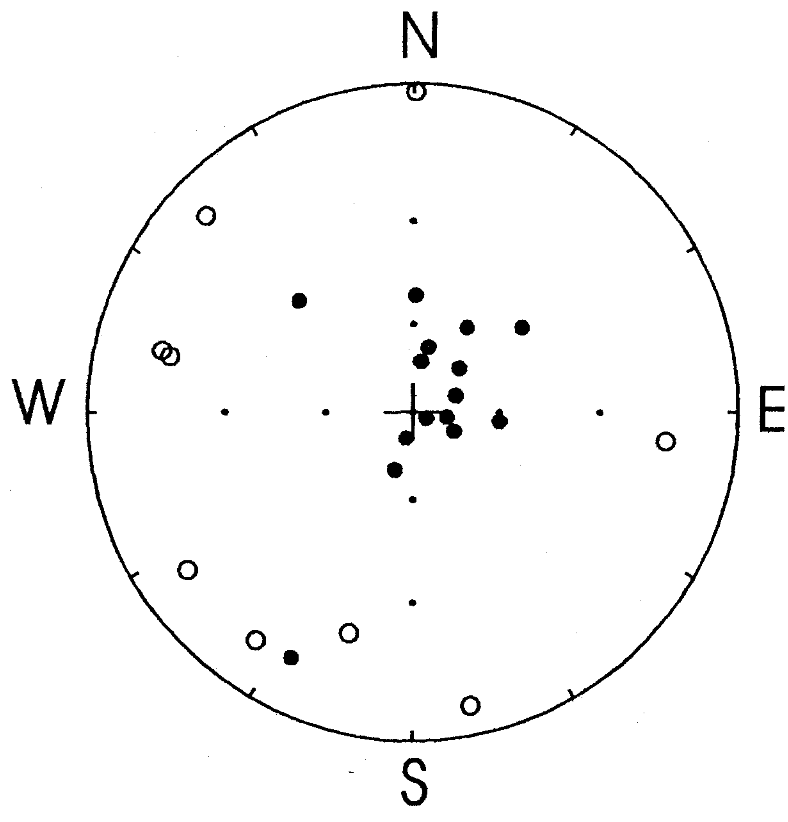


Figure 2.7. Equal-angle stereographs of unoriented segment means ChRMs from Well OGS-83. Open circles indicate negative inclinations.

2.3.3 Rock Magnetism

The two wells within the Dover Field reveal different pARM peak values. The pARM intensities in Well A typically peak between 30 and 40 mT, which indicates magnetite grains ranging between 1 to 2 microns in size (Jackson et al. 1988). Well B in the same field has intensity peaks between 10 and 20 mT, which corresponds to magnetite grains ranging from 2 to 5 microns in size. (Figure 2.8)

SIRM and thermal analysis of the specimens from the Dover Field indicates a mostly magnetite mineralogy with SD and PSD grains dominating the signal (Figure 2.9) Saturation occurred between 200 mT and 300 mT which indicates magnetite, although pyrrhotite cannot be excluded because it also partially falls within this range. Thermal demagnetization showed little drop in intensity at the pyrrhotite Curie temperature of 330°, suggesting that pyrrhotite was not a significant contributor to the magnetization.

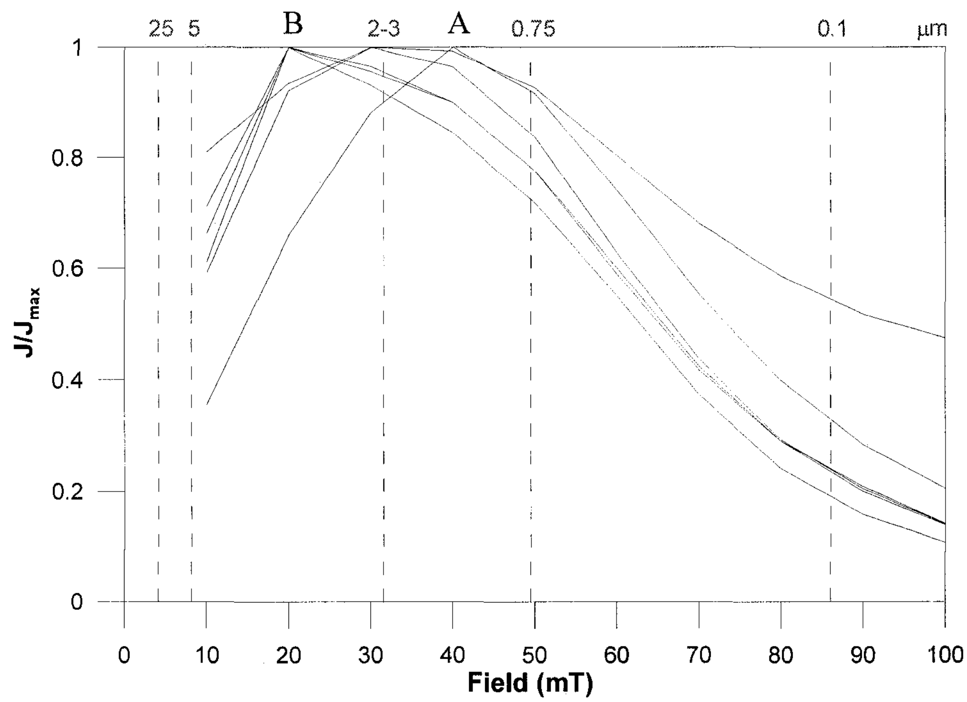


Figure 2.8. pARM curves for Well A and Well B of the Dover Field.

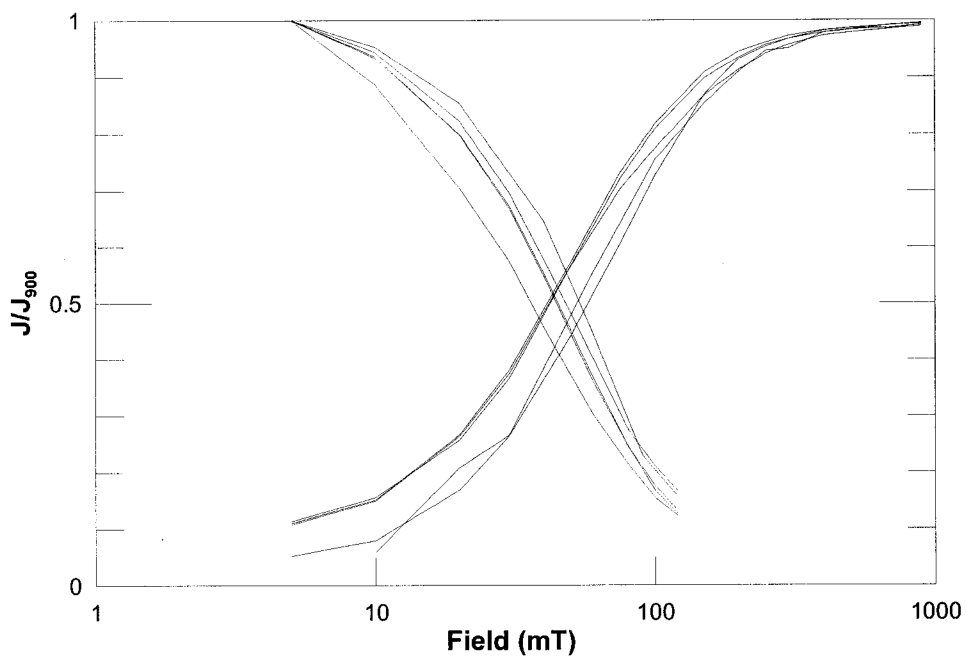


Figure 2.9. SIRM acquisition curves.

2.4 Petrography and Dolomitization

The Trenton Group in the Dover Field of Southern Ontario comprises partially dolomitized limestones (mudstones and wackestones). Petrographic analysis of twenty thin sections showed a variety of minerals and numerous diagenetic events, including several episodes of dolomitization, silicification, and calcite cementation. Minor amounts of non-carbonate minerals include: bladed anhydrite; subrounded to rounded detrital quartz, chert and chalcedony. Fossils such as brachiopods, bryozoans and crinoids were also present in a majority of the thin sections, some of which had undergone dolomitization or replacement by chert.

2.4.1 Dolomitization

The petrographic analysis was focused mainly on dolomitization events and their sequence in the paragenetic history of the area, in order to directly compare the results to those of Colquhoun (1991), later incorporated into Garner (2006). The analysis revealed there are at least three types of dolomite evident in both Well A and Well B of the Trenton Group- within the Dover Field. These types of dolomite represent several diagenetic events which, combined with the geochemical data, reveal a complex sequence involving early and late stages of dolomitization.

Dolomicrite/Fine Crystalline Dolomite

Type A dolomite is subdivided into two types which formed about the same time and represent the earliest dolomitization event. The first subtype is dolomicrite (Plates 1-1 and 1-2) which may be very finely crystalline and pervasive or may occur as single crystals (Plate 1-3 and 1-4). Most thin sections in both Wells A and B have a mud-supported fine grained calcitic matrix (micrite), indicating deposition within a lagoonal environment (as suggested by Brookfield, 1988). All samples containing micrite show fine crystalline dolomite replacing the micrite, termed here as dolomicrite. These fine crystalline dolomite crystals are euhedral to subhedral, are both ferroan and non-ferroan in nature, and typically are no larger than 5 μm in size. The dolomicrite ranges from sparse (< 2% of matrix) to pervasive (75 – 80% of matrix).

The second subtype of Type A dolomite is represented by a fine crystalline dolomite associated with burrows (Plate 1-5) and dissolution seams (Plate 1-6). The crystals typically are not larger than 40 μm and are subhedral in nature. The two subtypes are not found in association with each other, and thus their relative age is hard to determine. However, both formed early in the diagenetic sequence and have been combined.

Medium to Coarse Crystalline Dolomite

The second type of dolomite is represented by medium to large, generally euhedral (minor subhedral) dolomite crystals (Plates 2-1 and 2-2). This type of dolomite formed after the dolomicrite and fine crystalline dolomite. The larger dolomite crystals occasionally have zoning and both medium and coarse crystalline are replacive in nature. The crystals range in size from 100 μm up to 800 μm in size, and are euhedral.

Very Coarse Crystalline Dolomite

The third type of dolomite is represented by coarse crystalline dolomite approximately 800 μm in size and is anhedral in nature. This type of dolomite is the youngest in the age sequence. These crystals can have cloudy centers and occasionally show zoning (Plate 2-3) and are usually fabric destructive. Occasionally the dolomite crystals show saddleization, as represented by curved crystal faces and undulose extinction (Plate 2-4 and Plate 2-5). The saddle dolomite crystals observed here are approximately 600-1000 μm in size. This dolomite can also be seen replacing early calcite cementation as seen in Plate 3-4.

2.4.2 Other Diagenetic Phases

Dissolution Seams

Dissolution seams crosscut the Type A2 dolomite (Plate 1-6) as post dolomitization events (Plate 2-6). Plate 1-6 shows fine grained dolomite occurring between 2 dissolution seams while Plate 2-6 shows a dissolution seam cross cutting fine grained dolomite.

Blocky Calcite

Medium to large blocky calcite crystals also occurs in the Dover Field, either as cement, such as syntaxial calcite cement in crinoids, or occluding fractures. These large calcite crystals occasionally show twinning, possibly indicating some form of compaction or stress. Plate 1-6 shows a large blocky calcite vein truncating a dissolution seam and fine crystalline dolomite. Plate 3-1 shows a thin calcite vein cross cutting large anhedral dolomite crystals. There is also a later stage thin calcite veining that can be seen in Plate 3-2 cross cutting the large anhedral dolomite crystals.

Quartz

Well rounded detrital quartz grains ranging from 80 μm to 100 μm in size with a few much larger diagenetic crystals that are 800 μm in size are visible in Plate 1-2. Fine crystalline quartz crystals have also been observed in one thin section. This suggests there may be two generations (diagenetic events) that formed quartz within the wells; an earlier fine to medium grain quartz and a later stage quartz consisting of larger grains. Chalcedony was observed replacing an allochem in one thin section (Plate 3-3).

Chert also occurs within the thin sections examined and appears to be earlier than the medium to coarse crystalline dolomite as shown in Plate 3-3 which also shows the large anhedral dolomite replacing the chert. Plate 3-4 shows early chertification of a fossil.

Anhydrite

Anhydrite was visible in a few of the thin sections and is recognized by its long bladed crystal habit. Anhydrite generally displays bright colors when under cross polars as seen in Plate 3-6, and tends to replace micrite. The timing of replacement is not clear from the thin section analysis.

Plate 1: Lithofacies

(1) Photomicrograph of fine crystalline euhedral dolomite crystals occurring in the micrite and dolomicrite. Field of view is 1900 μm.

(2) Photomicrograph of a) dolomicrite replacing the calcite based micrite and b) rounded detrital quartz occurring in the dolomiticrite. Field of view is 1900 μm.

(3) Photomicrograph of pervasive dolomite occurring in the dolomicrite notice there is zoning of the fine grained calcite crystals. Field of view is 1900 μm.

(4) Photomicrograph of fine crystalline pervasive dolomite occurring with dolomicrite and fine crystalline calcite and micrite. Field of view is 1900 μm.

(5) Photomicrograph of the fine crystalline dolomite occurring in a burrow and surrounded by dolomicrite. Field of view is 1900 μm.

(6) Photomicrograph of a) fine crystalline dolomite occurring between two dissolution seams and surrounded by dolomicrite and b) a blocky calcite crystal truncating at a dissolution seam. Field of view is 1900 μm.

Plate 1: Lithofacies

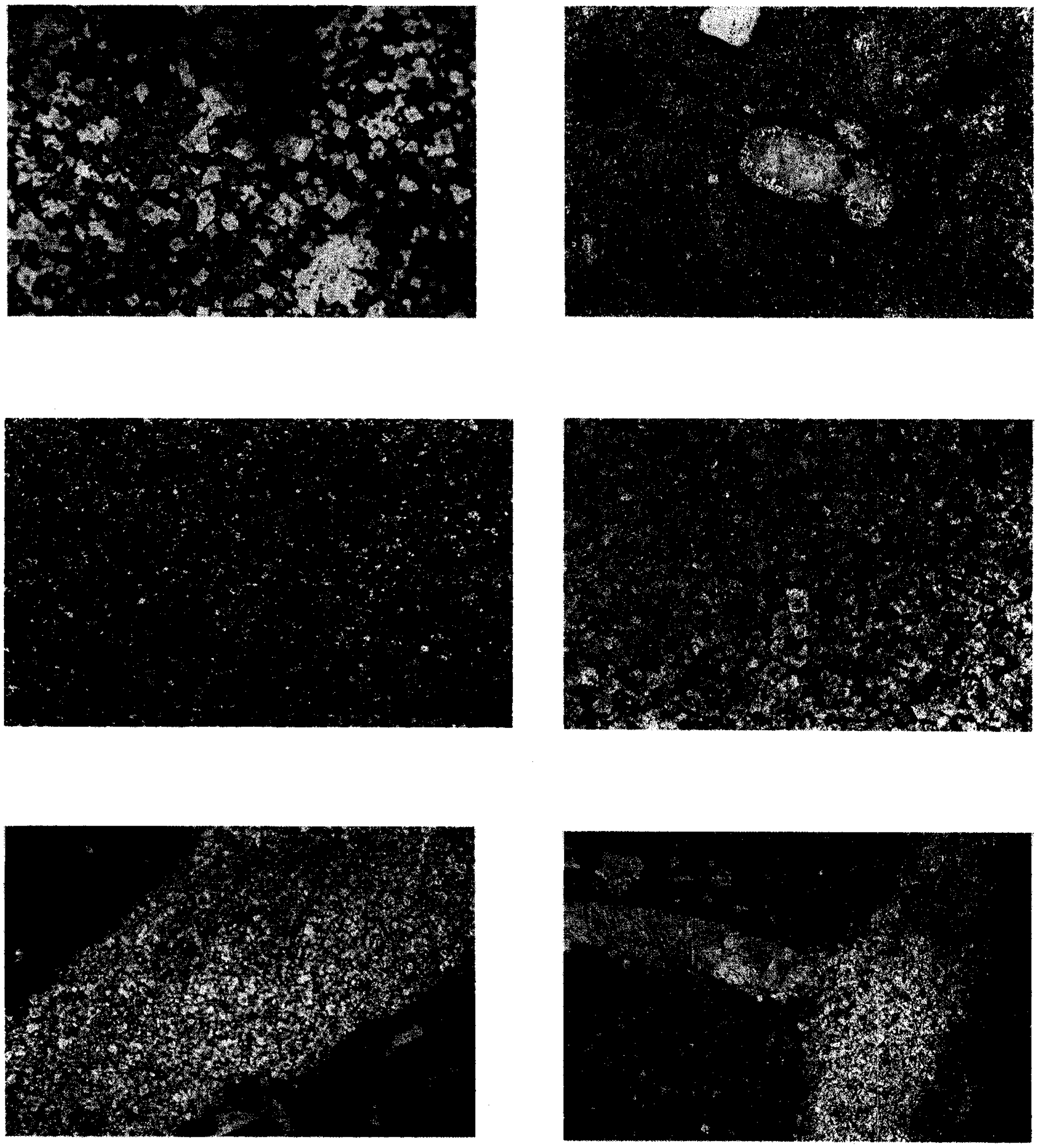


Plate 2: Lithofacies

(1) Photomicrograph of medium to coarse euhedral dolomite replacing an allochem. There is some dissolution evident around the edges of the dolomite crystals. Note the presence of fine crystalline dolomite in the lower portion of the photomicrograph. Field of view is 1900 μm.

(2) Photomicrograph of medium to coarse crystalline dolomite occurring in dolomicrite and fine crystalline dolomite. Field of view is 1020 μm.

(3) Photomicrograph of large anhedral dolomite crystals; note the cloudy centres and the fabric destructive nature of the crystals. Field of view is 1020 μm.

(4) Photomicrograph of large anhedral dolomite crystals occasional cloudy centres. Field of view is 1900 μm.

(5) Photomicrograph same as above but under cross polars note the presence of saddlization by the curved crystal faces. Field of view is 1900 μm.

(6) Photomicrograph of a fine crystalline dolomite with a later stage dissolution seam cross cutting through it. Field of view is 1900 μm.

Plate 2: Lithofacies

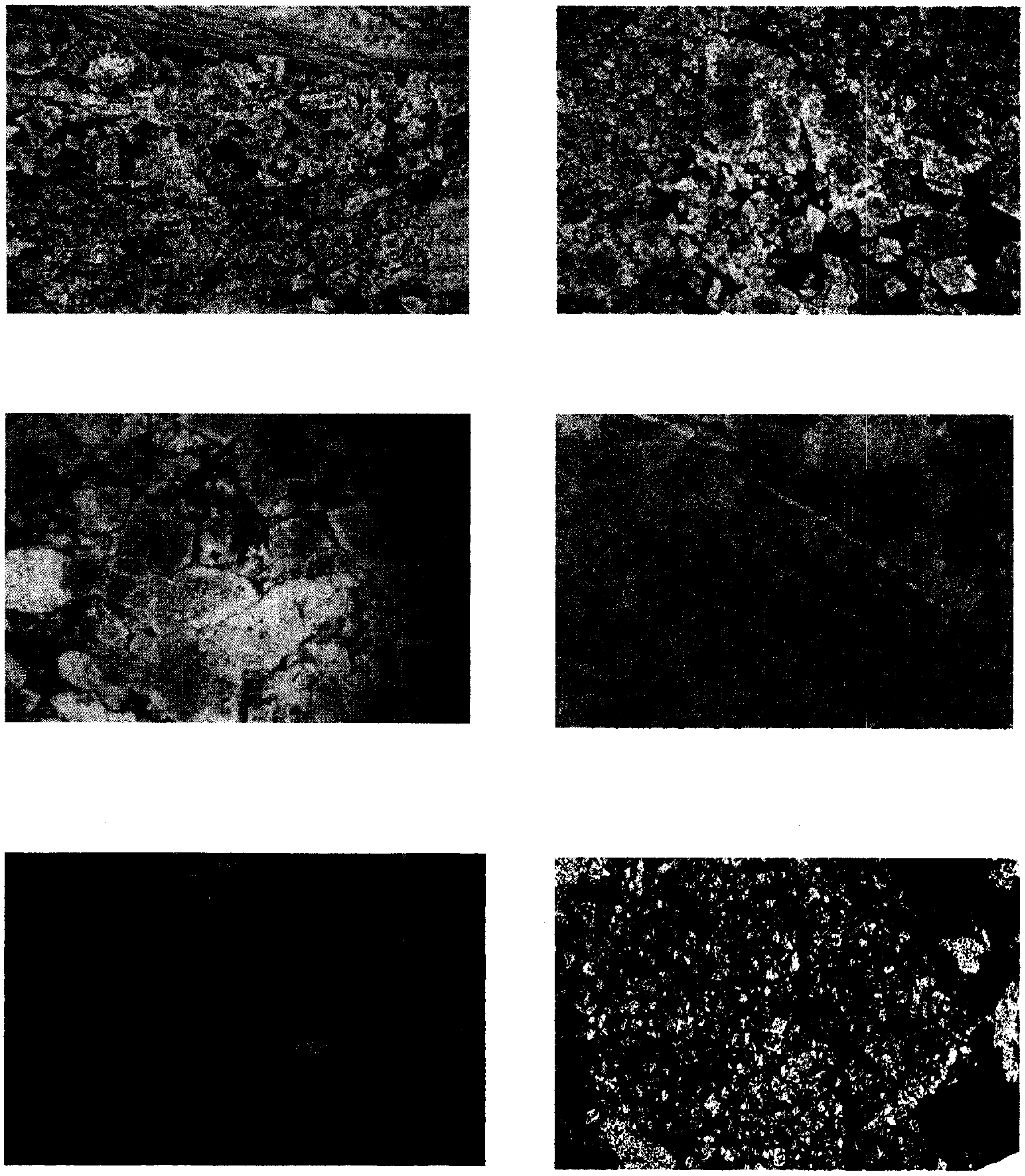


Plate 3: Lithofacies

(1) Photomicrograph of a late stage thin calcite vein truncating an anhedral dolomite vein. Field of view is 1900 µm.

(2) Photomicrograph of a) a thin late stage thin calcite vein cross cutting larger anhedral dolomite crystals and b) anhydrite crystals occurring with medium crystalline dolomite crystals. Field of view is 1020 µm.

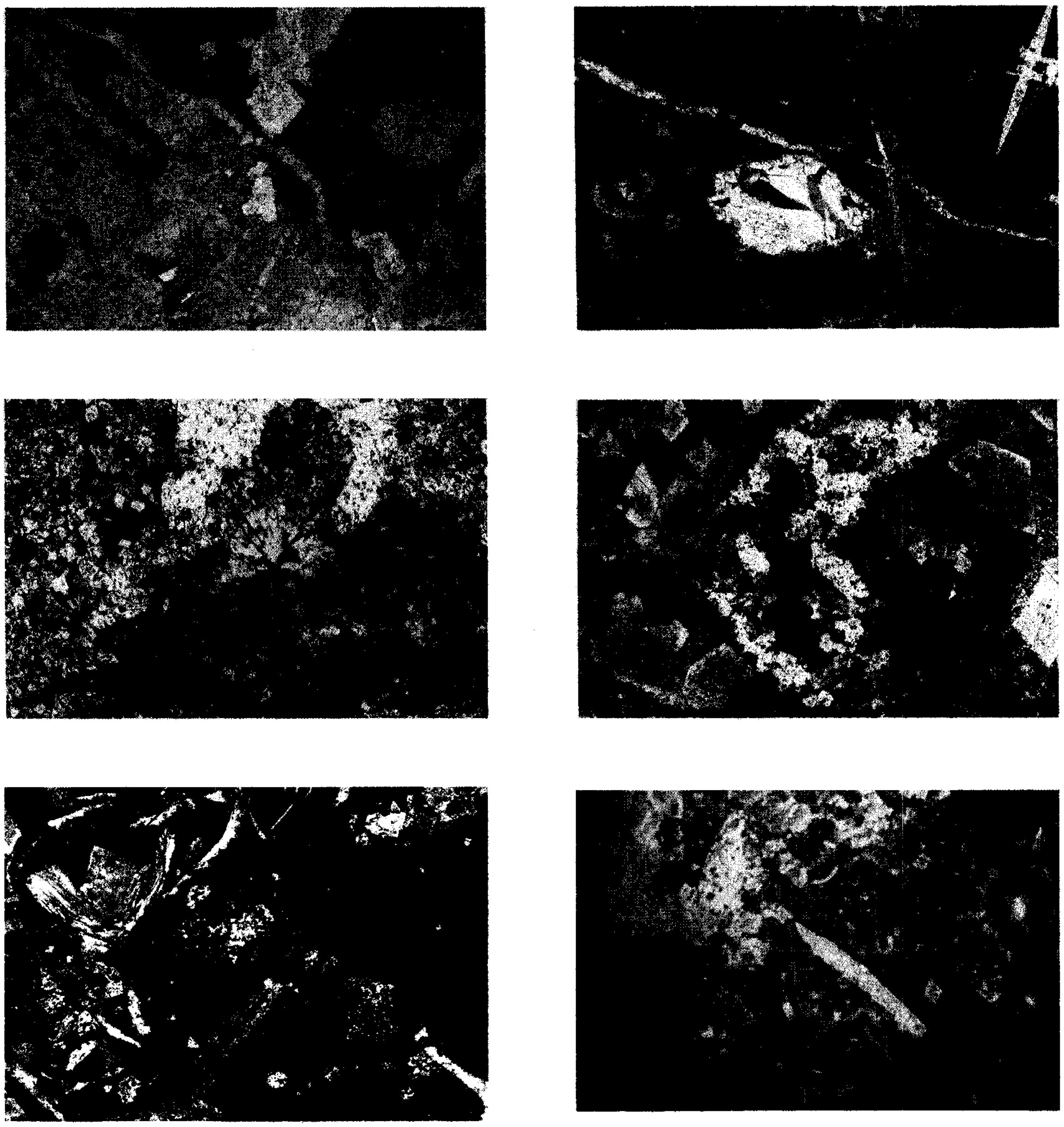
(3) Photomicrograph of chalcedony replacing an allochem. Field of view is 1900 µm.

(4) Photomicrograph of chert replacing a fossil with large anhedral dolomite crystals replacing the chert. Field of view is 1020 µm.

(5) Photomicrograph of certification of a fossil. Field of view is 1900 µm.

(6) Photomicrograph of bladed anhydrite crystal occurring in the dolomitcrite/micrite. Field of view is 1900 µm.

Plate 3: Lithofacies



2.4.3 Stable Isotope Geochemistry

Analysis of stable isotopes can give some insight into the diagenetic processes that affected the Trenton Group within the Dover Field. Isotopic analysis was conducted on limestone, fine to medium crystalline dolomite and saddle dolomite. Table 2.1 and Figure 2.10 shows the results obtained from the analysis.

When compared to what would be expected if the dolomites were precipitated from seawater, the limestone shows depleted $\delta^{18}O$ values ranging between -5.59 and -6.31 ‰ (average of -5.92 ‰, n=4) and $\delta^{13}C$ between -1.40 and 0.57 ‰ (average -0.28 ‰). The stable isotopic composition of the fine to medium crystalline dolomite ranges from $\delta^{18}O$ -7.47 to -10.2 ‰ 1 (average -8.69 ‰ n=9) and $\delta^{13}C$ between 0.31 and 2.22 ‰ (average 1.03 ‰ n=9). The stable isotopic composition of the saddle dolomites ranges between $\delta^{18}O$ values of -9.40 and -9.63 ‰ (average -9.52 ‰ n=2) and $\delta^{13}C$ between 0.27 and 0.59 ‰ (average 0.43 ‰).

Sample Number	Lithology	Sample Weight (mg)	$^{13}C_{VPDB}$ (‰)	$^{18}O_{VPDB}$ (‰)
2	fine-medium dolomite	3.10	2.22	-9.63
3	fine-medium dolomite	4.10	1.38	-9.51
4	medium dolomite	2.80	1.03	-7.75
6	coarse dolomite	3.20	0.62	-9.67
5	fine-medium dolomite	4.10	0.82	-7.47
8	fine-medium dolomite	3.80	0.55	-7.76
1	fine-medium dolomite	0.60	1.80	-10.21
10	fine-medium dolomite	4.50	0.58	-8.28
11	medium dolomite	5.00	0.31	-7.92
7	saddle dolomite	3.40	0.59	-9.63
15	saddle dolomite vein	0.40	-0.29	-8.11
14	saddle dolomite	2.40	0.27	-9.40
9	limestone	3.10	0.57	-6.18
13	limestone	5.80	-0.36	-6.31
11a	limestone	2.60	0.05	-5.59
12	limestone	5.60	-1.40	-5.61

Table 2.1. Stable Isotopic Analysis Results

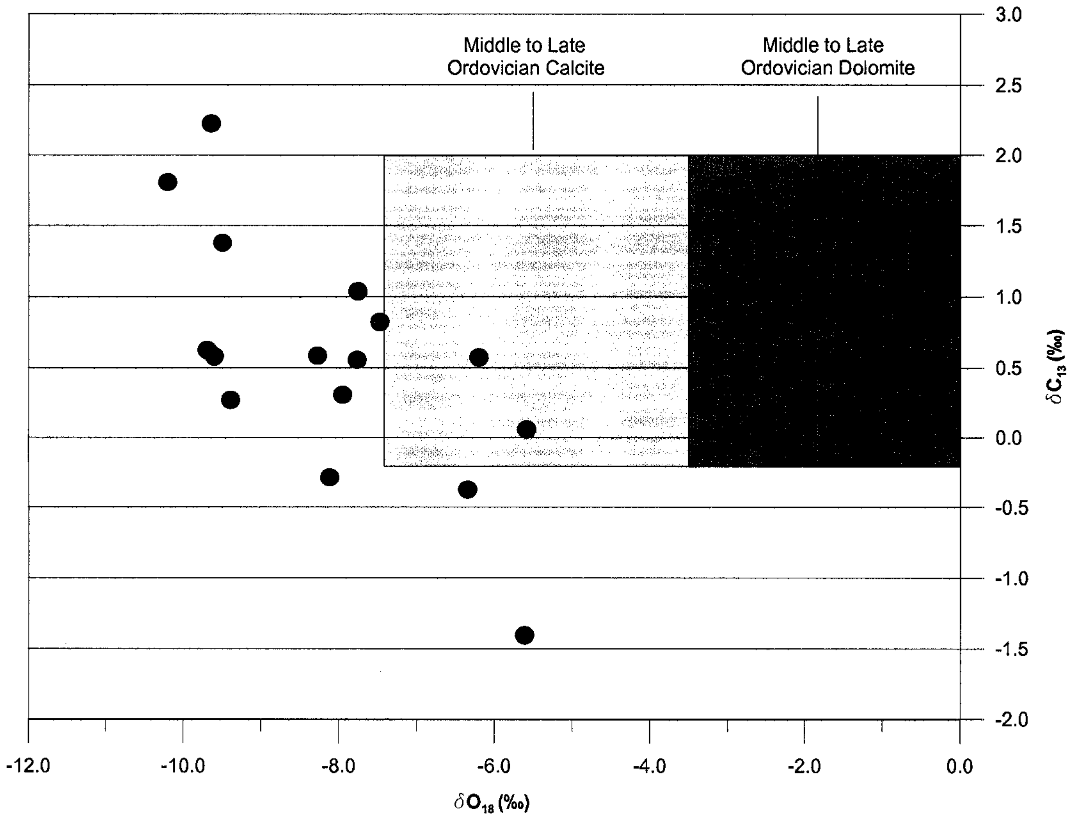


Figure 2.10. Graphical distribution of dolomite and limestone isotope results in comparison to the Middle to Late Ordovician marine calcite and dolomite (Savard et al, 2000 citing Quig and Veizer, 1994). Blue represents the limestone, red represents the dolomites and black represents the saddle dolomite.

2.5 Discussion

2.5.1 Paleomagnetic Directions

The Dover Field, the Hillman/Goldsmith-Lakeshore Fields and the reference core OGS-83 used unoriented core for paleomagnetc analysis, and thus the most direct comparison is through inclination-only means. There are distinct variations when the inclination-only means from the Hillman/Goldsmith-Lakeshore Fields and the Dover Field are compared. The inclination-only mean for the dolomites from the Hillman/Lakeshore-Goldsmith field is -10.2°, while the limestones are -0.1° and 1.0° (Garner, 2006). The results for the limestones of from the Dover Field (Well B, see previous section) have an inclination-only mean of -15.8° and -8.3° while the dolomites and partially dolomitized limestones of Well A had a value of -1.0° (Table 2.2). The paleolatitudinal arc produced by the dolomite from the Hillman/Goldsmith-Lakeshore Field passes through the entire Permian and Middle Triassic (~262-227 Ma) portions of North America (Garner, 2006). Thus, when plotted as a paleolatitudinal arc on an apparent polar wander path the inclination-only mean from the dolomites in the Dover Field are approximately 10° shallower and produce a slightly older age ranging from Late Pennsylvanian to Permian (~296-248 Ma) (Figure 2.11). However, the paleolatitudinal arc from the non-reservoir reference core OGS-83 has a Permian age which is similar to both areas, but tends to agree more with the results of the Hillman/Goldsmith-Lakeshore study (Garner, 2006).

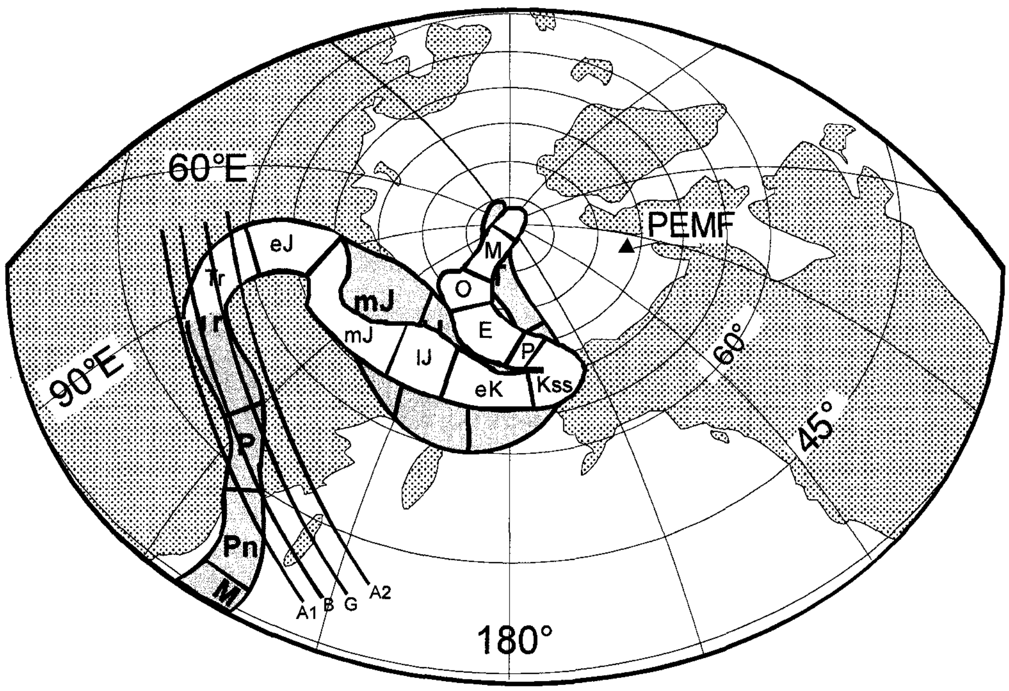


Figure 2.11. Apparent polar wander oath for North America from Besse and Courtillot (1988) and Van der Voo (1993) for the Cambrian through Tertiary. A1 and A2 represents the paleolatitudinal arc for the dolomites from the Dover Field, B represents the paleolatitudinal arc for the limestones from the Dover Field, and G represents the paleolatitudinal arc for the dolomites of the Hillman/Goldsmith-Lakeshore Fields.

	Dover Field	Hillman/Goldsmith-Lakeshore Fields	Reference Field
Dolomites	-1.0°	-10.2°	---
Limestones	-15.8°/-8.3	-0.1°/1.0°	-6.6°

Table 2.2. Summary of inclinations from the Dover Field, Hillamn/Goldsmith-Lakeshore Fields and the reference field.

Garner (2006) concluded that the limestone magnetization age in the Hillman/Goldsmith-Lakeshore Fields could be from Early Permian to Middle Triassic (~303-227 Ma), which was most likely related to an Early Permian fluid pulse that McCabe and Elmore (1989) associated with the Alleghanian Orogeny, and which occurred before hydrothermal dolomitization. The limestones in the Dover Field produce an age of Triassic to Early Pennsylvanian (~320-219 Ma) which encompasses the ages observed by Garner (2006) and by McCabe (1984). Since the DIRM precluded the orientation of the limestone, there are two options present for the age of magnetization – Triassic or Early Pennsylvanian. The limestone in the reference core OGS-83 produced a similar inclination mean to the Hillman/Goldsmith-Lakeshore Field. The results for the limestones in the Dover Field suggest it may also have been affected by fluid pulses during the Alleghanian Orogeny. Additionally, the Hillman/Goldsmith-Lakeshore Fields also contained fracture related calcite that is Triassic in age (Garner, 2006). This calcite was absent in the Dover Field or, if present, was only visible in thin sections, i.e. the late blocky calcite, and could not be isolated for paleomagnetic analysis. The lack of the fracture related calcite may indicate that the fluids precipitating the fracture fill did not affect the Dover Field or did not affect it to the same degree as the Hillman/Goldsmith-Lakeshore Fields.

There are implications from the lack of coarse crystalline fracture related calcite in the Dover Field. Garner (2006) suggested the fluids that formed the calcite came from the south; the lack of this calcite in the Dover Field suggests these fluids may not have migrated as far north as the Dove Field. Additionally, the presence of gas in the Dover Field and the presence of oil in the Hillman/Lakeshore-Goldsmith Fields suggests the fracturing that resulted in the calcite formation in the Hillman/Lakeshore-Goldsmith Fields may have provided the pathway for oil migration, explaining the lack of oil in the Dover Field.

The dolomites present in the Dover Field have the shallowest inclination which represents the oldest age. The limestones from the Hillman/Goldsmith-Lakeshore Fields are slightly younger than the dolomites from the Dover Field. The sequence of ages continues with the dolomites from the Hillman/Goldsmith-Lakeshore Fields and the limestones from the Dover Field having roughly the same age which also correlates with the reference core. The youngest age is represented by the fracture fill calcite that is present only in the Hillman/Goldsmith-Lakeshore Fields. These results suggest more than one fluid flow event.

2.5.2 Rock Magnetism Discussion

Studies conducted by Cioppa et al. (2000), Cioppa et al. (2001), Cioppa et al. (2002) and Cioppa et al. (2003) have shown that rock magnetism combined with paleomagnetic and geochemical data can be used to date specific diagenetic events associated with hydrocarbon reservoirs. Thus, an important part of this study was the comparison of the rock magnetic properties between the two areas.

The grain size produced by the pARM analysis of Well A of the Dover Field, which consists of dolomites and partially dolomitized limestones, produced a similar range in grain size to the Hillman/Goldsmith-Lakeshore Field (1 to 2 microns). However, pARM analysis of the limestone from Well B in the Dover Field resulted in a slightly larger grain size (2 to 5 microns). These results suggest grain size may have decreased slightly with dolomitization or recrystallization.

Thermal demagnetization and SIRM results from the Dover Field indicate a mostly magnetite mineralogy of single domain (SD) and pseudosingle domain (PSD) grains. The study by Garner (2006) revealed a predominantly SD and PSD pyrrhotite mineralogy with minor magnetite based on SIRM and S-ratio analysis. While pyrrhotite cannot be completely excluded from the Dover Field study, the results suggest that the two separate study areas contain different magnetic minerals that have similar grain sizes within the dolomitized rocks. Garner (2006) suggested vertically migrating fluids substituted pyrrhotite for magnetite in the Hillman fields. The lack of pyrrhotite in core from the Dover Field suggests the fluids that affected the Hillman/Goldsmith/Lakeshore Field either did not affect the Dover Field to the same degree, or were different fluids. The presence of pyrrhotite in the Hillman/Goldsmith-Lakeshore Field could be related to the late stage fracture fill calcite which was not present in the Dover Field. If the late stage fracture fill is assumed to be the conduit for the fluids which resulted in the pyrrhotite presence in the Hillman/Lakeshore-Goldsmith Field, this would explain its absence in the Dover Field.

2.5.3 Paragenesis of the Dover Field

There is a complex series of diagenetic events evident from the thin sections examined. Figure 2.12 is a paragenetic sequence for the Trenton Group in the Dover Field as defined by petrographic analysis. After deposition of lime mud and minor silicilastics (detrital quartz, Plate 1-2) in a lagoonal or tidal flat environment, the earliest diagenetic events include the formation of an early calcite cement in and around fossil fragments (Plate 1-6), which was subsequently recrystallized, as evidenced by the depleted oxygen isotope values.

Concurrent with, or slightly after the recrystallization event, partial to total dolomitization of the lime micrite substrate occurred. Nearly all thin sections show evidence of the dolomicrite (A1 dolomite) replacing early calcite cement with some of the early calcite cement remaining (e.g. Plate 1-3). The stable isotopic and petrographic analysis of the Dover Field indicates that this dolomite was probably not precipitated directly from seawater, since the isotopic values are more negative than would be expected (Figure 2.10), and the textural analysis shows that all the dolomites are replacive. Alternatively, the negative oxygen isotope values may result from recrystallization.

At the same time or shortly after, minor dissolution of type A2 dolomite occurred, along with chert precipitation. In Plate 3-4, it is evident that the chert is being cross-cut by the medium to coarse crystalline dolomite (Type B), indicating that this dolomite formed after the chert precipitated.

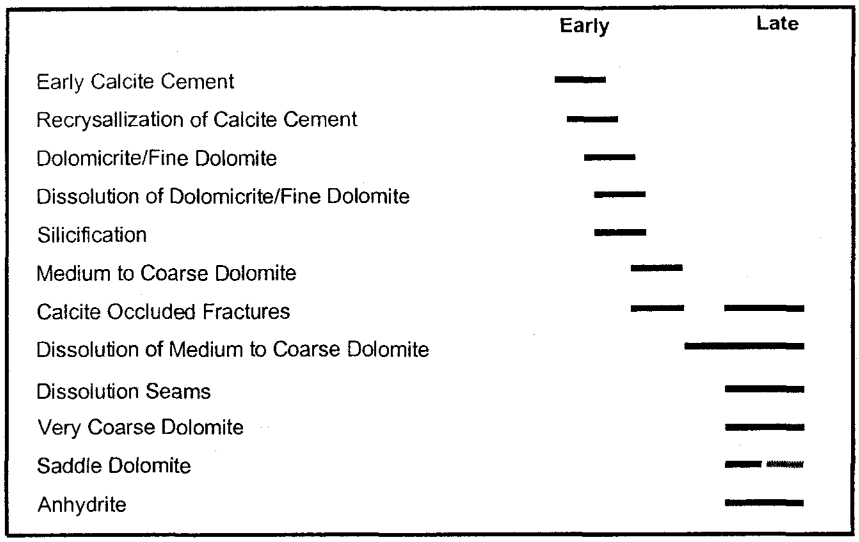
The precipitation or replacement of the precursor lime mud and/or dolomicrite, by the medium to coarse crystalline dolomite post-dates the formation of the dolomicrite (Plate 2–2). Dissolution seams (stylolites) postdate the formation of the medium-to coarse crystalline dolomite (Plate 2-6), suggesting that both Types A and B dolomite were relatively early, shallow burial events, as chemical compaction in limestones starts at burial depths of as little as 500 m (Einsele, 2000). In one thin section, a blocky calcite vein pre-dates the dissolution seams (Plate 1-6; the dissolution seam cross-cuts the calcite vein).

The formation of very coarse, crystalline dolomite (Type C) occurred after the medium to coarse crystalline dolomitization. The crystals are anhedral, late stage, and appear to have undergone subsequent dissolution, as evidenced by the ragged edges along some of the dolomite crystals. Colquhoun (1991) concluded the presence of coarsely crystalline dolomite and stylolitic seams which post-date Type B dolomitization is evidence for dolomitization occurring during late burial of sediments at increased temperatures. The similar coarse crystalline dolomite and dissolutions seams present in the samples from the Dover Field suggest the same manner of formation therein.

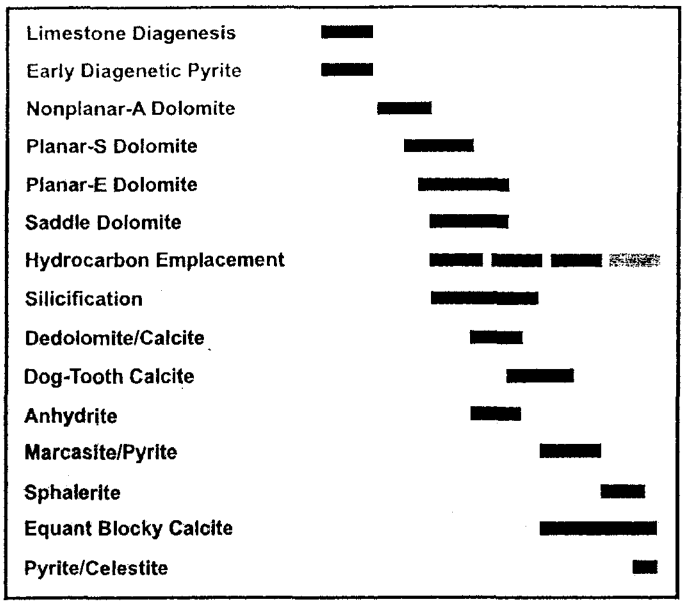
Plate 2-1 and other thin sections examined, show a late-stage dissolution event occurring after the formation large anhedral dolomite and the medium to coarse crystalline dolomite crystals, evidenced by the irregular edges of the crystals. However, its timing cannot be more accurately constrained.

The last diagenetic event affecting the dolomites is the saddlerization (Nadjiwon et al., 2001) of the very coarse crystalline dolomite, and minor precipitation of saddle dolomite in veins. The cross-cutting relationships of the saddlerized coarse crystalline dolomite are not observable, but it is likely to post-date all other forms of dolomitization. This is supported by the conclusion of Colquhoun (1991) that saddle dolomite is a result of extensive rock-fluid interactions occurring late in the tectonic history of the area.

Shortly after the medium to coarse crystalline and very coarse crystalline dolomite formation, blocky calcite cement occluded fractures. This event may be associated with the anhydrite formation or the anhydrite may have formed shortly after the saddle dolomite, however, there is not enough evidence to specify further.



a)



b)

Figure 2.12. a) Paragenetic sequence for the Trenton Group carbonates from the Dover Field. The gray bar represents the interval when saddle dolomite may or may not have formed. b) Paragenetic sequence for the Trenton Group carbonates in the Hillman/Goldsmith-Lakeshore Fields (Garner, 2006, modeified from Colquhoun, 1991).

2.5.5 Geochemistry Discussion

The stable isotope composition of the dolomites and limestones are plotted in Figure 2-10. The oxygen isotope composition tends to become more negative with dolomitization. This suggests that dolomites were either not precipitated directly from seawater or recrystallization occurred during burial, as temperature increases with depth cause more negative oxygen isotope values. Colquhoun (1991) cited Degens and Epstein (1964) and Veizer and Hoefs (1976) as suggesting that, if the dolomites had formed at the same time as the parent solution responsible for the precipitation of limestone, the dolomites' $\delta^{18}O$ composition should be heavier than the limestones.

The isotopic composition of the massive saddle dolomites has an average of approximately -9.52 ‰ which is similar to the value obtained by Colquhoun (1991) of -9.7 ‰. It was concluded by Colquhoun (1991) that saddle dolomite formed as a result of extensive rock-fluid interactions with diagenetic pore fluids and the host dolomite rock-matrix. Due to the similarities of the values and habit it is probable that the saddle dolomite in the Dover Field formed in the same manner.

The $\delta^{13}C$ values show a range of ~ 2.5 ‰ for the fine to medium crystalline dolomites (2.22 ‰ to -0.29 ‰) and the $\delta^{18}O$ values range from -7.47 ‰ to -10.21 ‰. (Colquhoun 1991) cites Friedman and O'Neil (1977) in suggesting that a 4‰ change in oxygen isotope values corresponds to a ~20°C change in temperature of formation. Thus the similar difference in samples of this study, suggests that the temperature of formation for the fine to medium crystalline dolomite may have varied by as much as 15° C. Similarly, the limestones from the Dover Field have a $\delta^{18}O$ range of -6.31 ‰ to -5.59 ‰, suggesting a narrower temperature range during formation. Using the calculations of Colquhoun (1991; Table 1), reconstruction of the temperature of formation / alteration indicates that the limestones were probably precipitated at temperatures of 30-45°C, as the values are slightly less negative than those of Colquhoun (1991). Similarly, the fine to medium crystalline dolomite had slightly less negative values than Colquhoun's values of -9.00 to -11.60 ‰, suggesting a slightly shallower depth of burial and lower temperatures during formation. Colquhoun (1991) concluded from isotopic analysis that the average burial temperature for the Trenton Group dolomites from Mersea and Romney Townships in southwestern Ontario was between 60-76°C; values in the Dover field were probably towards the colder end of this range.

2.6 Fluid Flow Models and Comparisons

2.6.1 Fluid migration and comparison models for the Dover and Hillman pools

There are several differences in ages and in magnetic minerals between the two study areas that may explain the results obtained. First, the spatial distribution of the three study areas may have an affect on the results obtained in this study. The Dover Field is located in a structural depression known as the Chatham Sag, while the Hillman/Lakeshore-Goldsmith Fields are located further to the south on the edge of the Findlay Arch and closer to the northern edge of the Appalachian Basin. The difference in proximity to the Appalachian Basin could have had several effects on fluid migration episodes; a single event may have impacted the two fields to different degrees, or a weak event may have impacted the closer field (Hillman/Lakeshore-Goldsmith), but not the more distal Dover Field. Additionally, Garner (2006) concluded that a single fluid event could not be responsible for the precipitation of all magnetic minerals in the Hillman/Lakeshore-Goldsmith Fields, but, rather multiple events are the sources. Garner (2006) associated hematite with the Triassic-age calcite fracture fill event; however, hematite was not found in the Dover Field. Therefore, the fluid event producing the hematite and calcite fracture fill during the Triassic may not have migrated as far north as the Dover Field, resulting in the difference in age and the absence of fracture fill calcite, as well as the difference in magnetic mineralogy.

Secondly, the lack of coarse fracture fill calcite in the Dover Field may explain the lack of oil in the Dover Field. The fluid event that resulted in the fracture fill calcite may have provided the conduit for oil migration in the Hillman/Lakeshore-Goldsmith Fields. Since two of the main differences between the Dover Field and the Hillman/Goldsmith-Lakeshore Fields were the lack of oil and calcite fracture fill in the Dover Field, it is suggested that they may be related. However, there are two possible scenarios for the oil in the Hillman/Goldsmith-Lakeshore Fields: 1) the event that caused the calcite precipitation could have been the hydrocarbon migration event, and 2) the fluid event occurred before the hydrocarbon migration event. Due to the structural difference of the locations of the Dover and Hillman/Lakeshore-Goldsmith Fields a small scale or weak fluid event may not have reached the Dover Field. Garner (2006) suggested the fluids that affected the Hillman/Lakeshore-Goldsmith Fields originated in the south around

Illinois and not from the Appalachian Basin which is located in the southeast. The structural trend of both fields is north-west. If dolomitization and hydrocarbon migration are related to the fault and fracture systems the fluids may not have reached the Dover Field if they were coming from the south. This fluid flow may have contained oil which did not reach the Dover Field.

Garner (2006) concluded the remagnetization of limestones was a result of Alleghanian fluids which is an event separate from the fluid which caused the fracture fill calcite. The similarity in ages from the limestones (Dover Field ~320-219 Ma and Hillman/ Lakeshore-Goldsmith ~303-227 Ma) suggest both fields may have been affected by the same fluids from the Allegheniah Orogeny.

2.7.1 Fluid Flow Model

There is a complex sequence of events which resulted in the various paleomagnetic ages and magnetic and geochemical results from the Hillman/Goldsmith-Lakeshore Fields and the Dover Field. This sequence of events can explain the lack of oil in the Dover Field as well as the lack of wide spread dolomitization in the Dover Field that is present in the Hillman/Goldsmith-Lakeshore Fields.

1) A magnesium-rich fluid caused the dolomitization of the Hillman/Goldsmith-Lakeshore Fields and caused a partial dolomitization of the Dover Field, probably no later than the Early Permian, and possibly as early as the Pennsylvanian. The fluid flow

event may have been caused by a fluid pulse associated with the Alleghanian Orogeny. The partial dolomitization may be a result of depletion of magnesium in the fluid before it reached the Dover Field. This magnetization is very clearly observed in the dolomites of the Dover Field. It is noted that the Hillman/Goldsmith-Lakeshore Fields and area may not have been entirely dolomitized by this fluid flow (Garner, 2006), leaving some of the original limestone unaltered.

2) After the early fluid flow event, burial resulting from an influx of sediments eroding off the Appalachian Orogeny and thus coinciding with subsidence of the basin, caused remagnetization of the Hillman/Goldsmith-Lakeshore Fields, and the reference core. This resulted in the dominant magnetization observed in most of the dolomites in the Hillman/Goldsmith-Lakeshore Fields and the limestones of the reference core, thus explaining the similarities in ages from these lithologies. The dolomites in the Dover Field were not buried as deeply as those in the Hillma/Goldsmith-Lakeshore fields during this event, and were not remagnetized.

3) An additional fluid flow event that may have carried the oil that is present in the Hillman/Goldsmith-Lakeshore Fields resulted in fracture fill calcite. A Triassic-age magnetization is associated with this event (Garner, 2006). These fluids either did not reach the Dover Field or may not have had a conduit (such as the fractures present in the Hillman/Goldsmith-Lakeshore Fields (Colquhoun, 1991)) to the Dover Field.

This model suggests that multiple fluid flow events as well as other major diagenetic events have affected both fields over time. However, there are other possible explanations that must also be considered.

First, it is possible that during the alternating field and thermal demagnetization processes a viscous and/or drilling-induced magnetization was not completely removed from specimens of the Dover Field. This could produce inclinations that would be shallower than would normally be expected, and thus would produce a different age from the Hillman/Goldsmith-Lakeshore Fields. However, the University of Windsor standard demagnetization procedure was followed for both studies, and given the results; there is no real reason to think that the secondary magnetizations were completely removed in one field (Hillman/Goldsmith-Lakeshore) and not the other (Dover).

Second, there may have been an early dolomitization event that was limited to the region near the Dover Field, rather than a large-scale fluid flow event that did not reach or only partially affected the Dover Field. This event could have resulted in the observed partial dolomitization, and remagnetized the limestones in the vicinity of the Dover Field. This local dolomite event could explain the differences in dolomite characteristics and lithology that were observed between the dolomites from the Hillman/Goldsmith-Lakeshore Fields and the Dover Field. Such a local dolomitization event might result from meteoric water influx on the edge of the basin, where the Dover Field is located. However, additional cores in the Dover Field and surrounding areas would need to be examined to verify this hypothesis.

2.8 Conclusions

1) The paleomagnetic analysis reveals different dates for the dolomitization of the Dover Field (Late Pennsylvanian to Permian) than the dolomites from the Hillman/Goldsmith-Lakeshore Fields (Permian and Middle Triassic) suggesting the dolomitization of the Dover Field and that of the Hillman/Goldsmith-Lakeshore Fields may have been caused by different events.

2) The rock magnetic analysis revealed the magnetic mineralogy of the Dover Field consisted mostly of magnetite mineralogy of single domain (SD) and psuedosingle domain (PSD) grains. The study by Garner (2006) revealed a predominantly SD and PSD pyrrhotite mineralogy with minor magnetite based on SIRM and S-ration analysis. These results also suggest dolomitization and remagnetization was caused by different fluids carrying different magnetic minerals.

3) The petrography of the dolomites from Dover Field and the dolomite samples from Mersea and Romney Townships (Colquhoun 1991) are similar, however there is a lack of the massive blocky calcite in the Dover Field that was present in the samples obtained by Colquhoun (1991). This suggests fluids that caused the formation of the massive blocky calcite were not present or did not affect the Dover Field to the same degree.

4) The isotopic analysis indicated a shallower burial depth and a lower burial temperature in the Dover Field than those in the vicinity of the Hillman/Goldsmith-Lakeshore Fields. However, the isotopic composition of the

saddle dolomites were similar to those determined by Colquhoun (1991) indicating the saddle dolomite may have formed in the same manner or by the same fluids.

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3.0 The Effects of Whole Core Analysis for Permeability and Porosity on Paleomagnetic and Rock Magnetic Signatures

3.1 Introduction

It has been demonstrated that changes in rock chemistry as a result of the formation of hydrocarbons can cause changes in the magnetic mineralogy and grain size causing the formation of new magnetic remanences (Banerjee & Elmore, 1997; Cioppa & Symons, 2000; Cioppa et al, 2002). In the never-ending quest to discover new economic hydrocarbon reservoirs, a variety of tests including an evaluation of porosity and permeability are often conducted on the same core used for paleomagnetic and rock magnetic analysis. The question that arises is whether these tests can affect the new magnetic remanences, and if so, what are the results? This is important because if the magnetic results are used in models of hydrocarbon formation and flow, changes in the remanences will affect the models.

The relationship between porosity and permeability is not clear at best. Lucia (1983, 1995, 1999) describes a method of pore classification using pore geometries and flow properties based on textural and particle size information. More recently Lonoy (2006) describes a new classification scheme for relating porosity and permeability, using thin section analysis of plug specimens. Lonoy (2006) used specimens that had a dominance of only one pore type, were unfractured and had available porosity and permeability information. Specimens were examined in 2-D, using a petrographic microscope and in 3-D using a scanning electron microscopy image processing. The authors indicate that which-ever method is employed, porosity and permeability testing is required. If these tests are used in conjunction with rock magnetic or paleomagnetic analysis it becomes necessary to define the effects of the tests, if any, on the magnetic minerals and remanences. The purpose of this study is to evaluate the effects of these porosity and permeability tests on previously characterized specimens.

3.2 Methodology

Nine samples were selected from Well A (PPC/ROMA-#13-7-16-IV) and Well B (PPC/RAM-#12-7-6-IV) and ten samples were selected from the Hillman/Goldsmith-Lakeshore Field (Garner, 2006). The samples underwent alternating field demagnetization using a Sapphire Instruments SI-4 demagnetizer in 14 steps from 5 to 140 mT. Once AF demagnetization was completed, partial anhysteretic magnetization (pARM) and saturation isothermal demagnetization (SIRM) analyses was conducted to determine the grain size and mineralogy of the specimens.

pARM treatment magnetizes a fracture of the magnetic grains in the corresponding coercivity range (Jackson et al. 1988). The grain size is inversely related to the coercivity (Jackson et al. 1988), therefore, a decrease in grain size gives greater values of pARM at higher coercivities. pARM's were imparted by exposing samples to a small direct magnetic field in the presence of a large, decreasing alternating field. The result of this treatment is the placement of a remanent magnetization on grains that have coercivities in the range of the biasing field. pARM's were imparted in 10 steps from 10 to 100 mT with a DC field magnitude of 0.05 mT.

SIRM is performed after pARM analysis because the pARM imparted on the samples can be removed by normal demagnetization.. SIRM analysis was conducted on the nineteen samples by treating them in 16 steps from 5 to 1200 mT, increasing the field intensity after each step. Following acquisition the samples were demagnetized using AF demagnetization in nine steps from 5 to 120 mT. To determine the magnetic mineral composition and their corresponding grain size, both sets of results from the analysis were plotted on a log graph and the curves of specific magnetic minerals (Symons and Cioppa, 2000). Cross-over points were determined from these graphs by visual analysis. Cross-over points represent the point on the graph where the acquisition and demagnetization values are equal. Typically lower magnetization fields and normalized intensity values of the cross-over point indicate larger grain sizes.

Once the pARM and SIRM analysis was complete, the samples were shipped to Core Laboratories Canada, Ltd (Calgary, AB) for porosity and permeability analysis. At the core laboratory each sample underwent conventional, plug type analysis. Prior to analysis, the samples were cleaned in a vapor phase extractor in which toluene (C_7H_8) percolates through the samples to clean them. Toluene is a cleaning solvent, and the sample is soaked in this solution to remove dirt followed by the removal of the dirt/toluene by vapor phase extraction. During this process the toluene may undergo oxidation. Following the cleaning process the samples are dried in a gravity oven at approximately 115°C to remove the toluene and water. Once the samples were dry, the porosity was analyzed by Boyle's Law technique using helium as the gaseous medium, at ambient pressure and temperature. Boyle's Law dictates if temperature is constant when the volume is increased the pressure will decrease and if the volume is decreased the pressure will increase. Horizontal permeability using air was run at 400 psi confining stress. The samples were then returned to the University of Windsor for further analysis.

Ten of the nineteen samples were chosen for comparison to pre-treatment data. Prior to the post-treatment testing, all specimens were demagnetized to 160 mT to remove any magnetization acquired outside of the magnetically shielded room. Following the treatment the pARM and SIRM was measured using the exact technique described above.

3.3 Results

The comparison of the pre-treatment and post-treatment analysis is given in Table 1. The table provides a range and standard deviation for each of the samples before and after the permeability and porosity analysis. The cross-over points were obtained from visually analyzing the SIRM graphs. The 100/SIRM, 200/SIRM, 300/SIRM and 400/SIRM values are a variation of the S-ratio analysis and were calculated for each sample using SIRM data. The values obtained for these ratios will range from 0 to 1, with higher values indicating a greater low coercivity-high coercivity ratio.

The cross-over point for the SIRM acquisition prior to the porosity and permeability analysis ranges from 42.3 mT to 53.8 mT with an average of 47.1 mT (Table 3.1, Figure 3.1). Figure 3.2 shows the SIRM curves produced after the porosity and permeability analysis; the cross-over point changes for seven of the eight samples and ranges from 34.6 mT to 50.0 mT with an average of 42.3 mT. There was no change in 012301 from the Dover Field. The values for the 100/SIRM, 200/SIRM, 300/SIRM and 400/SIRM ratios increase for nearly all of the samples. The average value for 100/SIRM, 200/SIRM, 300/SIRM and 400/SIRM increases by 6.1×10^2 A/m, 4.3×10^2 A/m, 2.5×10^2 A/m and 90 A/m, respectively. Additionally, the saturation increased for each sample with the average saturation value increasimg from 1.03 A/m to 1.14 A/m. The exception to this is 012401 from the Dover Field which decreased by 2.2×10^{-1} A/m

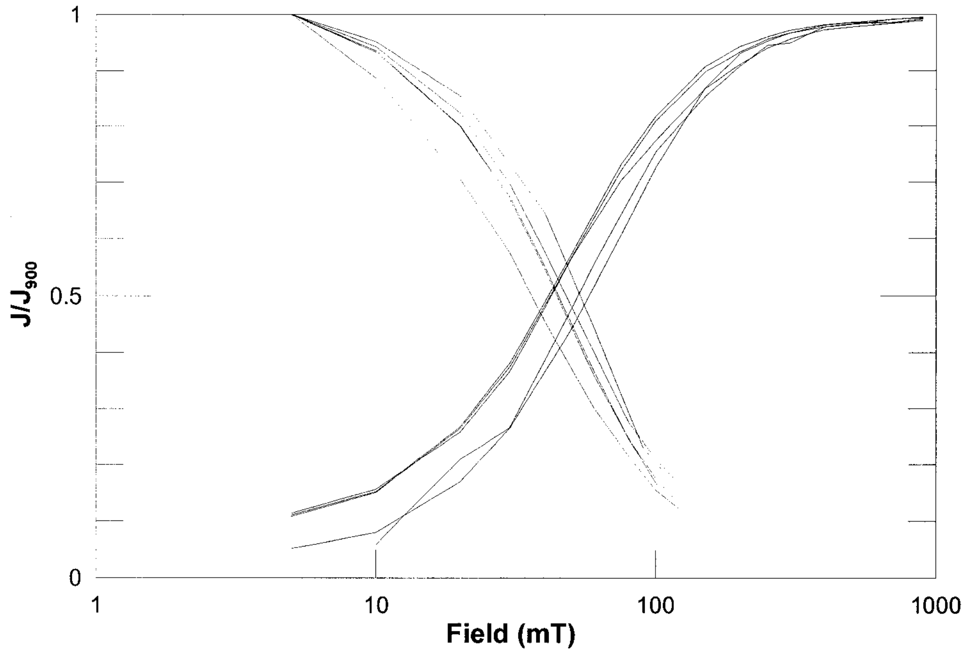

Figure 3.1. SIRM acquisition curves before porosity and permeability analysis.

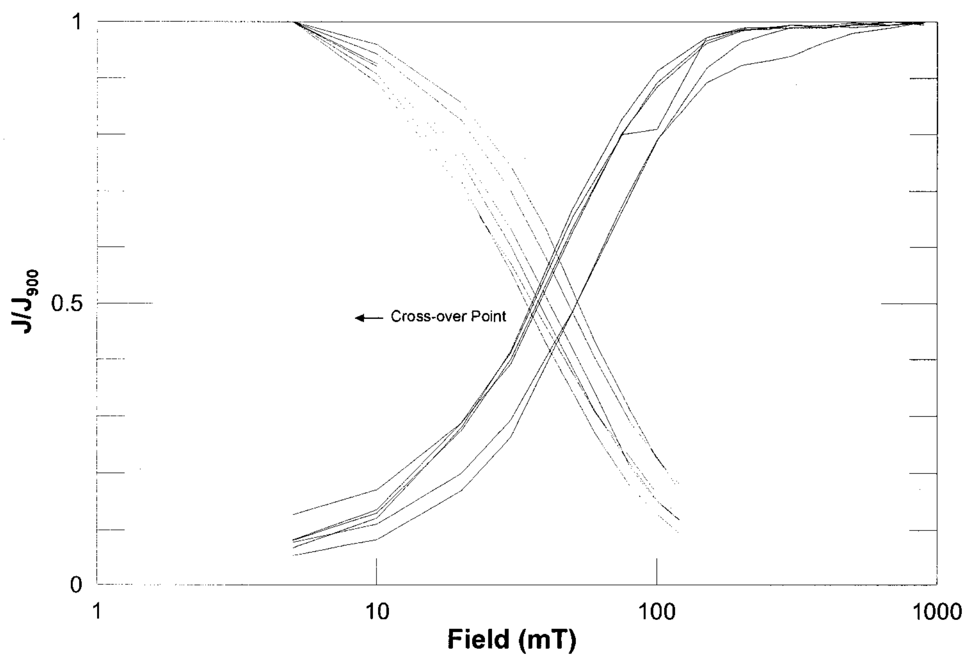

Figure 3.2. SIRM acquisition curves after porosity and permeability analysis. Notice the cross-over point moves slightly to the left.

Post-treatment	Range	1.94E-04 - 1.06E-05	34.6 - 50.0	7.89E-01 - 9.13E-01	9.17E-01 - 9.89E-01	9.39E-01 - 9.94E-01	9.64E-01 - 9.99E-01		
	Average + Standard Deviation	1.08E-04 + 4.66E-05	42.9 + 5.75	8.53E-01 + 0.052	9.65E-01 + 0.026	9.78E-01 + 0.02	9.86E-01 + 0.01		

Sample No.		SIRM Value	Cross-over Point	100/SIRM	200/SIRM	300/SIRM	400/SIRM	Porosity	Permeability
101401	Pre-treatment	8.20E-05	---	5.30E-01	8.38E-01	9.26E-01	---	0.031	0.31
	Post-treatment	8.41E-05	50.0	7.93E-01	9.17E-01	9.45E-01	9.69E-01		
204001	Pre-treatment	7.93E-05	40.0	8.79E-01	9.39E-01	9.49E-01	9.70E-01	0.096	1320
	Post-treatment	8.42E-05	40.0	8.40E-01	9.57E-01	9.83E-01	9.99E-01		
302002	Pre-treatment	1.15E-04	53.8	8.39E-01	9.22E-01	9.30E-01	---	0.015	<0.01
	Post-treatment	1.19E-04	50.0	8.19E-01	9.58E-01	9.66E-01	9.83E-01		
200501	Pre-treatment	4.38E-05	46.2	8.56E-01	9.32E-01	9.43E-01	9.66E-01	0.011	0.03
	Post-treatment	1.05E-04	34.6	9.11E-01	9.81E-01	9.90E-01	9.90E-01		
025201	Pre-treatment	7.25E-05	42.3	8.10E-01	9.34E-01	9.67E-01	9.78E-01	0.006	0.03
	Post-treatment	8.85E-05	38.5	9.00E-01	9.89E-01	9.94E-01	9.93E-01		
024701	Pre-treatment	5.01E-05	42.3	8.18E-01	9.44E-01	9.72E-01	9.82E-01	0.005	0.02
	Post-treatment	5.53E-05	38.5	8.92E-01	9.86E-01	9.95E-01	9.93E-01		
020401	Pre-treatment	4.79E-05	46.2	8.37E-01	9.39E-01	9.75E-01	9.87E-01	0.006	0.03
	Post-treatment	6.24E-05	38.5	9.13E-01	9.87E-01	9.94E-01	9.90E-01		
014102	Pre-treatment	9.93E-05	53.8	7.55E-01	9.09E-01	9.49E-01	9.78E-01	0.025	<0.01
	Post-treatment	1.03E-04	50.0	7.91E-01	9.23E-01	9.39E-01	9.64E-01		
012401	Pre-treatment	2.16E-04	46.2	7.27E-01	9.31E-01	9.68E-01	9.81E-01	0.139	86
	Post-treatment	1.94E-04	42.3	7.89E-01	9.64E-01	9.90E-01	9.90E-01		
012301	Pre-treatment	1.82E-04	46.2	7.75E-01	9.12E-01	9.56E-01	9.73E-01	0.011	0.04
	Post-treatment	1.83E-04	46.2	8.85E-01	9.84E-01	9.89E-01	9.89E-01		

Table 3.1 SIRM values before and after the porosity and permeability analysis as well as the results of the porosity and permeanbility analysis.

The pARM analysis of the Dover Field before the porosity and permeability analysis reveals two different peak values as shown in Figure 3.3. The first peak is between 10 and 30 mT, which indicates magnetite grains ranging between 2 to 5 microns in size. The second peak is between 30 and 40 mT, which indicates magnetite grains ranging from 0.75 to 2 microns in size. Figure 3.4 shows the pARM analysis of the Dover Field after the porosity and permeability analysis produced peak values between 10 and 30 mT indicating a grain size of 2 to 5 microns. Note the difference in the shape of the curves, which will be discussed later.

The Hillman/Goldsmith Lakeshore pARM curves produced before the porosity and permeability analysis (Figure 3.5) reveals a peak between 30 and 40 mT, which gives a grain size of approximately 2 to 3 microns. The pARM curves in Figure 3.6 produced after the porosity and permeability analysis give an inverse curve, which will be discussed later.

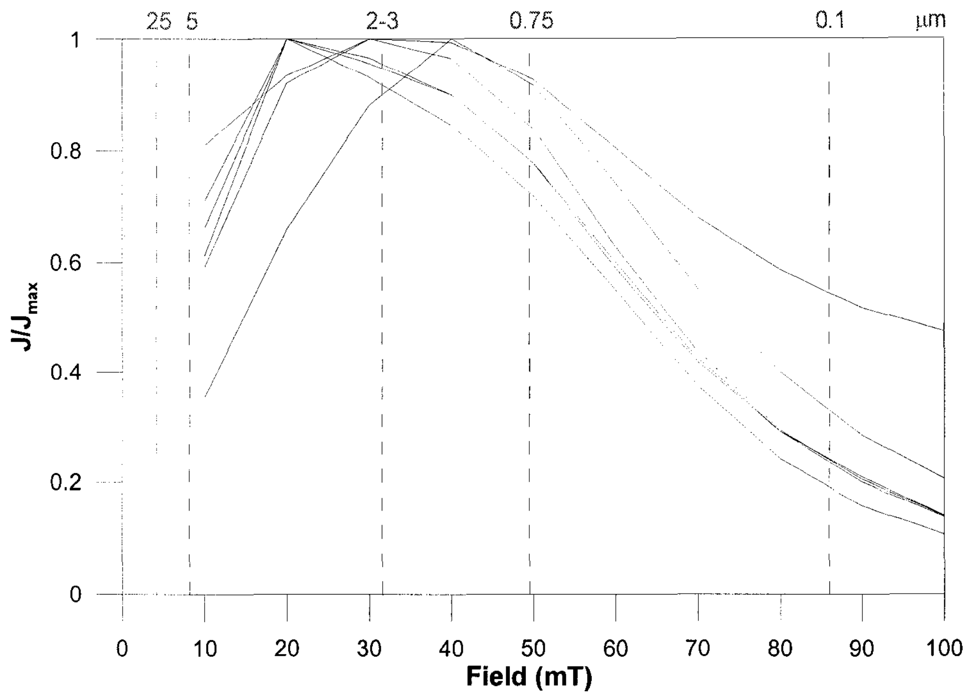

Figure 3.3. pARM curves for the Dover Field before porosity and permeability analysis

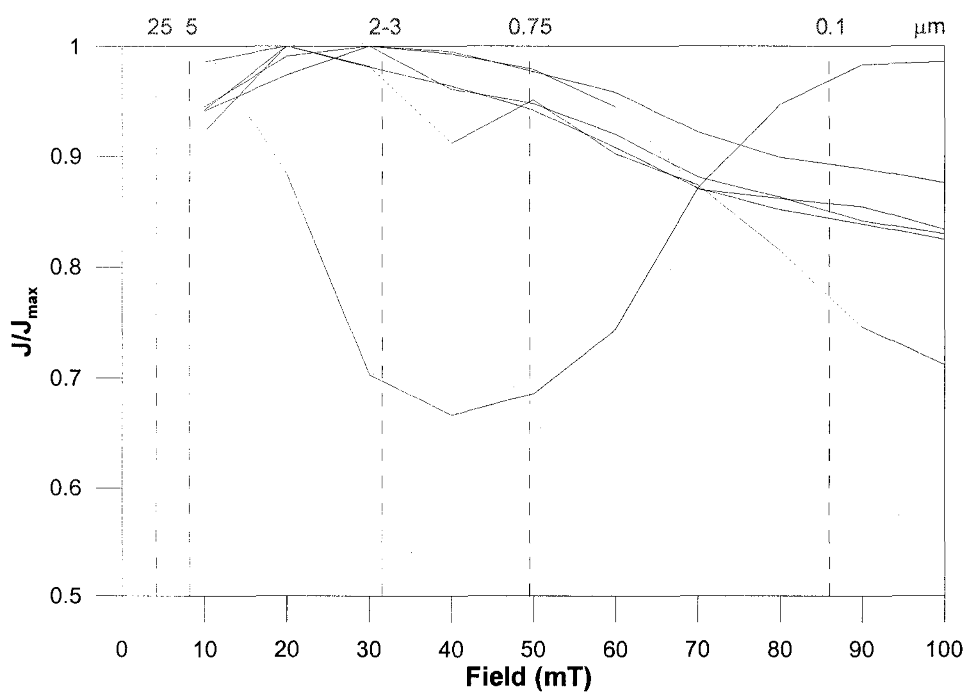

Figure 3.4. pARM curves for the Dover Field after porosity and permeability analysis

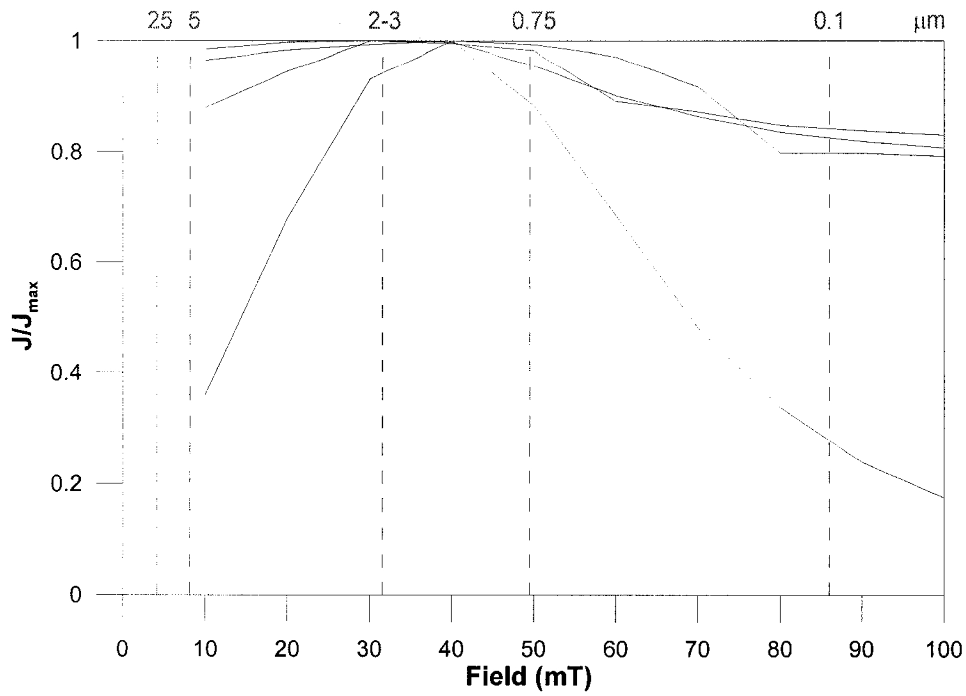

Figure 3.5. pARM analysis for the Hillman/Goldsmith-Lakeshore Fields before porosity and permeability analysis (Garner, 2006)

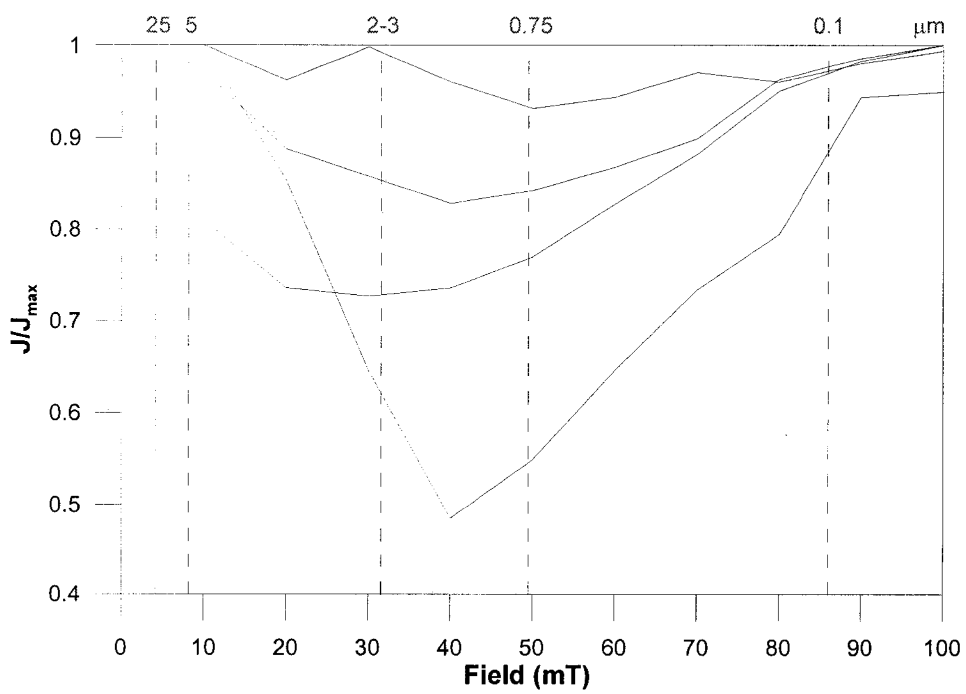

Figure 3.6. pARM curves for the Hillman/Goldsmith-Lakeshore Fields after porosity and permeability analysis.

3.4 Discussion

The pARM results indicated that demagnetizing the samples to 160 mT did not remove the magnetization obtained either during the SIRM process or while outside the magnetically shielded laboratory. The samples from the Dover Field show similar pARM magnetization peaks in the spectra before and after the porosity and permeability analysis, however, this overall curve is subdued due to the presence of a magnetization probably acquired during the SIRM analysis. One sample from the Dover Field and all the samples from the Hillman Field produced inverse curves which indicate the SIRM acquisition and S-ratio analysis may have affected the samples in a way which rendered further pARM analysis inaccurate.

The SIRM acquisition curves after the permeability and porosity analysis shows a tendency for the curves to shift to the left with corresponding decreases in the field value of the crossover point, indicating an increase in grain size. By examining the SIRM acquisition curves before and after the permeability and porosity analysis, it shows the cross-over point decreased 3.8 mT to 11.6 mT, with two samples (012301 from the Dover Field and 204001 from the Hillman/Goldsmith-Lakeshore Fields) showing no change. The cross-over point increases toward the fifty percent point (moving upward on the graph). A slight increase in the normalized intensity value occurs, possibly indicating a decrease in grain size. However, the potential of contamination by other magnetic minerals cannot be ignored.

The saturation remanence values increase from 1 to 58% with the exception of 012401 from the Dover Field, which decreased by 10%. However, the saturation value for 012401 decreases by approximately 2.2×10^{-1} A/m. As the porosity and permeability analysis showed higher values than the other specimens with the exception of 204001 from the Hillman/Goldsmith-Lakeshore Fields (Table 3.1), we looked at the cross-over point. The cross-over point for the sample decreases and the 100/SIRM, 200/SIRM, 300/SIRM and 400/SIRM values also increase for this sample which is consistent with nearly all of the other samples. There is no indication of any other difference between this specimen and the others. In addition, the 300/SIRM value (standard S-ratio equivalent) consistently increased for all samples with the exception of 014102 from the Hillman/Goldsmith-Lakeshore Fields. The increase in SIRM value and in S-ratio equivalent suggests that either there is an increase in magnetite content relative to the higher coercivity minerals during the porosity and permeability analysis, or the grain size of the magnetic grains has increased.

It is clear that during the analysis at the core lab, some factor or combination of factors affected the magnetic properties of the samples. Given the procedure used (see section 3.2), the potential factors are the use of toluene as a cleaning solvent, heating during the drying phase and the use of helium during the actual porosity/permeability analysis. The samples were only dried at temperatures of < 100°C, and such temperatures are unlikely to remagnetize or cause significant changes in magnetic mineralogy. Helium is an inert gas and it, in and of itself, would likely not have caused a chemical reaction. However, since magnetite forms under reducing conditions, it is possible that reducing conditions were instigated during the porosity and permeability analysis which resulted in the formation of magnetite. Alternatively, the cleaning process, and potentially the use of toluene as the solvent, may have affected the samples. However, more analysis is needed to determine exactly what, if any, effect the toluene and the analysis process may have had. If the described procedure was not followed exactly, other factors could have affected the magnetic results.

3.5 Conclusions

1) It is unclear whether porosity and permeability analysis has an affect on the pARM curves due to the inability to remove either or both of an induced magnetization which was acquired outside of the laboratory or the isothermal remanence (IRM) induced during SIRM analysis.
2) The porosity and permeability analysis did have an affect on the SIRM analysis by shifting the cross-over point to the left in nearly all of the samples. Additionally, the SIRM values and the 100/SIRM, 200/SIRM, 300/SIRM and 400/SIRM values increased for nearly all samples suggesting the porosity and permeability analysis has an effect on the magnetic minerals.
3) No discernable patterns were established for the pARM and SIRM analysis of the samples before and after porosity and permeability analysis in relation to the values obtained from the porosity and permeability treatment. Further study on a larger number of samples may be required to determine if a consistent pattern exists.

4) Further studies need to be conducted using samples that undergo either pARM or SIRM analysis, but not both on the same specimen, to control the study more accurately.
5) Determination of the cause of physical or chemical changes in the samples that resulted in the changes in magnetic properties requires a much more controlled setting and detailed observation of the cleaning and analysis process.

3.6 References

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4.0 Conclusions

The paleomagnetic analysis of the 146 samples from the Dover Field revealed different dates for the dolomitization of this area in Sarnia than the Hillman/Lakeshore-Goldsmith Field in Leamington. The 24 samples from the limestone non-reservoir reference core revealed a similar age for the dolomitization event that affected the Hillman/Goldsmith-Lakeshore Fields. These results indicate the fluids that caused the dolomitization of the Hillman/Lakeshore-Goldsmith Fields are not the same fluids that affected the Dover Field or are fluids depleted in the magnesium necessary for dolomitization. It can also be concluded by the lack of fracture fill calcite and hematite in the Dover Field as well as the little to no presence of pyrrhotite that the fluid event that resulted in the precipitation of the fracture fill calcite, hematite and pyrrhotite in the Hillman/Lakeshore-Goldsmith Fields did affect the Dover Field. This fluid may have contained the oil that is present in the Hillman/Goldsmith-Lakeshore Fields which would explain the absence of oil in the Dover Field.

Garner (2006) suggested vertically migrating fluids caused the fracture fill remagnetization with fluids that originated south of the Hillman/Goldsmith-Lakeshore Fields. Garner (2006) also suggested that the Hillman/Lakeshore-Goldsmith Fields were affected overall by multiple remagnetization events either by burial or fluid migration. The results obtained from this study of the Dover Field do not suggest the same multiple dolomitization events occurred in this area. It can be concluded that since similar results were obtained for the OGS-83 reference will that the fluids from the multiple events that affected the Hillman/Lakeshore-Goldsmith Fields did not reach the Dover Field and that the Dover Field was not affected by the vertical fluid migration that caused the fracture fill remagnetization. It can be suggested that a dolomitization event that was limited to the Dover Field could have resulted in a partial dolomitization and remagnetization of the limestones in the vicinity of the Dover Field.

Isotopic analysis of the Dover Field and a comparison of the isotopic study of the Hillman/Lakeshore-Goldsmith Field by Colquhoun (1991)suggest the Hillman/ Lakeshore-Goldsmith Fields may have undergone deeper burial and higher formation temperatures than the Dover Field which may result in greater dolomitization of the Hillman/Lakeshore-Goldsmith Fields.

No discernable patterns were established for the pARM and SIRM analysis of the samples before and after porosity and permeability analysis in relation to the values obtained from the porosity and permeability treatment. It is unclear whether porosity and permeability analysis has an affect on the pARM curves due to the inability to remove either or both of an induced magnetization which was acquired outside of the laboratory or the isothermal remanence (IRM) induced during SIRM analysis. The porosity and permeability analysis did have an affect on the SIRM analysis by shifting the cross-over point to the left in nearly all of the samples. Additionally, the SIRM values and the 100/SIRM, 200/SIRM, 300/SIRM and 400/SIRM values increased for nearly all samples suggesting the porosity and permeability analysis has an effect on the magnetic minerals. Further study on a larger number of samples may be required to determine if a consistent pattern exists.

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