

**Summary of Research through Phase II/Year 2 of initially approved  
3 Phase/3 Year Project – Establishing the Relationship between Fracture-  
Related Dolomite and Primary Rock Fabric on the Distribution of Reservoirs  
in the Michigan Basin**

**Final Scientific/Technical Report: DE-FC26-04NT15513**

**Reporting Period Start:      October 1, 2004  
Reporting Period End:        September 30, 2007**

**Principal Author and Project Manager:  
G. Michael Grammer, Ph.D.**

**Final Report Issued:            December 21, 2007  
Revised report issued:        March 1, 2008**

**DOE Award Number: DE-FC26-04NT15513**

**Department of Geosciences  
Western Michigan University  
1903 W. Michigan Ave.  
Kalamazoo, MI 49008-5241**

## **DISCLAIMER**

“This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof”.

## ABSTRACT

This final scientific/technical report covers the first 2 years (Phases I and II of an originally planned 3 Year/3 Phase program). The project was focused on evaluating the relationship between fracture-related dolomite and dolomite constrained by primary rock fabric in the 3 most prolific reservoir intervals in the Michigan Basin. The characterization of select dolomite reservoirs was the major focus of our efforts in Phases I and II of the project. Structural mapping and log analysis in the Dundee (Devonian) and Trenton/Black River (Ordovician) suggest a close spatial relationship among gross dolomite distribution and regional-scale, wrench fault-related NW-SE and NE-SW structural trends. A high temperature origin for much of the dolomite in these 2 studied intervals (based upon fluid inclusion homogenization temperatures and stable isotopic analyses,) coupled with persistent association of this dolomite in reservoirs coincident with wrench fault-related features, is strong evidence for these reservoirs being influenced by hydrothermal dolomitization.

In the Niagaran (Silurian), there is a general trend of increasing dolomitization shelfward, with limestone predominant in more basinward positions. A major finding is that facies types, when analyzed at a detailed level, are directly related to reservoir porosity and permeability in these dolomites which increases the predictability of reservoir quality in these units. This pattern is consistent with our original hypothesis of primary facies control on dolomitization and resulting reservoir quality at some level. The identification of distinct and predictable vertical stacking patterns within a hierarchical sequence and cycle framework provides a high degree of confidence at this point that the results should be exportable throughout the basin.

Much of the data synthesis and modeling for the project was scheduled to be part of Year 3/Phase III, but the discontinuation of funding after Year 2 precluded those efforts. Therefore, the results presented in this document are not final, and in many cases represent a report of “progress to date” as numerous tasks were scheduled to extend into Year 3.

## TABLE OF CONTENTS

|                                                                                                                                                           |       |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| Abstract                                                                                                                                                  | p. 3  |
| Executive Summary                                                                                                                                         | p. 7  |
| Introduction                                                                                                                                              |       |
| • Rationale and Goals of the Project                                                                                                                      | p. 9  |
| • Background – Mechanisms for Dolomitization                                                                                                              | p. 13 |
| • Stratigraphy and Dolomite Occurrences in Michigan Basin Paleozoic Carbonate Reservoirs                                                                  | p. 17 |
| -Trenton/Black River Formations                                                                                                                           |       |
| -Occurrence of Dolomite in the Trenton/Black River                                                                                                        |       |
| -Silurian Niagara Group                                                                                                                                   |       |
| -Dolomite in the Niagara Group                                                                                                                            |       |
| -Dundee Limestone                                                                                                                                         |       |
| -Dolomite in the Dundee Limestone                                                                                                                         |       |
| • Structural Elements, Thermal Evolution, and Hydrothermal Mineralization in the Michigan Basin                                                           | p. 25 |
| • Variations in Dolomitization and Reservoir Geometries in the Michigan Basin                                                                             | p. 32 |
| • Petrographic and Analytical Study of Dolomitized Carbonate Reservoirs                                                                                   | p. 34 |
| • Reservoir Characterization – Petrophysical Properties of Carbonate Sediments and Rocks                                                                  | p. 39 |
| Project Approach and Discussion of Results by Task (Phase I and II)                                                                                       |       |
| • Development of a Reservoir Catalog for selected dolomite reservoirs in the Michigan Basin                                                               | p. 45 |
| • Summary of Phase I and II – Devonian and Ordovician                                                                                                     | p. 50 |
| -Devonian Dundee Formation                                                                                                                                |       |
| -Trenton/Black River Formations                                                                                                                           |       |
| • Summary of Phase I and II – Silurian (Niagaran)                                                                                                         | p. 54 |
| -Facies                                                                                                                                                   |       |
| -Sonic Velocity Characterization                                                                                                                          |       |
| • Development of 3-D Geological Models and Assessment of Application Potential                                                                            | p. 60 |
| • Technology Transfer                                                                                                                                     | p. 60 |
| Discussion: Phase I and II- Initial Results from Tasks 2 and 3                                                                                            |       |
| • “Controls on Dolomitization in the Middle Devonian Dundee Formation - Oil Field Scale Structure and the Distribution of Log-Based Dolomite Lithofacies” | p. 91 |
| -Introduction                                                                                                                                             |       |



- Geological Background – Dundee Formation
- Dolomite Reservoirs in the Dundee Formation
- Study Methodology and Objectives
- Dundee Field Water Production Characteristics
- Fracture Related Hydrothermal Reservoirs in Michigan
- Distribution of Wire-line Log Based Lithofacies in the Dundee Formation
- Regional Dundee Structure Mapping and Log-based Lithofacies Distribution
- Field Scale Structure Mapping and Log-based Lithofacies
- Implications for Petroleum Geology in Michigan and other U.S. Hydrocarbon Basin
- Silurian (Niagaran) – Petrophysical Facies and Image Analysis p. 114
  - Petrophysically Significant Facies
  - Image Analysis
  - Image Analysis Results (by Facies)
  - Sonic Velocity

#### Summary of Currently Available Geologic Data through Phase II

- Ordovician Trenton/Black River Production p. 144
  - Trenton-Black river Discovery and Development
  - Stratigraphy and Structure
  - Trenton-Black River Reservoir Characteristics
  - Origin of Dolomite
  - Exploration
  - Exploitation
  - Summary
- Silurian Niagaran Production p. 150
  - General Observations
- Devonian Dundee Trend Production p. 153
  - General Observations

Report References p. 155

Bibliography – part of Task 2 (Compilation of currently available geologic data and literature). p. 164

Appendix 1: Practical Synergies for Increasing Domestic Oil Production and Geological Sequestration of Anthropogenic CO<sub>2</sub>: An example from the Silurian of the Michigan Basin p. 203

Appendix 2: Summary of Currently Available Geologic Data (Task 2) p. 238

Production analysis data and graphs.

1. Ordovician Trenton/Black River
2. Silurian Niagaran
3. Devonian Dundee

Appendix 3: Representative project presentations (abstracts) at professional meetings p. 302

Appendix 4: Miscellaneous Project Presentations (titles) p. 308

## EXECUTIVE SUMMARY

This final scientific/technical report covers the first 2 years (Phases I and II of an originally planned 3 Year/3 Phase program). The project was focused on evaluating the relationship between fracture-related dolomite and dolomite constrained by primary rock fabric in the 3 most prolific reservoir intervals in the Michigan Basin (Ordovician Trenton-Black River Formations; Silurian Niagara Group; and the Devonian Dundee Formation). Much of the data synthesis and modeling for the project was scheduled to be part of Year 3/Phase III, but the discontinuation of funding after Year 2 precluded those efforts.

Dolomitization is widespread and generally a critical factor in the origin of these most prolific, hydrocarbon reservoirs in the Michigan Basin: i.e. the Middle Ordovician Trenton/Black River Formations, the Silurian Niagara Group and the Middle Devonian Dundee Limestone. These units are the most economically important reservoirs in the basin. However, they consist of a wide range of dolomite types resulting in complex spatial variability of both geometry and quality of dolomite reservoirs.

The characterization of select dolomite reservoirs was the major focus of our efforts in Phases I and II of the project. Fields were prioritized based upon the availability of rock data for interpretation of depositional environments, fracture density and distribution as well as thin section, geochemical, and petrophysical analyses. Structural mapping and log analysis in the Dundee (Devonian) and Trenton/Black River (Ordovician) suggest a close spatial relationship among gross dolomite distribution and regional-scale, wrench fault-related NW-SE and NE-SW structural trends. A high temperature origin for much of the dolomite in these 2 studied intervals (based upon initial fluid inclusion homogenization temperatures and stable isotopic analyses,) coupled with persistent association of this dolomite in reservoirs coincident with wrench fault-related features, is strong evidence for these reservoirs being influenced by hydrothermal dolomitization.

For the Niagaran (Silurian), there is a general trend of increasing dolomitization shelfward, with limestone predominant in more basinward positions. Reservoir quality porosity and permeability is characterized by a combination of dissolution-related molds, vugs, and locally cavernous porosity that is enhanced in the dolomite sections by intercrystalline porosity. A comprehensive high resolution sequence stratigraphic framework was developed for a pinnacle reef in the northern reef trend where we had 100% core coverage throughout the reef section. This sequence framework was then compared with major Niagaran fields in the southern reef trend, although comprehensive correlation and 3-D modeling did not occur because these tasks were part of Phase III. Major findings to date are that facies types, when analyzed at a detailed level, have direct links to reservoir porosity and permeability in these dolomites. This pattern is consistent with our original hypothesis of primary facies control on dolomitization and resulting reservoir quality at some level. The identification of distinct and predictable vertical stacking patterns within a hierarchical sequence and cycle framework provides a high degree of confidence at this point that the results should be exportable throughout the basin.

Ten reservoir significant lithofacies were described in the northern reef trend, providing significantly more resolution than the standard 4-6 that are used most often in the basin (e.g. Gill, 1977). Initial petrophysical characterization (sonic velocity analysis under confining pressures) showed a clear pattern that is dependent upon facies and resulting pore architecture. Primary facies is a key factor in the ultimate diagenetic modification of the rock and the resulting pore architecture. Facies with good porosity and permeability clearly showed relatively slow velocity values as would be expected, and low porosity and permeability samples exhibit fast sonic velocity values, again as expected. What is significant is that some facies that have high porosity values, either measured directly or from wireline logs, also have very fast sonic velocity values. This is due to these facies having a pore architecture characterized by more localized pores (vugs, molds or fractures) that are not in communication.

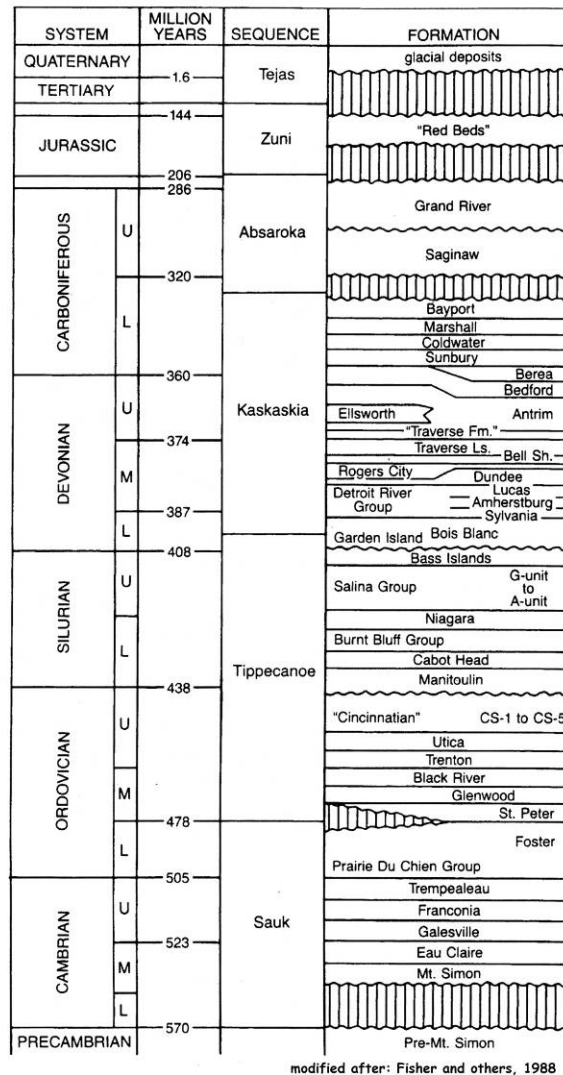
The discontinuation of the project following Year 2/Phase II was unfortunate in that most of the synthesis and modeling of the dolomite and reservoir distribution in the 3 intervals was scheduled to be done during Phase III. Even partial funding of Phase III would have allowed for a more thorough synthesis of the data collected and summarized during Phases I and II. Because much of the data synthesis and modeling for the project was scheduled to be part of Year 3/Phase III, the results presented in this document are not final, and in many cases represent a report of “progress to date” as numerous tasks were scheduled to extend into Year 3.

# **INTRODUCTION**

## **RATIONALE AND GOALS OF PROJECT**

The Michigan Basin is a mature hydrocarbon basin that has been recognized by the United States Geological Survey as one of the 25 “priority basins” in the United States which contain some 90-95% of known and undiscovered domestic hydrocarbon resources (USGS National Assessment of Oil and Gas Resources Program, 2004). Current activity in the basin is mostly concentrated on step-out development and enhanced production efforts, although moderate exploration efforts continue to be pursued. Over the past 75+ years, the basin has produced in excess of 1.3 billion barrels of oil and 5.9 trillion cubic feet of natural gas. The most prolific oil producing formations in the basin, with total cumulative production of approximately 900 million barrels of oil and 4.5 trillion cubic feet of gas, are the Ordovician Trenton and Black River Formations, the Silurian Niagara Group, and the Devonian Dundee Limestone (Figure I-1). Each of these units is comprised of volumetrically significant dolomitized reservoir facies for which several models of formation have been proposed. To maximize the discovery of new reservoirs and for the recovery of bypassed or stranded hydrocarbons in these intervals, it is critically important that the operator have access to scientifically-constrained reservoir models that are able to predict the geometrical distribution of the reservoir facies in the subsurface. Utilization of such models will allow the operator to better pursue new exploration efforts, high-grade placement of step-out development wells, and to more accurately orient directional or horizontal wells. It was the stated goal of this project to fully characterize reservoir dolomites in the three units indicated above, specifically to determine the relationship of dolomite to fracture

trends/fracture density, and/or to primary depositional facies, and to develop improved models for exploration and development of these reservoirs based upon a better understanding of their 3-D distribution in the subsurface.



**Figure I-1. Paleozoic stratigraphy of the Michigan Basin**

Despite the fact that these intervals have been exploited for more than 75 years, surprisingly little published information exists from regional well log mapping and detailed petrologic and analytical/geochemical study of the dolomites making up these

reservoirs. The majority of “recent” and authoritative work dates back to the mid 1980’s. Effective exploitation of these reservoirs is dependent upon being able to predict the distribution and reservoir quality of the units in the subsurface, and this information is critically dependent upon the mode of formation and distribution of the dolomitized reservoir facies. While many operators assume that, for example, the Trenton/Black River is strictly a hydrothermal dolomite play associated with deep-basin fractures, and therefore expect a linear distribution in the subsurface, recent work has suggested that distribution of reservoir quality rock is also dependent upon the original rock fabrics which are related to primary depositional facies. In this case, some reservoirs may be strictly limited to linear distribution while others, where hydrothermal dolomitizing fluids expand laterally away from the fractures in rocks that are already porous and permeable, may form more complex geometrical patterns related to the original 3-D depositionally-controlled rock fabric/facies.

At the beginning of the project, there was no document that summarized and synthesized the available data and knowledge base for these reservoirs. Because most of the current models are based upon areally limited and often “first-look” studies coupled with “common knowledge”, limited scientific basis existed to support useful models for the origin and subsurface distribution of dolomite reservoirs in these units. In addition, very little had been done to critically evaluate, and scientifically document, the relative contribution of fracture-related, epigenetic dolomite involving structural controls versus spatial distribution patterns that may also be affected by primary depositional fabrics.

The specific goals of this project therefore were threefold. First, to summarize and critically synthesize all of the publicly-available data on the geometrical distribution

and reservoir quality of dolomitized reservoirs in the Trenton-Black River, Niagaran, and Dundee formations and how they may be related to fractures. Second, to perform a scientifically rigorous characterization of the various structural and stratigraphic controls and modes of dolomite formation in the three intervals. This was to include evaluation of the impact dolomitization has on reservoir quality and documentation of the regional and field scale distribution of these reservoirs utilizing state of the art methods such as isotopic and trace element analysis, fluid inclusion analysis, determination of pore system architecture, and sonic velocity characterization from 6-9 representative fields. Third, to develop geological models for the 3-D distribution of reservoir facies for the different types of dolomite reservoirs that would provide operators with a means to high-grade exploration, development, and enhanced recovery efforts in a cost-effective manner. Major goals 2 and 3 above were targeted to be the focus of Year 3/Phase III of the project and thus were only initiated in Phase II (i.e. without a full synthesis as planned in the original proposal).

Results of this project have led to an increased understanding of regional and field scale dolomitized reservoirs in the Michigan Basin and may be exportable to other domestic oil and gas producing basins. We anticipate that these results would likely lead to new, reduced risk exploration and step-out development play concepts in the Michigan Basin, as well as a better and more complete understanding of the local subsurface distribution of reservoirs to guide enhanced production efforts. Increasing production in the Michigan Basin, and potentially in other domestic basins, has national security implications through the reduction of the amount of foreign oil and gas imports needed to sustain our current national infrastructure. A 10% increase in hydrocarbons produced



from the three main producing intervals in the Michigan Basin alone would result in approximately 150 MMBOE of additional hydrocarbon production for the nation.

## **BACKGROUND - MECHANISMS FOR DOLOMITIZATION**

Numerous models have been invoked to explain the occurrence of dolomite in shallow carbonate platform settings (Figure I-2a). Some of the more commonly discussed models include mixing zone (Hanshaw, et al., 1971; Badiozamani, 1973; Humphrey and Quinn, 1989), seepage reflux (Adams and Rhodes, 1960; Sears and Lucia, 1980; Kaldi and Gidman, 1982; Simms, 1984; Whitaker and Smart, 1990; Whitaker et al., 1994) tidal pumping (Carballo et al., 1987), evaporative pumping (McKenzie, 1981; Ruppel and Cander, 1988) and Kohout convection (Simms, 1984; Swart and Melim, 2000).

The distribution of depositional-facies-controlled, early diagenetic *reflux dolomite* is related to the spatial distribution of peritidal carbonate and evaporite-rich successions. Hypersaline brines, the so-called “special fluids” necessary for low temperature dolomitization (<60°-70° C), originate as interstitial fluids in evaporitic facies found at the margins of sedimentary basins in supratidal or sabhka environments. Dolomitized strata are found in proximity (both stratigraphically and areally) to these evaporite-rich facies. Analysis of these dolomites confirms evaporative formation with isotopically heavy  $\delta^{18}\text{O}$  values but  $^{87}\text{Sr}/^{86}\text{Sr}$  isotopic ratios of normal, age-equivalent sea waters.

*Mixing zone dolomite* (Badiozamani, 1973) is thought to originate through the interaction of normal marine waters and fresh waters in basin margin or shoal water/island settings. It is an especially attractive model for early diagenetic dolomitization in areas where evaporitic facies and evidence for hypersaline formation

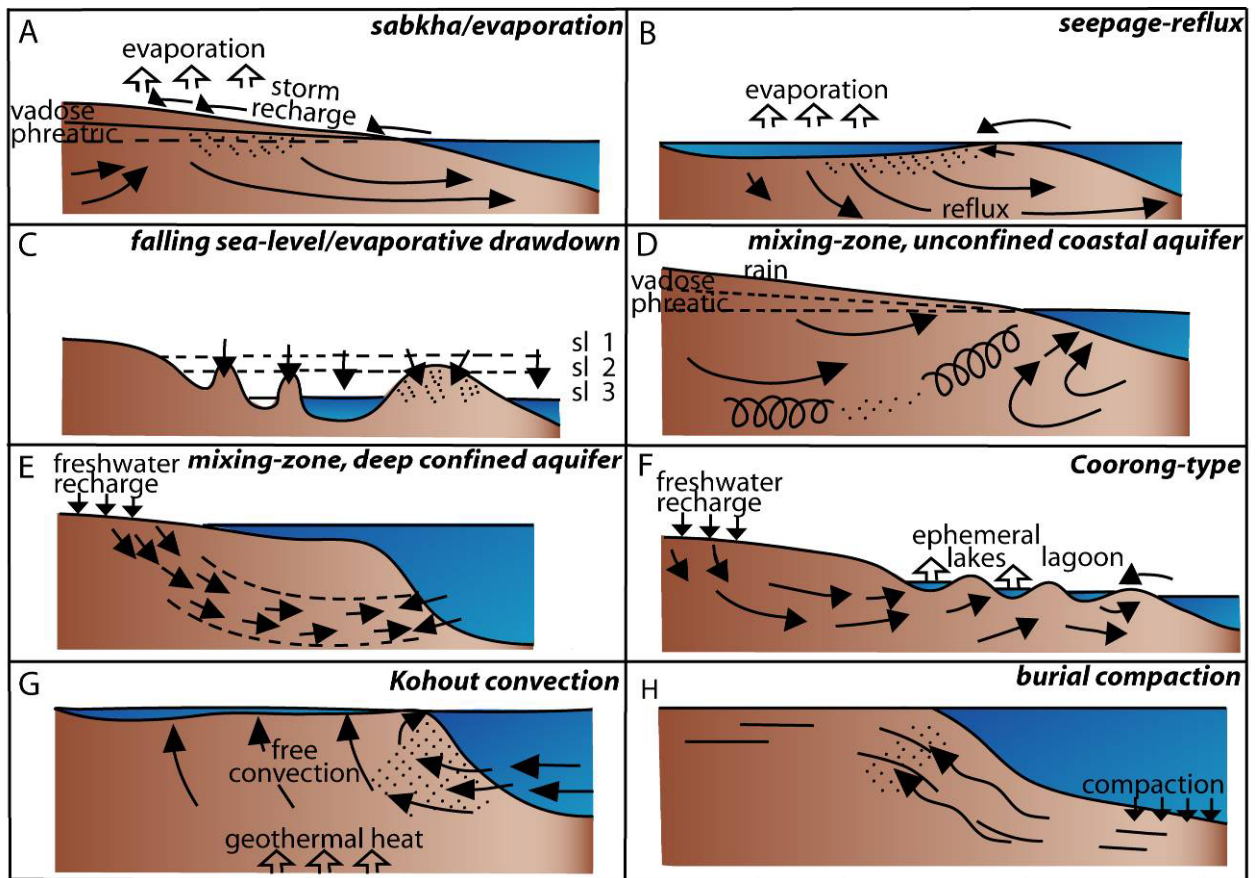


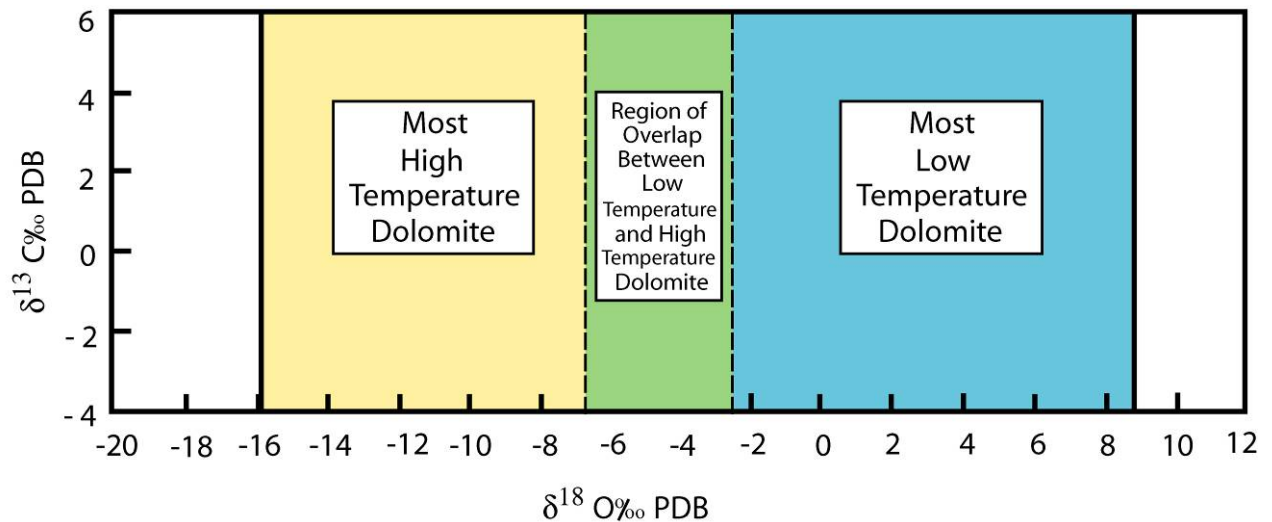
Figure I-2a. Generalized models for the various published mechanisms for dolomitization.

Modified from Land (1985).

fluids are not observed. The main criteria for recognition of mixing zone dolomites are:

- 1) elevated (relative to sea water of appropriate geological age), radiogenic Sr isotope composition (due to the influence of terrestrial clastic sources of Sr in the dolomitizing fluids); and 2) low homogenization temperature, single phase, primary fluid inclusions with indications of low salinity (on the basis of freezing temperatures).

*Burial dolomite* (Figure I-2b) results from the migration of dolomitizing fluids and associated mass transport originating from “burial” or other processes resulting in elevated temperatures (>60°C- 100°C). Hydrothermal (or simply “warm”, see Machal and Lonnee, 2002) fluids are favored as a key component of the dolomitization mechanism because there is no need for “special” (either hypersaline or “mixing zone”) fluids in many settings.



**Figure I-2b. Generalized relationship between  $\delta^{18}\text{O}$  and temperature of formation. Modified from Allan and Wiggins (1993).**

The observation that much “burial” dolomite has isotopic and fluid inclusion composition consistent with origins from hypersaline brines is currently an unexplained, empirical one (Allen and Wiggins, 1993).

The origins and migration pathways of fluids responsible for “burial” dolomitization can be highly variable from one basin to another, and even within an individual basin. Since most normal, “warm” formation fluids ( $>70^{\circ}\text{C}$ ) can theoretically produce “burial” dolomite, fluid migration pathways are the main controlling factor on the spatial distribution of burial dolomite. Vertical, convective flow through fractures of tectonic origin is most commonly cited (Davies, 2000) as the controlling factor of spatial distribution of “burial” or hydrothermal dolomite, but lateral flow of dolomitizing fluids and areal enhancement of reservoirs may also be dependent upon primary facies porosity and permeability distribution (Zempolich and Hardie, 1997).

An important constraint on the “burial” dolomitization mechanism is the requisite association of elevated temperature fluids with a pre-cursor rock matrix sufficiently porous to provide fluid flow conduits for the fluid volumes necessary to complete the dolomitization process. The generation of “burial” dolomitizing fluids is normally assumed to require “deep” burial. Extensive fracturing (tectonic, karst-related collapse, etc.) is commonly assumed to be a prerequisite for creation of dolomite-host rock permeability and resulting transport of “burial” fluids. Lateral flow of “burial” dolomitizing fluids should also be important on a local to regional scale if strataform, fluid flow conduits, including porous, primary depositional facies exist at the time of “burial” dolomitization.

The most reliable and least equivocal characteristic for establishing the genetic relationship of diagenetic minerals in reservoir rocks (including dolomite) is temperature of formation. Recent, critical reviews of models for dolomitization (Hardie, 1987; Davies, 2000) emphasize the importance of elevated temperatures of formation to

resolving the mechanistic problems of important dolomite occurrences. The important conclusion of this work is that “almost any warm (*epigenetic*, > *about 100°C*) groundwater becomes a potential dolomitizing fluid” (Hardie, 1987).

The principal mechanistic constraints on widespread dolomitization, therefore, are available “warm” fluids and suitable, interconnected fluid-flow conduits within a basin and not on “special” dolomitizing fluids. Studies of fluid inclusion homogenization temperatures, coupled with stable isotopic analyses, are critical to the assessment of dolomite genesis and basin hydrodynamics. Understanding processes of dolomitization, will in turn, lead to enhanced prediction of the spatial distribution of dolomitized hydrocarbon reservoirs in the subsurface.

### ***Stratigraphy and Dolomite Occurrences in Michigan Basin Paleozoic Carbonate Reservoirs***

Dolomitization is widespread and generally a critical factor in the origin of the most prolific, hydrocarbon reservoirs in the Michigan Basin: the Middle Ordovician Trenton/Black River Formations, the Silurian Niagara Group and the Middle Devonian Dundee Limestone (Figure I-1). These units are the most economically important reservoirs in the basin. However, they consist of a wide range of dolomite types resulting in complex spatial variability of both geometry and quality of dolomite reservoirs. The most utilized models for dolomite formation and distribution in the Michigan Basin indicate that dolomite results from a variety of processes, most commonly related to: 1) refluxing brines from overlying sabkha type environments; 2) hydrothermal, fracture-related brines; 3) burial (but not hydrothermal) brines localized along fractures; and 4)

mixing zone dolomitization. These models, however, are mostly “generic” and mono-phase in nature, are based upon limited scientific justification (most of which is 2-4 decades old), and have minimal detail about the expected geometrical distribution of reservoir quality dolomites in the subsurface.

#### Trenton/Black River Formations

The Middle Ordovician, Trenton and Black River Formations are major carbonate units that can be readily correlated over much of the eastern U.S. to the transcontinental arch in the west (Wilson and Sengupta, 1985). Trenton-Black River reservoirs in Michigan have produced over 145 million barrels of oil and 250 BCF of gas, most notably in the Albion Scipio and Stony Point fields. The Trenton and Black River Formations are predominantly micritic limestone in the Michigan Basin (Catacosinos and Daniels, 1991) although dolomite is both stratigraphically and areally significant (see below). The Trenton is lithologically similar to the Black River Formation and generally indistinguishable in well logs. Prominent, regionally correlative Middle Ordovician K-bentonites are used to separate the Trenton from the Black River in Michigan and elsewhere in the eastern United States. These bentonites represent ash falls throughout the Appalachian basin resulting from Taconic orogenic events and volcanism (Kolata, et al., 1986).

The Trenton is overlain by the Utica/Maquoketa shale in the Michigan Basin and adjacent cratonic arch areas (Fisher et al., 1988). The Trenton/Black River succession increases in combined stratigraphic thickness from 400 ft to 1000 ft from southwest to east in the Michigan Basin. In the basin, the Trenton consists of open marine limestone facies deposited in a relatively high energy, subtidal or deeper water ramp environment

(Keith, 1985), and lacking basin margin or tidal flat facies (Wilson and Sengupta, 1985). Local intervals of grain-rich fabrics are interpreted as either carbonate shoals or storm (tempestite) deposits (Fara and Keith, 1988).

#### *Occurrence of Dolomite in the Trenton/Black River*

Dolomite, of various origins, is an important lithologic component of the Trenton and Black River Formations in the Michigan Basin, and contains distinct spatial and stratigraphic distribution as well as variable petrologic character. Well-documented, but somewhat contradictory petrographic and analytical characterization of dolomite types in the Trenton/Black River have resulted in at least three distinct dolomite types recognized in the Michigan Basin. These are:

1) a dense, finely crystalline, ferroan “cap dolomite” that occurs in the top 10-40 ft of the Trenton below the Utica Shale throughout much of the basin (Taylor and Sibley, 1987). This dolomite contains moderately well-preserved primary fabrics. Oxygen isotopic composition, trace element chemistry, and stratigraphic/cross cutting relationships in this dolomite are interpreted to indicate a relatively early, burial origin related to diagenesis and fluid expulsion from shales in the overlying Utica/Maquokata (Taylor and Sibley, 1987; Coniglio et al., 1994).

2) a coarsely crystalline, “saddle” dolomite that typically fills fractures and vugs, that is common in highly faulted and fractured zones such as the Albion-Pulaski-Scipio trend. Petrologic and analytical data (Allan and Wiggins, 1993; Coniglio, et al., 1994; this study), including those from oxygen isotopes and primary fluid inclusions, clearly indicate that this “fracture related” dolomite was produced during “burial” from fluids

with elevated temperatures (> at least 100°C), that were most likely transported through fracture systems and involved formation fluids of complex origins.

3) a medium- to coarsely-crystalline, variably ferroan, “regional”, fabric destructive dolomite that may be volumetrically more significant compared to “cap” and fracture-related dolomites discussed above. Genesis of this dolomite type is somewhat enigmatic. Taylor and Sibley (1987) initially identified this “regional” dolomite to be of early diagenetic origin, and thought it to be distributed mainly in the margins to the south and west of the Michigan Basin. Later studies (Fara and Keith, 1988; Coniglio, et al., 1994; Budai and Wilson, 1991) related Taylor and Sibley’s “regional dolomite” to “fracture related” burial dolomite with distribution controlled by proximity to fractures. This dolomite type is typically matrix replacive, may or may not preserve primary limestone textures, and probably constitutes substantial volumes of porous and permeable reservoir facies in fracture-trend Trenton/Black River fields.

#### Silurian Niagara Group

Hydrocarbon reservoirs in the Middle Silurian (Niagaran) “pinnacle” reefs have been established in two well-defined trends in the northern and southern parts of the Michigan Basin. Over 700 individual fields have been found in the northern part of the basin with an additional 300+ fields known along the southern trend. Recent work suggests that a continuation of the trend on the western side of the basin may provide new opportunities for exploration (PTTC Workshop on Horizontal Drilling, 2003). Current production from Niagaran reefs has totaled nearly 400 million barrels of oil and nearly 4 TCF of gas. Individual reefs range from approximately 50-400 acres in area and typically have 50-200m in topographic relief. Early in the development of the reef trend,



it became apparent that both limestone and dolomite reefs were present in the basin and that the dolomitized reefs were by far the most productive (Sears and Lucia, 1980, p.215).

#### *Dolomite in the Niagara Group*

There is a general trend of increasing dolomitization shelfward, with limestone predominant in more basinward positions. Reservoir quality porosity and permeability is characterized by a combination of dissolution-related molds, vugs, and locally cavernous porosity that is enhanced in the dolomite sections by intercrystalline porosity (Gill, 1977; Sears and Lucia, 1980; Lucia, 1999). Detailed petrographic work by Sears and Lucia (1980) on reefs from the northern trend is the framework for much of the currently available information and interpretive models for reservoir formation in the Niagaran reefs.

According to Sears and Lucia (1980), dolomitization in the pinnacle reefs was a combination of precipitation from a mixture of freshwater and seawater that occurred during subaerial exposure of the reefs, and later more extensive replacement dolomites related to refluxing brines from overlying sabkha type environments. This second stage of dolomitization is volumetrically the most important, and forms massive dolomitized sections with good to excellent intercrystalline porosity (Sears and Lucia, 1980; Cercone and Lohmann, 1985). In a more recent discussion by Lucia (1999), the pervasive second stage dolomitization and related “burial dissolution and fractures” shows little conformance to primary depositional facies other than the association with overlying tidal flat facies.

Although the Sears and Lucia (1980) models for dolomitization of the Niagaran reefs is often referred to in local discussions of the reservoir trend, additional work done

by Cercone and Lohmann (1985) indicates that, in at least some reefs, there is also a late stage of dolomite related to deep burial brines. These late burial dolomites are associated with fractures and late solution voids and have distinctly different carbon and oxygen stable isotopic values as well as fluid inclusions with homogenization temperatures greater than 80°C.

### Dundee Limestone

The Middle Devonian Dundee Limestone is the longest lived and one of the most prolific oil producing formations within the Michigan Basin. The initial discovery was in 1927 with subsequent discoveries of over 125 fields basin-wide leading to production in excess of 350 MMBO and substantial natural gas. Gardner (1974) defined the Dundee Limestone in the western part of the basin as consisting of the Rogers City Member above, and the Reed City Member below, separated by a prominent anhydrite unit called the Reed City Anhydrite. This subdivision is less obvious in the central and eastern basin where the Reed City Anhydrite is not present. A “Reed City Equivalent” member is commonly identified by petroleum geologists in this area and consists of variably dolomitized, shallow marine carbonate strata. The Dundee is known to range from a wedge edge, 0' isopach in southwest Michigan to a maximum thickness of 400 ft in the basin center. Complex onlap/offlap and unconformable relationships exist on the basin margins (Gardner, 1974) comparable to many other formations in the Michigan Basin.

Facies in the Reed City Member indicate an east facing marine embayment that shoaled upwards from fossiliferous and grainy carbonates, deposited on a shallow marine carbonate shelf or ramp, to laminated and anhydritic dolomite deposited in a sabkha setting. Dolomitized, Reed City member carbonate strata are more common in the

western and central basin while limestone is more common in this unit in the eastern basin. In the central and eastern basin the Reed City member is also predominantly fossiliferous and grainy with important patch reef facies in places (Montgomery, 1986). Facies relationships are locally complex, however, with indication of syndepositional, structural control on facies in some fields but not others (Montgomery, 1986; Curran and Hurley, 1992).

The Rogers City Member throughout the Michigan Basin consists mostly of nodular wackestone with subordinate skeletal wackestones and packstones. This unit is interpreted as a transgressive package deposited from east to west (Gardner, 1974). In the eastern part of the basin, the Rogers City Member overlies pyritized hardgrounds and bioeroded *Glossifungites* traces in the underlying Reed City Member that are indicative of a regional, marine flooding event (Curran and Hurley, 1992). Isopach mapping and lithologic interpretation of wire line log data in the Rogers City Member indicate the presence of a shoal or bank in the central basin during deposition of the Reed City Member (Gardner, 1974).

#### *Dolomite in the Dundee Limestone*

Dolomite types, basin-wide spatial distribution, and models for genesis are generally poorly defined for the Dundee Limestone. Cohee and Underwood (1945) mapped decreasing dolomite in the Reed City member towards the east. A regional exploration model, including initial interpretations of depositional and diagenetic facies, reservoir types, and production characteristics was developed by Knapp (1947) and is

still referenced today. Likewise, an oft-cited generalized depositional model for the Dundee Limestone was published by Gardener (1974).

Pervasively dolomitized carbonate strata in the Reed City member of the Dundee is productive in the western basin in fields such as the Reed City field (Upp, 1968; Gardner, 1974). Dolomite is commonly fabric replacive in these reservoirs, but where preserved, primary textures indicate a generally open marine faunal assemblage shoaling upwards to intertidal/supratidal and sabhka facies below the Reed City Anhydrite. The majority of dolomite in the Dundee in the central and western Michigan Basin is widely believed, based on the work of Gardner (1974), to be both early diagenetic in origin and facies dependent. Primary porosity in grainy and biohermal facies of the Reed City member is thought to have influenced the flow of dolomitizing fluids derived from the overlying Reed City Anhydrite.

Both Knapp (1947) and Gardener (1974), however, were less clear concerning the description, distribution, and genesis of dolomite, especially in the Rogers City member in the western and central portions of the basin. Jodry (1955) demonstrated a correlation between dolomite and occurrence of oil, and Tinklepaugh (1957) showed that the presence of dolomite was related to structural positioning. Both the Reed City equivalent and the Rogers City members are oil productive in a small number of clearly fracture-related, hydrothermal “chimneys” in the central and eastern basin (e.g. the Deep River Field in Arenac Co., Lundy, 1968; and the Winterfield Field of Clare Co., Chittick, 1995).

Prouty (1988) described a model for reactivated basement wrench faults and the influence on fracture-related, hydrothermal dolomite occurrences in both the

Trenton/Black River as well as several Dundee fields in Michigan. Later, detailed work by Curran and Hurley (1992) on one of Prouty's "case study" fracture-related dolomite fields in the Dundee showed the field to be mostly limestone, leading to questions about the importance of fracture-related dolomite in the Dundee.

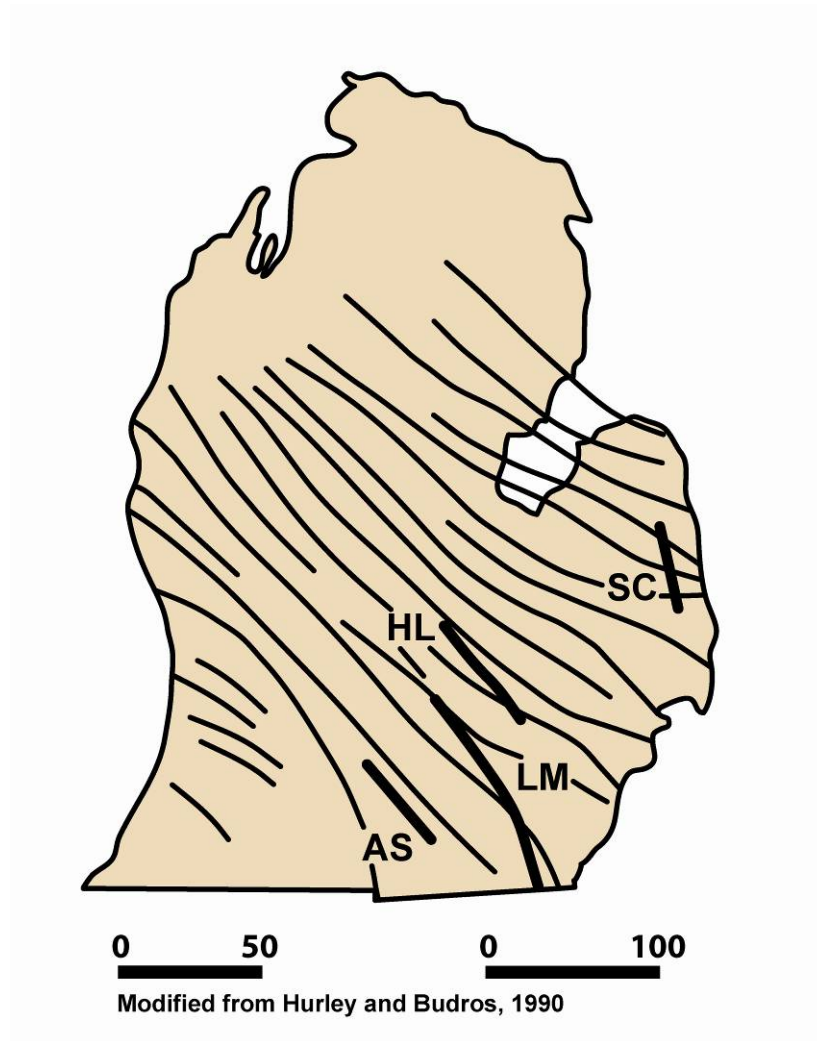
Dolomite occurrences in most Dundee fields were not initially well described, in part because of limited rock material available from the pre-1950's drilling methods used on most wells. Preliminary descriptions of dolomite in core from more recently drilled wells in Crystal Field, in the central portion of the basin, indicate that dolomitization was complex and multi-generational (Montgomery, et al., 1998). These studies indicate that massive, "matrix" dolomite (replacive) is transitional to white sparry saddle dolomite that fills fractures, vugs, and solution-enhanced, primary intraparticle pores.

Preliminary petrologic analysis of dolomite in core and cuttings from nearby wells (unpublished work by Harrison, 2000) indicates "light" oxygen isotopic composition consistent with origin at elevated temperatures for the sparry dolomite. Initial study of primary fluid inclusions in saddle dolomite from two samples in central Michigan by Luczaj (2001), indicate a temperature of formation for the saddle dolomite of approximately 120° to 150° C.

### ***Structural Elements, Thermal Evolution, and Hydrothermal Mineralization in the Michigan Basin***

Decades of study of the structural geology and structural evolution of the Michigan Basin (summarized by Fisher et al., 1988) suggest a predominant, northwest-southeast structural grain defined by faults and folds throughout the basin (Figure I-3). A subordinate, antithetic southwest-northeast component, is thought to have developed

due to periodic reactivation of basement faults and left lateral wrenching (Sanford, et al., 1985; Prouty, 1988). The timing of basement fault reactivation and folding is not clear,



**Figure I-3. Schematic diagram illustrating the general northwest/southeastern trends of structural elements (faults and folds) in the Michigan Basin. AS = Albion-Scipio trend.**

although stratigraphic studies indicate that isolated, positive bathymetric features existed periodically throughout the early Paleozoic in the basin and were probably the result of syndepositional growth faults (Fisher, et al., 1988). Regional stratigraphic studies (Lillianthal, 1978) and structural analysis (Prouty, 1988) suggest that the most widespread and intense period of basement fault reactivation occurred at the end of the Mississippian (~350 mybp) coincident with Alleghenian orogenic activity outboard in the Appalachian orogen. The timing of the fault reactivation coincides closely with an important basin-wide diagenetic event (age dated at about 346 +/- 11 mybp), that includes the formation of “burial” dolomite in the Ordovician St. Peter Sandstone and siliciclastic-dominated Glenwood Formation (Barnes and Girard, 1992; Girard and Barnes, 1995). Models for hydrothermal mineralization associated with basement fault reactivation have long been used to explain linear fault and fracture-related oil fields (e.g. Hurley and Budros, 1990), as well as pervasive epigenetic dolomitization and related Mississippi Valley Type (MVT) mineralization (Budai and Wilson, 1991).

The significant global association of giant oil fields, hydrothermal dolomite, MVT type mineralization, and wrench tectonics related to basement fault reactivation has been recently summarized and documented by Davies (2000). The “hydrothermal dolomite reservoir facies” model and major hydrocarbon accumulations world wide are thought to be, at least in part, controlled by the localization of hydrothermal fluid movement and mineralization, including hydrothermal dolomitization associated with faults (Figure I-4), especially extensional or transtensional faults (Davies, 2000). A number of important examples of giant hydrocarbon reservoirs apparently controlled by reactivated basement faults and formation fluids transported through related fractures in cover rocks exist,

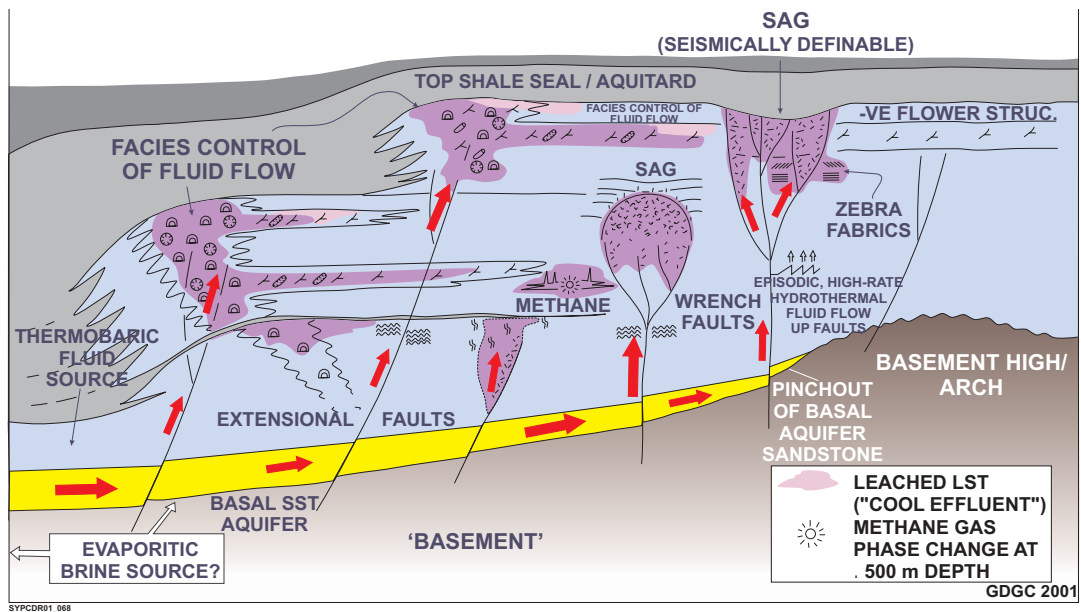
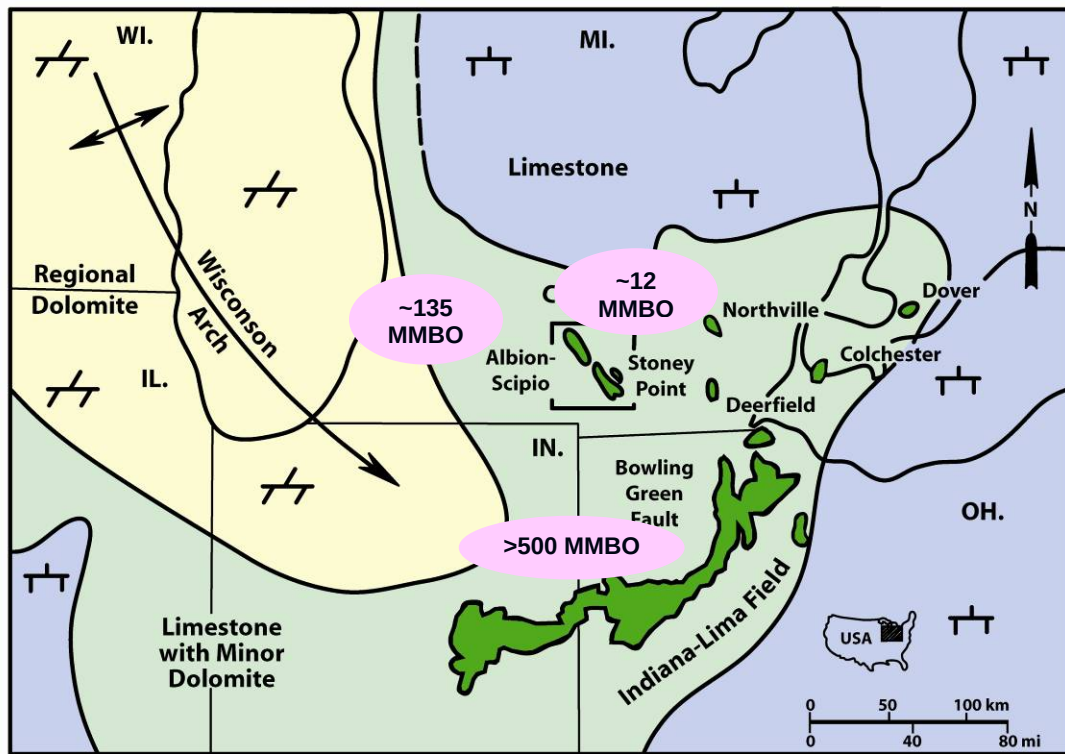


Figure I-4. Diagram showing various associations of hydrothermal dolomite related to extensional tectonics. Modified from Davies (2000).



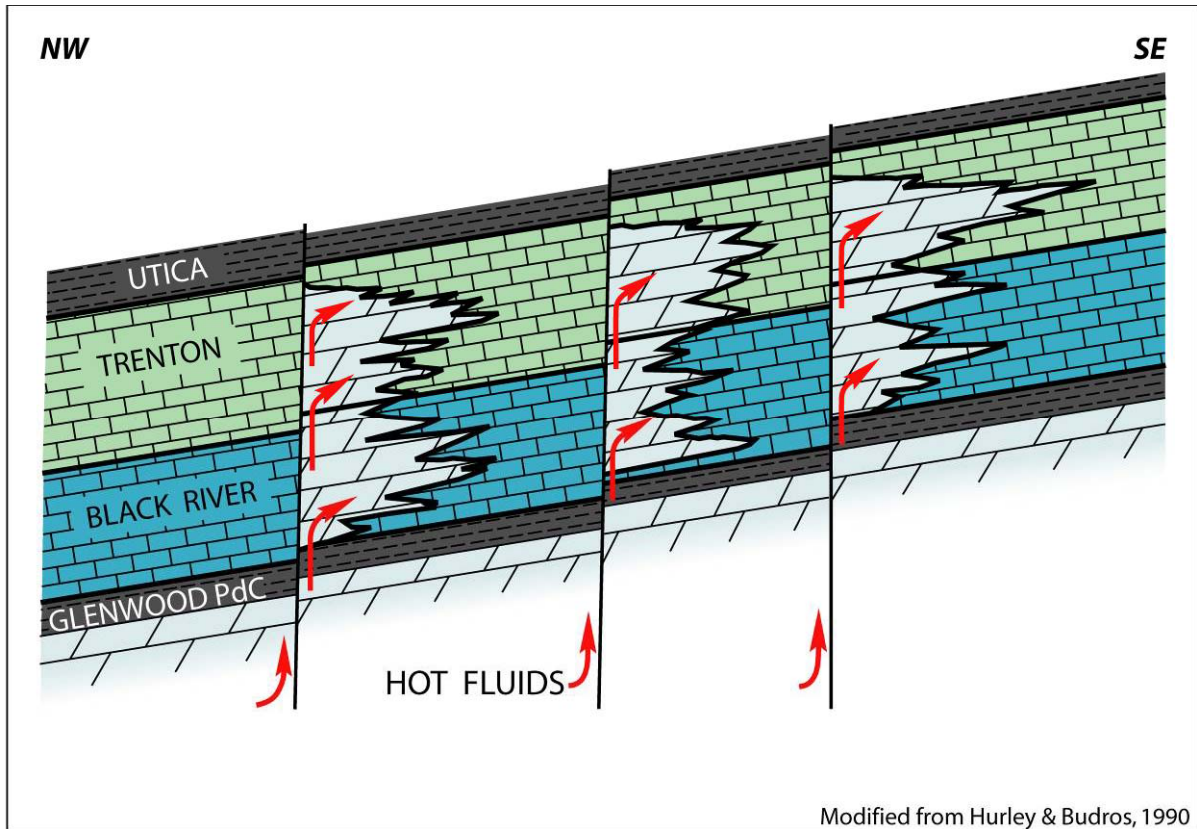
including the Albion-Scipio pool and other Ordovician Trenton/Black River fields (Figure I-5) distributed throughout the Michigan Basin, Ontario, northwest Ohio, northeastern Indiana, and other locations in the eastern U.S. (Tedesco, 1994).



Modified from Hurley and Budros, 1990

Figure I-5. Map showing distribution of major known hydrothermal dolomite trends in and around the Michigan Basin. Total production from the Albion-Scipio trend (approximately 135 MMBO), Stoney Point field (approximately 12 MMBO) and the Indiana-Lima trend (>500 MMBO) are illustrated. Modified from Hurley and Budros (1990).

Numerous studies of the thermal evolution of the Michigan Basin (summary in Catcosinos and Daniels, 1991) suggest at least three different models to explain the anomalous thermal maturity of organic matter, and temperatures and timing of formation of authigenic minerals in the Michigan Basin, relative to current depths of burial (no more than approximately 10,500' at the deepest for the Ordovician Trenton/Black River Formations). Nunn, et al., (1984) suggested that anomalously elevated geothermal gradients existed during the early Paleozoic throughout the Michigan Basin. Cercone (1984) called upon impressive erosional stripping of thousands of feet of late Paleozoic strata in the basin to account for thermal maturities of organic material. Hogarth and Sibley (1985) and Hurley and Budros (1990) emphasize the probable importance of spatially isolated hydrothermal fluid conduits that created areally restricted hydrothermal anomalies to explain the spatial distribution of thermal maturity in organic matter and the temperatures of formation of authigenic minerals, including hydrothermal dolomite (Figure I-6). Girard and Barnes (1995) suggested that a Late Devonian-Mississippian (345 +/- 11mybp) episode of authigenic mineralization in the Ordovician St. Peter Sandstone, including hydrothermal dolomitization, suggested anomalously high thermal regimes related to spatial location in proximity to faulted and fractured Precambrian basement in the vicinity of the Mid-Continent Rift in the central Michigan Basin.



**Figure I-6. Albion-Scipio model for hydrothermal dolomitization. Dolomitizing fluids are concentrated along fault-controlled conduits and typically dolomitize rocks close to the fault plane. Note however, how the lateral extent of reservoir dolomite is illustrated schematically to vary in a vertical sense. One of the main hypotheses of this project was that this lateral variability is likely controlled by primary depositional facies, and thus is predictable within a sequence stratigraphic framework.**

Preliminary investigation of fluid inclusions in calcite cements in the Mississippian Bayport Limestone exposed in surface quarries in Eaton county, Michigan, indicate that a fluid inclusion assemblage is present with mean homogenization temperature of  $146 \pm 12^{\circ}\text{C}$  (Blaske, 2000; Panter, 2001). Calcite cements are found in conjunction with pyrite, fluorite, and other fracture-filling minerals suggestive of hydrothermal mineralization. Other examples of upper Paleozoic, highly fractured bedrock formations in the surface and shallow subsurface are known to contain exotic

suites of authigenic minerals not in chemical equilibrium with modern, fresh ground water (Westjohn and Weaver, 1996).

### ***Variations in Dolomitization and Reservoir Geometries in the Michigan Basin***

Fundamentally different mechanisms of dolomitization will result in distinctly different reservoir geometry and rock properties. Primary depositional facies controls result in regional scale geometric distribution and rock properties in early diagenetic dolomite that are distinctly different from burial, epigenetic dolomite typically related to structural controls and fracturing (Zempolich and Hardie, 1997; Melim and Scholle, 2002). From a reservoir perspective, outcrop studies such as that by Zempolich and Hardie (1997) offer key insight into the preferential control on distribution of dolomite by primary sedimentary facies and resulting variability in the spatial distribution of dolomitized reservoirs. For example, Zempolich and Hardie (1997) showed that the size and distribution of fracture-related dolomite bodies may range from kilometers in areal distribution and hundreds of meters thick when fractures cut across certain primary sedimentary facies/fabrics, to only tens to hundreds of meters in area and only a few meters thick.

All mechanisms for dolomitization require fluid flow and mass transport that is imposed or imprinted on pre-cursor facies patterns and primary facies-controlled fluid flow pathways. A well-documented geological model for the volumetric significance, spatial distribution, and the various mechanisms of dolomitization in a petroleum system is essential to decreasing risk and supporting new exploration, step-out and enhanced recovery activities.

For the Michigan Basin, existing geological models for the origin of dolomite in Paleozoic hydrocarbon reservoirs are diverse. In different regions and stratigraphic intervals of the Michigan Basin (and surrounding areas), the origin of dolomite is interpreted to result from a variety of mechanisms and processes:

1) Non-fabric selective, non-facies controlled, fracture related burial/epigenetic processes in the Trenton/Black River (Ells, 1962; Hurley and Budros, 1990) and the Dundee (Knapp, 1947; Lundy, 1968; Prouty, 1988). The influence of epigenetic, fracture related dolomite in the Niagaran is also reported by Coniglio, et al. (2003) in Ontario.

2) Facies-related, early diagenetic/reflux processes in the Niagaran (Sears and Lucia, 1980; Bay, 1983) and Dundee (Knapp, 1947; Champion, 1968; Gardner, 1974).

3) Complex interrelationship between intense solution/karst related to syndepositional subaerial exposure surfaces, regional “early” dolomitization, and localized stratigraphic trapping in the Trenton/Black River (DeHaas and Jones, 1988) and Dundee zones (Montgomery, et al., 1998);

4) “Regional” dolomite interpreted to have resulted from either early diagenetic process (Taylor and Sibley, 1987) or epigenetic, “heated subsurface brines” (Fara, and Keith, 1988) in the Trenton/Black River. Coniglio et al. (1994) distinguish a pervasive, “cap” dolomite from “fracture related” dolomite in the Trenton/Black River in the subsurface in Ontario and recognize textural relationships indicating recrystallization of “cap” dolomite by later fracture related, epigenetic dolomite resembling the “regional” dolomite of Taylor and Sibley (1987).

As a result of the apparent complexity and diversity of dolomite origins in these units, and a general lack of understanding of the spatial distribution of dolomite facies

basin-wide, the implications of dolomite genesis on hydrocarbon reservoir distribution and quality is poorly, or at least incompletely, understood in the Michigan Basin. In the absence of well-documented geological models for the origins and spatial distribution of disparate dolomite types in these units, predictive models for the spatial distribution, field scale geometry, and properties of hydrocarbon reservoir rocks are not well-established. Although patterns of spatial distribution and types of dolomite have been studied in these reservoir units individually and in selected fields, only Coniglio et al. (1994) have suggested that cross-formational mechanisms common to each of the Trenton/Black River, Niagaran, and Dundee zones are probably important to the creation of many/most dolomite reservoirs in these units.

#### ***Petrographic and Analytical Study of Dolomitized Carbonate Reservoirs***

The spatial distribution of limestone versus dolomite in the subsurface can be mapped using conventional wire-line log data. Cross plot of FDC/CNL log response, in conjunction with gamma-ray logs, can effectively distinguish dolomite from limestone and provide a basis for preliminary geological models relating sedimentary facies and structural deformation to dolomite occurrences and hydrocarbon reservoirs on a regional scale.

Geological models for the spatial distribution of dolomite based on conventional, subsurface, wire-line log mapping and rudimentary well sample analysis, however, typically provide only incomplete and equivocal evidence to distinguish the geological origin of dolomite. Confident prediction of dolomite reservoir geometry and distribution, on all relevant scales in any hydrocarbon system, requires rigorous, scientific testing and

development of geological models for dolomite genesis. Petrographic and analytical methods are required to differentiate dolomite types and infer mechanisms of dolomite formation. Reliable geological models for the spatial distribution of dolomite reservoirs and dolomitized hydrocarbon reservoir rock properties is fundamentally dependent on data relating geological conditions and controls during dolomite genesis to the spatial distribution of dolomitized reservoirs.

Routine petrographic analysis is typically insufficient to discriminate multi-phase dolomite that results from differing mechanisms of formation. Complex, multistage, diagenetic alteration including partial to complete replacement or recrystallization of precursor limestone and dolomite textures, can superimpose petrographic characteristics that are genetically ambiguous. Analytical methods to distinguish the conditions and mechanisms responsible for dolomitization, including the temperature and composition of dolomitizing fluids, are required to relate dolomite occurrences to mechanisms of dolomite formation and hence the prediction of spatial distribution and properties of dolomitized hydrocarbon reservoirs within the framework of primary depositional fabrics.

#### Overview of Analytical Methods to determine Genesis of Dolomite

Allan and Wiggins (1993) provide a comprehensive treatment of analytical approaches to the petrologic study of dolomitized hydrocarbon reservoirs in petroleum systems. These state-of-the-art analytical techniques should be conducted with careful consideration of the spatial occurrence of reservoir quality dolomite relative to primary depositional facies patterns, and to structural features including faulting and folding.

Sample suites should then be tied to variations in dolomite phases observed with cathodoluminescence, and placed within the context of primary depositional facies as well as vertical stacking patterns of facies units. The following analytical techniques are most relevant to the interpretation of genesis and spatial distribution of dolomite in carbonate reservoirs:

1. Trace element, Fe and Mn composition. Dolomite enriched in iron (Fe, ferroan dolomite) relative to iron-poor/free dolomite typically indicates a burial origin because burial fluids are, on average, 1000x enriched in Fe compared to sea water (Allan and Wiggins, 1993). Significant amounts of ferroan dolomite in hydrocarbon reservoirs in basin scale petroleum systems, are therefore, a good indication of burial processes during dolomite genesis.

The trace element composition of petrographically distinct dolomite types can be initially established using microbeam analytical instruments (SEM-EDX). More routine petrographic characterization of Fe composition in dolomite can then be established using stains and cathodoluminescence petrographic techniques since Fe/Mn ratios determine luminescence properties and can be correlated to trace element composition.

2. Oxygen and carbon isotopic composition. The genesis and migration pathways of subsurface fluids can be inferred from the isotopic composition of diagenetic minerals (Allan and Wiggins, 1993). The oxygen isotopic composition of dolomite is a function of formation fluid isotopic composition as well as isotopic fractionation related to the temperature of formation. Micro-sampling of petrographically distinct dolomite can yield important constraints on dolomite



genesis. Decreased  $^{18}\text{O}/^{16}\text{O}$  relative to normal marine carbonate is indicative of elevated temperatures and/or influence of meteoric waters during formation. Increased  $^{18}\text{O}/^{16}\text{O}$  in dolomite indicates lower temperatures during formation and/or derivation from evaporative (hypersaline) fluids.

3. Primary fluid inclusion homogenization and freezing temperatures. Almost all minerals that grow in the presence of a fluid contain microscopic (1-10 microns or greater) inclusions of that fluid (Bodnar, 2003). Primary, two phase (liquid and vapor) fluid inclusions are common along crystal growth faces in much epigenetic (formed at temperature in excess of  $\sim 50^{\circ}\text{-}70^{\circ}\text{ C}$ ) dolomite and can contain unaltered fluids trapped during the initial growth of the mineral crystal (Figure I-7). Single phase fluid inclusions typically form at lower temperatures (due to the pressure/temperature phase relationships of water).

Analysis of homogenization and freezing temperatures of primary fluid inclusions using petrographic, gas flow heating/cooling stage techniques may be used to estimate temperature and salinity (respectively) of the fluid present during formation of diagenetic dolomite crystals. Careful petrographic analysis of inclusions is necessary to establish the timing and history of formation of fluid inclusion assemblages (FIA) to produce meaningful data. The ideal situation for analysis of primary fluid inclusions in dolomite, to determine reliable temperatures of formation, is initial formation of the fluid inclusion at elevated temperature with subsequent thermal/burial history of lower temperature and pressure (Goldstein, 2003). Thermal/burial history analysis in the Michigan Basin (see discussion below), suggests that current burial temperatures and pressures are

probably less to substantially less than what existed early in the burial history of most subsurface formations at least locally in the Michigan Basin. Relatively

## Two-phase Fluid Inclusions

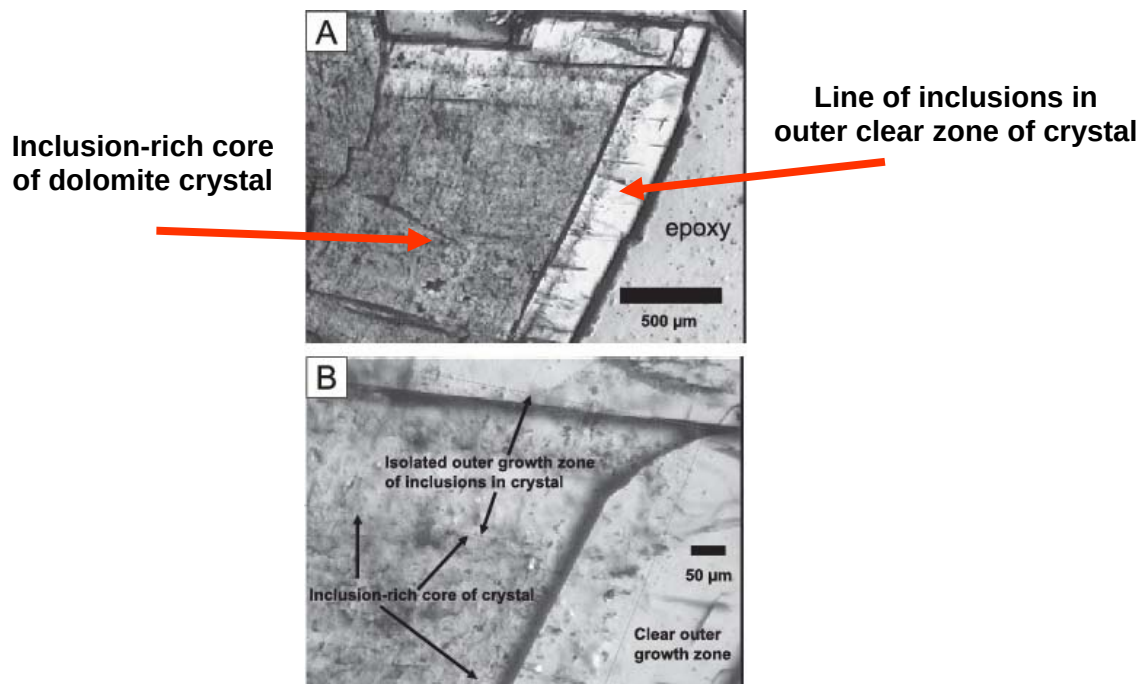


Figure I-7. Photomicrograph of two-phase fluid inclusions in HTD crystals. From Luczaj and Harrison, 2006.

shallow burial (<5000' to 10,000' maximum) for all formations of interest in this study and burial/thermal history relationships suggest that stretching of fluid inclusions and modification of original inclusion volume, resulting in re-equilibration of primary fluid inclusions, is not likely to be the case. Therefore, fluid inclusion data should provide reliable indications of dolomite temperatures of formation.

4. Strontium isotopic analysis. Strontium isotope composition ( $^{87}\text{Sr}/^{86}\text{Sr}$ ) in dolomite can be used as a tracer of formation fluid movement in the subsurface. Formation fluids that have interacted with silicate minerals in clastic or crystalline basement rocks typically have elevated  $^{87}\text{Sr}/^{86}\text{Sr}$  relative to normal marine water (see normal marine  $^{87}\text{Sr}/^{86}\text{Sr}$  secular variation curve, Elderfield, 1986). Burial fluids that have interacted with these rock types, therefore, typically form dolomite with elevated  $^{87}\text{Sr}/^{86}\text{Sr}$ . Dolomite formed from normal or evaporatively concentrated marine waters can often be discriminated from formation fluids of burial origin on the basis of lower  $^{87}\text{Sr}/^{86}\text{Sr}$ .

#### ***Reservoir Characterization - Petrophysical Properties of Carbonate Sediments and Rocks***

A major task in reservoir characterization and modeling is to translate geological information into petrophysical properties that can be extracted from geophysical data sets and/or used to populate sedimentary bodies in reservoir modeling. This task is particularly challenging in carbonates, where cementation and dissolution processes continuously modify the mineralogy and pore structure. In extreme cases, this

modification can completely reverse the original pore distribution so that grains are dissolved to produce pores, while the original pore space is filled with cement to form the rock. All these modifications alter the physical properties of the rock, thereby resulting in a dynamic relationship between depositional facies and diagenesis which is recorded by physical parameters such as porosity, permeability and sonic velocity (Grammer et al. 2004).

#### Sonic velocity tied to pore architecture

Establishing a predictable connection between pore type and pore architecture to measured sonic velocity values will help operators more fully recognize, and ultimately predict reservoir type and quality in the subsurface with increased confidence. Because pore geometry is a crucial factor in controlling acoustic properties in carbonates, detailed characterization of pore types and pore architecture through petrographic and SEM analysis should provide the operator a tool to predict pore architecture, and therefore permeability of reservoir rocks, through refined analysis and interpretation of sonic log borehole and seismic data.

Seismic data has proven to be increasingly important in reservoir characterization. High-resolution 3-D seismic surveys produce data sets from which amplitude variations can be used to interpolate between wells. Reservoir saturation is evaluated with AVO (amplitude variation with offset), and time lapse surveys delineate production histories and assist in secondary recovery. Inversions of seismic volumes into a porosity volume can be used to predict high porosity intervals. Because of the degree of uncertainty in these geophysical data, accurate interpretation is dependent upon the understanding of the rock physics in the imaged sediments (Mavko et al., 1998). Although sonic velocity is

largely controlled by porosity, many factors such as clay content and mineralogy, may complicate the relationship. This is especially true in carbonates where, as discussed above, velocity is controlled by the combined effect of depositional lithology and several post-depositional processes that cause a unique velocity distribution (Wang, 1997, Rafavich et al. 1984; Anselmetti and Eberli, 1993).

Laboratory measurements from cores in Neogene strata from the Bahamas display the porosity-velocity relationship in carbonates and, together with diagenetic studies, help explain the wide scattering of velocity data (Anselmetti and Eberli, 1993, 1997, 2001). Velocity is strongly dependent on the rock-porosity (Wang, 1997, Rafavich et al. 1984). A plot of porosity versus velocity displays a clear inverse trend; an increase in porosity produces a decrease in velocity (Figure I-8). The measured values, however, display a large scatter around this inverse correlation in the velocity-porosity diagram. Velocity differences at equal porosities can be over 2500 m/s, particularly at higher porosities. For example, rocks with porosities of 39% can have velocities between 2400 m/s and 5000 m/s. Even at porosities of less than 10% the velocity can still vary about 2000 m/s, which is an extraordinary range for rocks with the same chemical composition and the same amount of porosity. Likewise, porosity can vary widely at any given velocity. For example, rocks with a  $V_p$  of 4100 m/s can have porosities anywhere between 12% and 43% (Figure I-8).

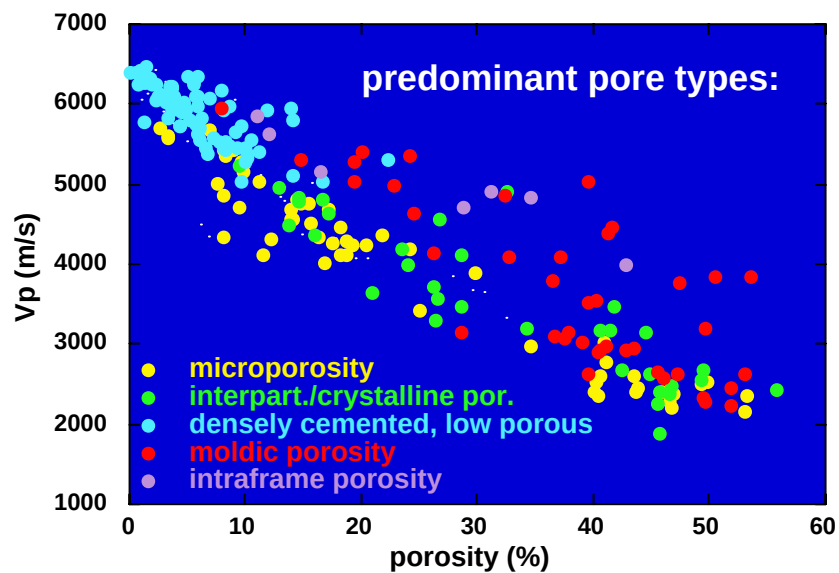


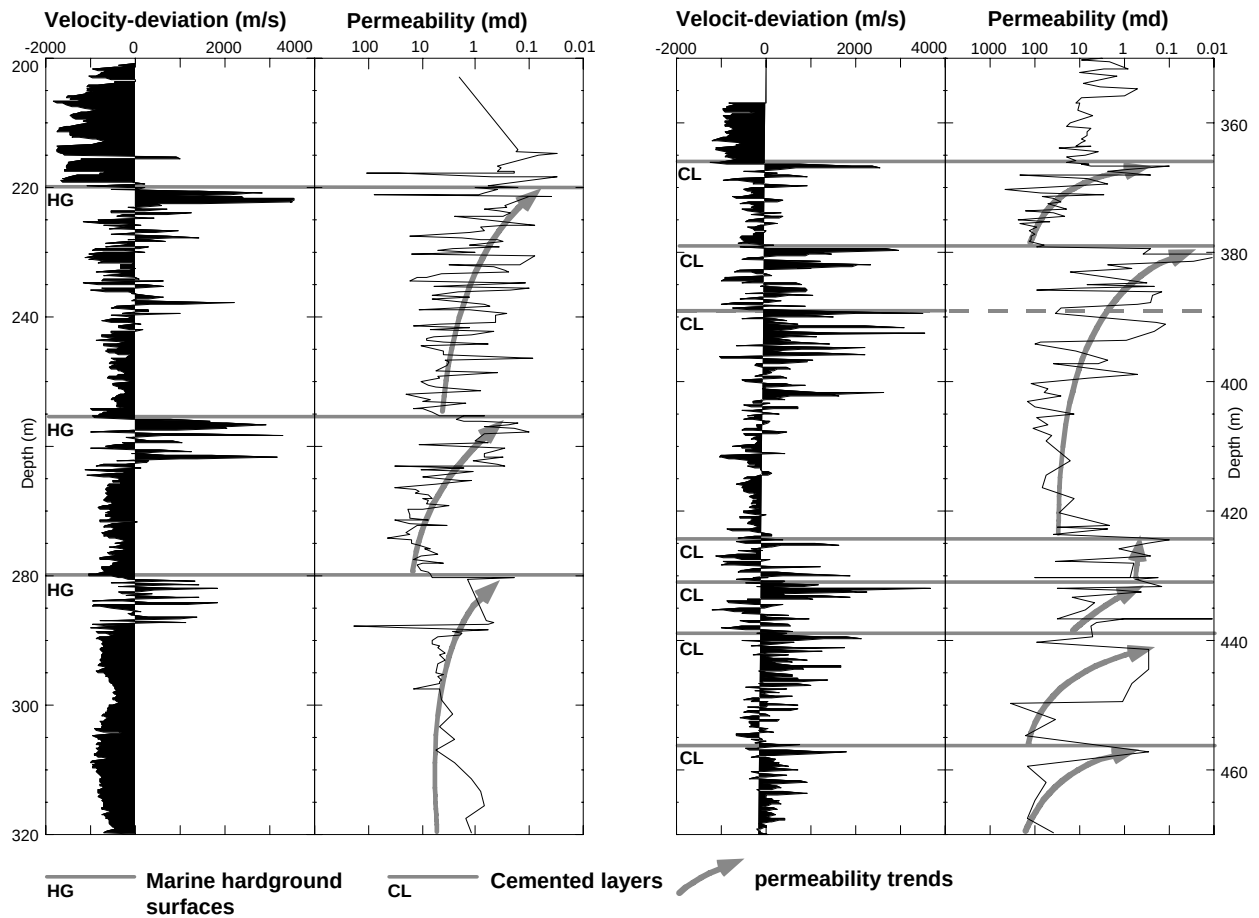
Figure I-8. Graph of velocity vs. porosity of various pore types of carbonates with an exponential best fit curve through the data for reference. Different pore types cluster in the porosity-velocity field, indicating that scattering at equal porosity is caused by the specific pore type and its resulting elastic property. From Grammer et al., 2004.

The poor relationship between porosity and velocity in carbonates results from the ability of carbonates to form cements and special fabrics with pore types that can enhance the elastic properties of the rock without filling all the pore space. The importance of the pore type on the elastic property, and thus the velocity, is illustrated in Figure I-8, which shows that different pore types form clusters in the velocity-porosity diagram. The resulting characteristic pattern observed for every group with the same dominant pore type can explain why rocks with equal porosity can have very different velocities. The most prominent velocity contrasts at equal porosities are measured between coarse moldic rocks and rocks with interparticle porosity. Moldic rocks at 40-50% porosity can have  $V_p$  up to 5000 m/s, whereas rocks with similar amounts of interparticle porosity or microporosity have velocities that can be lower by over 2500 m/s.

The complicated relationship between porosity and velocity that is observed, which would also result in a similar porosity-impedance pattern, implies that impedance contrasts between two layers can occur even without a porosity change, i.e. solely as a result of different pore types and pore system architecture. To further complicate interpretation, two layers with different porosity values can have very similar velocities and may have, therefore, no impedance contrast between them (Grammer et al. 2004). As a result, the scattering in a porosity-velocity diagram has negative implications for seismic inversion and AVO analyses in carbonates. The scattering produces an uncertainty in seismic inversion that most current inversion techniques are not able to reduce. For example, if a single line from a theoretical equation or a best-fit line through the data set is used for inversion, all the velocity values above the line will underestimate porosity and reserves while all the data points below will overestimate porosity and reserves. Similarly, variations in pore type can cause variations in the amplitude with offset that might be more pronounced than variations in saturation or bed thickness. To reduce the uncertainties in seismic inversion and AVO analysis, additional study and development of new theoretical approaches are needed that show the physical relationship between pore types, the rock-frame flexibility, and the elastic behavior in carbonates.

The application of this approach in the identified intervals in the Michigan Basin should provide much needed data to help operators more fully recognize, and ultimately predict reservoir type and quality. Because pore geometry is a crucial factor in controlling acoustic properties in carbonates, detailed characterization of pore types and pore architecture through petrographic and SEM analysis should provide the operator a

means to predict the pore architecture, and therefore the permeability of reservoir rocks through refined analysis and interpretation of sonic log borehole data. Recent study has shown that there is a predictable pattern between pore type/architecture/permeability and sonic velocity through calculation of a “velocity deviation log” as illustrated in Figure I-9 (Anselmetti and Eberli, 1997). As indicated above, these data may also help to further refine targets on seismic data.



**Figure I-9. Correlation of velocity deviation log and permeability data in a borehole from Great Bahama Bank. This Neogene interval consists of fine-grained slope sediments that are intercalated by three marine hardgrounds (HG). Overall velocity increases upsection and decreases abruptly across the hardground surfaces. Permeability shows an inverse trend with decreasing values upsection and abrupt increases across the hardground surfaces indicating possible vertical flow barriers at the hardgrounds. The good inverse correlation between velocity deviation and permeability indicates a significant link between velocity deviation and trends in permeability. Figure and caption modified from Anselmetti and Eberli (1997).**



## PROJECT APPROACH AND DISCUSSION OF RESULTS BY TASK (PHASE I AND II)

### *Task 2.0 – Development of a Reservoir Catalog for selected dolomite reservoirs in the Michigan Basin*

(data bases available to on line at WMU/MGRRE at:  
[http://wst023.west.wmich.edu/ind/Data\\_on-line.htm](http://wst023.west.wmich.edu/ind/Data_on-line.htm))

Wireline Log Scanning – during Phases I and II we scanned over 14,000 wireline logs and were well underway digitizing selected logs for further data manipulation. The scans are digital raster images captured by using a Neuralog Scanner. Each image is a TIFF type image, scanned at 200 dpi resolution. These images can be used directly in Petra software for creating cross-sections and for stratigraphic correlation. They can also be pasted into text files as illustrations or used in PowerPoint presentations or on posters. These images can also be digitized into LAS files using the Neuralog software. Numerous logs for the Devonian section, the Ray Reef Field (Silurian) and the Albion-Scipio fields were digitized and used for analysis within the Petra software.

Digital Conventional Porosity and Permeability Core Analyses –core analysis data from paper copies was keypunched into Excel spreadsheets to supplement our current digital data bases. This data includes the depth of the analyzed core sample, conventional air permeability and helium porisimetry, oil and water saturations, descriptive lithology and (when available) gas chromatographic analyses of C-1 through C-5 on selected footages.

Brine Chemistry Data – Students key punched a paper data set from Dow Chemical containing brine analyses from the Michigan Basin. This data contains 218 analyses from numerous formations throughout the state and supplements our current digital data base. These were entered into an Excel spreadsheet and added to a previous data set of 165 wells. To give a reasonably comprehensive data set of 383 wells. Data includes well location information, depth of sample, total dissolved solids (salinity), major elements, some trace elements and some temperature data.

Dolomitized intervals in wells of Albion/Scipio Field – An Excel spreadsheet was created for all wells in the Albion/Scipio and Stoney Point fields, and wells were ranked based on available data for further study. Albion/Scipio is the largest field in Michigan and the largest Trenton-Black River Field in our study. The field contains 746 wells. The data set includes well location information and footage intervals in the Trenton and Black River formations that are dolomitized. This data was used in concert with other databases to define the distribution of the Albion Scipio reservoir and during Phase III our plans were to construct a three-dimensional model of the reservoir. The dolomitized intervals were identified from drilling records for each well.

Organizing and compiling other large digital datasets – Numerous digital datasets for Michigan oil and gas wells were combined into a single complete dataset (>25 million cells of data) for use in this project. An example of the parameters included are as follows:

- o Cored wells – this is a listing of all known cored wells from Michigan. This list is compiled from private and public sources. It includes well location information, cored interval, cored formations, storage location of the core (if known), any analyses performed on the core (e.g. P&P).
- o Thin sections – well name, footage interval, formation and repository location of thin sections.
- o Core Analyses – conventional or special core analyses with footage analyzed and core properties (usually P&P) as reported in item #2 above.
- o Drill cutting samples – well name and location along with depths and sample increment. There is also a database with numerous

chromatographic analyses of bulk cuttings. Data includes abundance of C-5 through C-26 derived from solvent extraction on cuttings samples.

- o Engineering parameters – lists of selected parameters and data including: bottomhole pressure, gas chemistry, and oil/gas ratio.
- o Mudlogs – contains lithologic descriptions, gas log and drilling comments.
- o Wireline logs – catalog of all logs run in Michigan wells, list of those in WMU collection, list of scanned images, and list of LAS digital logs.

Compiling bibliography and reference reprint collection – Using Endnotes software and extensive database of geologic and engineering references was compiled and entered into the Endnotes software system.

- Subtask 2.1 More than 1200 references were compiled and entered into an Endnote data base on reservoirs aspects of dolomite. Of these, some 400 are specifically on the Michigan Basin reservoirs in the zones of interest, with the remaining references covering various aspects of dolomitization and dolomite reservoirs that were thought to have application to our project goals. In Phase III, the references were to be added to a digital collection for distribution through WMU to Michigan Basin operators and others with interest.
- Subtask 2.2 Individual producing unit data bases were constructed in Microsoft Access and Excel that include fields, numbers of wells, oil and gas production, brine production, active and abandoned wells. Over 25 million data points were input in Phases I and II in various categories including well location coordinates and ID, TD, IP, Salinity and Water Chemistry, Production History, Core and Perforation locations, Formation tops, and results of various core analyses.

Production summaries and curves were created for 44 fields in the Trenton/Black River, 1151 fields in the Niagaran, and 141 fields in the Devonian. These data were

partially analyzed in Phase II in relationship to the distribution of mapped fracture areas in the basin, with our initial focus on the Devonian as mentioned previously. These results were correlated to fields with core data and petrophysical analyses to facilitate selection of samples for further petrographic and geochemical analysis for dolomite genesis and reservoir quality.

- Subtask 2.3

1. Devonian Dundee well penetration Petra projects (i.e. data bases) for 39 central Michigan Basin counties were created with detailed structure contour maps for a 24 county region (using error checked tops data). Data base includes digital logs for ~450 wells with numerous cross sections showing log-based (litho-density) variations in lithofacies. Dundee Formation, member scale mapping and member tops/log character analysis was continuing into Phase III, with the intention to test the feasibility of identifying primary facies (and therefore porosity/permeability distribution) from combined gamma ray and litho-density log analysis.
2. Silurian Niagaran well penetration Petra projects (data bases) for Macomb County (northern trend) and Ray Reef Field (southern trend) were developed along with preliminary structure maps. Included in Phase I and II are spatial data for ~700 wells and digitized logs for ~30 wells from Ray Reef.
3. Ordovician Trenton/Black River Group well penetration Petra project (data base) currently includes spatial data for 2080 wells and digital logs for 169 wells. An extensive library of maps and cross sections have been made from the Albion-Scipio and Stoney Point fields with an emphasis on lithofacies identification based upon litho-density log signatures.

### Task 3.0 – Characterization of Dolomite Reservoirs in Representative Fields

The characterization of select dolomite reservoirs (Task 3) was the major focus of our efforts in Phase II/Year 2. Fields were prioritized (after being identified in Task 2, Phase I) based upon the availability of rock data for interpretation of depositional environments, fracture density and distribution as well as thin section, geochemical, and petrophysical analyses. The majority of our Task 3 efforts through Phase I and II were in the Devonian and Silurian sections, and were presented at regional and national AAPG meetings (see Appendix 3). Our major push on the Ordovician part of the section ramped up in Quarter 3 of Phase II/Year 2 and significant progress was made prior to the end of Phase II. As an example, at the ES AAPG in October 2006, we presented one oral paper as well as a poster with core workshop on the Ordovician Trenton/Black River.

### Approach and Methodology

In order to investigate the geological origins and controls on the occurrence of dolostone reservoirs in the three formations of interest we compiled available digital subsurface geological data (mostly from the Michigan Department of Environmental Quality, Geological Survey Division {MDEQ-GSD}) including formation tops, wire-line logs, and driller's reports. Where appropriate we compiled these data into tabular spatial databases as discussed above. These spatial databases were used to construct Geographic Information Systems files (utilizing both ArcGIS and Petra software), maps and cross sections of important geological properties including the spatial distribution of dolomite versus limestone relative to structural features and oil field occurrences in the Michigan Basin. For the Devonian, quality controlled Dundee Formation tops from a well database with more than 25,000 wells (originating from J. R. Wood, MTU Subsurface Visualization Lab) were used in the structural mapping.

***Summary of Phase I and II – Devonian and Ordovician (Figures 1-6, and 26-28 respectively)***

Structural mapping and log analysis in the Dundee (Devonian) and Trenton/Black River (Ordovician) suggest a close spatial relationship among gross dolomite distribution and regional-scale, wrench fault-related NW-SE and NE-SW structural trends. A high temperature origin for much of the dolomite in the 3 studied intervals (based upon initial fluid inclusion homogenization temperatures and stable isotopic analyses, see Table 1) coupled with persistent association of this dolomite in reservoirs coincident with wrench fault-related features, is strong evidence for these reservoirs being influenced by hydrothermal dolomitization. Ongoing efforts in Phase III were to be focused on determining whether the hydrothermal dolomite represents the only phase of dolomite in these fault-related fields, or whether there is evidence of low temperature dolomitization as well. In either case, our main concentration was whether the reservoir quality of the dolomite can be tied to primary facies type and/or an established sequence stratigraphic framework, either of which will enhance the predictability of such reservoirs beyond that of just regional structural control.

**Devonian Dundee Formation**

The Middle Devonian Dundee Formation consists of two subsurface units, the Reed City and the Rogers City (Gardner, 1974). The Reed City Member initially transgressed the Michigan basin following restricted marine conditions that existed throughout lower Middle Devonian Detroit River Group time. The Reed City member is interpreted as a generally shoal water assemblage including grainy carbonates, stromatoporoid reefs, and supratidal/evaporitic facies in an overall regressive pattern stratigraphically. More open marine facies (Reed City “equivalent”) predominate in the eastern basin, while more restricted evaporite-bearing facies (Reed City Member) occur to the west (Gardner, 1974). The Reed City comprises a complex primary facies package in the basin that is not well known. The Rogers City Member overlies various facies of the Reed City at a generally sharp, probable marine flooding surface marking rapid marine transgression. Primary depositional facies in the Rogers City

are incompletely known but, in general, were apparently lithologically homogeneous basin wide and consisted mostly of open marine lime wackestone to mudstone.

Our analyses through Phase II have important implications for both new exploration plays and improved enhanced recovery methods, especially in the Dundee Formation "play" in Michigan – i.e. on the basis of interpreted (first order) fracture-related dolomitization control on the distribution of hydrocarbon reservoirs. In an exploration context high-resolution structure mapping using quality controlled well data should provide leads to convergence zones of fault/fracture trends not necessarily related to structural elevation. Acquisition of high-resolution seismic data in areas with prospective structural grain may provide decreased risk for fractured Dundee exploration drilling.

Field scale structural mapping of top Dundee with high quality well data indicates a spatial correlation between subtle structure and reservoir facies variations in the Rogers City Member. In fields with suitable well log control, mapped structure suggests faults with limited throw (generally less than tens of feet). These faults and related fractures may have provided geometrically-complex fracture conduits for dolomitizing fluids permeating through otherwise tight lime wackestone of the Rogers City.

Preliminary fluid inclusion homogenization temperatures and stable isotopic (C/O) analyses from Devonian Dundee/Rogers City dolostone samples suggest pervasive hydrothermal dolomitization in core samples from 2 wells studied through Phase II. Both the saddle dolomite which occurs as vein and vug fill, as well as much of the matrix dolomite is apparently of hydrothermal origin in these samples.

Application of fracture models to reservoir characterization in secondary and tertiary recovery projects in existing fractured Dundee fields, especially when tied to detailed facies mapping, may result in substantial additional recovery from fields that typically had low (<30%) primary recovery factors. Careful consideration of fracture orientations and water coning problems should decrease risk in enhanced recovery activities.

Undoubtedly more complex, hybrid reservoir types exist in dolomitized lower Dundee/Reed City Member lithofacies in the central basin as a result of complex, early fluid flow through primary limestone porosity conduits in a reflux system(?) in addition to fracture generated pathways in fault/fracture convergence zones. Continuing work in Phase 3/Year 3 was planned to understand Reed City Member dolomitization processes in Michigan with respect to the relationship between primary facies and/or sequence stratigraphic framework.

#### Trenton/Black River Formations

Fields in the Ordovician Trenton/Black River Formations in Michigan, most notably the Albion-Scipio Field, are classic examples of geometrically complex dolomite reservoirs modeled by the hydrothermal dolomite reservoir facies (HTDRF) concept. Application of models for reservoirs of this generic type are controversial but of great current interest for both exploration and enhanced recovery in the petroleum industry. Structural analysis of Michigan Trenton/Black River (e.g. Hurley and Budros, 1990) suggests a relationship between probable reactivated basement wrench faults, anticlines with steep margins, and fractured, hydrothermal dolomite reservoirs. Riedel shear deformation mechanisms, including complex flower structure fracture patterns, are suggested as important components in the development of these dolomitized fields. The transport of dolomitizing hydrothermal fluids delivered to various reservoir units is thought to result from flow through fractures, associated with periodically reactivated wrench faults, as well as primary permeability conduits. The presence of a regional hydrothermal fluid “aquifer” unit may be a critical component of these complex hydrothermal fluid flow systems.

Trenton-Black River Pools are characterized by stratigraphic traps in dolomitized limestone within the Upper and Middle Ordovician Trenton and Black River groups. The Albion-Pulaski-Scipio-Stoney Point trend, which was discovered in 1957 (Figure 5), makes up the largest field in the Michigan Basin (~120 MMBO). The Trenton/Black River rocks are present in the subsurface throughout the Lower Peninsula and in parts of the Upper Peninsula and Wisconsin, but, to date, almost all



discoveries have been from the southern part of the Lower Peninsula of Michigan and the adjoining parts of Indiana and Ohio. Oil and gas pools occur mainly as stratigraphic traps resulting from porosity and permeability variations between porous dolostone and tight regional limestone. In a definitive study by Hurley and Budros (1990) Trenton/Black River production in the Albion-Scipio field was shown to be from classic fracture-controlled dolostone reservoirs related to northwest-southeast fault and fold trends related to a regional structural grain. In the Albion-Pulaski-Scipio-Stoney Point trend, generally low porosity limestone is altered to a relatively “narrow fairway of vuggy, fractured, and cavernous dolomite” (Hurley and Budros, 1990).

An increased percentage of activity in Quarters 3 and 4 of Phase II was focused upon the Trenton/Black River formations. Based upon production data analysis completed during quarters 1 & 2, and a review of available core materials, it was decided to concentrate upon developing a new, updated analysis and interpretation of the Trenton – Black River cores from the Albion Scipio Field. This field is the only giant field (>120 MMBO) found to-date in Michigan. Discovered in 1957, this field has never been subjected to more recently developed geological analytical techniques and interpretation. In particular, there has never been a sequence stratigraphic framework developed for the producing Ordovician Trenton – Black River reservoirs in the field area. Work during Phase II has shown that it is possible to develop just such a stratigraphic framework, and that this framework will in turn allow for the development of new exploration models and concepts (originally planned for Phase III). Specific accomplishments include:

- (1.) The exploration, discovery and early drilling history of the Albion-Pulaski-Scipio Trend were compiled and analyzed for field-wide similarities and differences. These data were assembled into poster format and presented along with portions of three Trenton – Black River, Albion-Scipio Field cores at the “Core Blast” presentation at the “American Association of Petroleum Geologist

(AAPG) Eastern Section Meeting” in Buffalo, New York during October 10-16, 2006.

- (2.) The Hergert #2, Skinner #1 and Mann #6 cores from the Albion-Scipio field were examined in detail, fully described, and calibrated to other available data types such as electric logs, driller reports, porosity and permeability analyses, etc. These data were all assembled into poster format and presented at the “Core Blast” for the “American Association of Petroleum Geologist (AAPG) Eastern Section Meeting” in Buffalo, New York during October 10-16, 2006.
- (3.) Preliminary results from the examination of the Hergert, Skinner and Mann wells were compiled and organized into a presentation entitled “Albion-Scipio Field - What Does a Detailed Look at Cores Tells Us about the Reservoir?” (Gillespie, Robb; Barnes, David; Grammer, G. Michael; and Harrison, William, III). This was presented at the “American Association of Petroleum Geologist (AAPG) Eastern Section Meeting” in Buffalo, New York during October 10-16, 2006.
- (4.) Samples were selectively collected from the Hergert, Skinner and Mann cores for isotopic (C/O) analysis. Preliminary examination of the data indicates no difference between fracture fill dolomites and dolomite recrystallized within the host rock (matrix). It appears that: (1) all the dolomites resulted from the same emplacement episode, or (2) the matrix dolomites have been “reset” by high hydrothermal temperatures of subsequent episodes.

***Summary of Phase I and II – Silurian (Niagaran)*** (Figures 7-25)

For the Niagaran (Silurian), a first order, comprehensive high resolution sequence stratigraphic framework was developed for a pinnacle reef in the northern reef trend (Fig. 7) where we had 100% core coverage throughout the reef section. Our next step in Phase III was to test this sequence framework within a larger reef complex in the

southern reef trend (Ray Reef and Belle River Mills Fields) and to develop a detailed geological characterization and 3-D rock-based model of the field utilizing the 40+ cores available from the two fields.

Major findings through Phase II are that facies types, when analyzed at a detailed level, have direct links to reservoir porosity and permeability in these dolomites (Figures 8-25). This pattern is consistent with our original hypothesis of primary facies control on dolomitization and resulting reservoir quality at some level. The identification of distinct and predictable vertical stacking patterns within a hierarchical sequence and cycle framework provides a high degree of confidence at this point that results will be exportable throughout the basin.

Petrophysically significant facies (see below) were described in the northern and southern reef trends, providing significantly more resolution than the standard 4-6 that are used most often in the basin (e.g. Gill, 1977). Figures 24 & 25 illustrate how the higher resolution facies analysis can be crucial for establishing porosity and permeability relationships in these reservoirs. Porosity and permeability values tend to increase towards the top in both the large and smaller (higher frequency) cycles (see Figure 15).

### Facies

From basic core analysis, six facies were chosen based on rock fabric, composition and interpreted depositional environment. These six facies are: muddy bioherm, reef core, detrital wackestones to packstones, detrital packstones to grainstones, mudstones, and cyanobacterial mats. A seventh facies could be included for anhydrite, but the anhydrite is often associated within the other facies and can often be of diagenetic origin.

#### *Muddy Bioherm*

This is a mud dominated facies often associated at the initiation of reef growth in the “mud-mound” stage. This facies can be further divided into two lithofacies; a stylonitic mudstone with lithoclasts and <10% grains and another that is a mudstone to

wackestone containing stromatactis. Porosity and permeability within the muddy bioherm is relatively low compared to the other facies. The little porosity that exists may be due to molds and intercrystalline pore types. Occasionally some solution enhancement along stylolites and microfractures produce slightly higher porosity values.

The stylolitic mudstone with lithoclasts and a few grains is thought to actually be part of the Lockport formation, below the actual Pinnacle reef. The stylolites are wispy, indicating a primarily carbonate mudstone matrix. The lithoclasts give this facies a nodular look. Gill (1977) suggests that the elliptical shape of nodules and the presence of dark argillaceous material around the nodules are a result of compactional forces on heterogeneous sediment. He recognizes this fabric in the Belle River Mills field in St. Clair County. Most Niagaran reef cores do not reach down to the Lockport Formation and thus is only observable in a few wells.

The mudstone to wackestone lithofacies containing stromatactis marks the gradual transition from off reef to the biohermal rock. This facies contains more grains than the aforementioned mudstone. The stromatactis are characterized by classic features such as a flat bottom with an irregular upper surface, often filled with sediment and/or cement. The origin of stromatactis is a puzzle. Bathurst (1980) suggested that these features in carbonate mud mounds are a result of cement and sediment fill of cavities which have developed between submarine-cemented crusts. Recently, it has been suggested that it is a type of fenestral porosity caused by rapid, uninterrupted sedimentation (Hladil, 2005) and later filled with cements. Nonetheless, several studies have indicated stromatactis is a well known feature of carbonate mud mounds from around the world (Krause et. al, 2004).

### *Reef Core*

This facies is characterized by large framework organisms, little mud, and cavities filled with skeletal debris. This facies is quite often interbedded with skeletal wackestones, packstones, and grainstones. These facies within the reef must be differentiated from the wackestone to packstones and packstones to grainstones that

are not within the reef in order to interpret the depositional history. The pore architecture types that dominate the reef core facies are vugs, molds, and intraparticle porosity. Anhydrite and salt can also be seen occluding some of the pore space.

A lithofacies of reef framework is used when the rock is primarily composed of reef building organisms, such as stromatoporoids, tabulate corals, and algae (Gill, 1975 and 1977) or microbialites. Framebuilders in growth position are said to only make up about 30% of the reef of the actual reef core, the rest of the reef is composed of detritus (Gill, 1975; Wood, 1999). These organisms produced the wave-resistant framework of the reefs. The characteristics of this facies are vugular porosity, reef cavities, cavity fills of cement and/or sediment, and intraparticle porosity if corals are present. In addition, there should be little to no mud in this facies except inside cavities.

The reef framework with detritus facies consists of reef framework with abundant detritus. Between 40 and 90% of the rock volume of a reef typically consists of rubble, sediment, and voids (Wood, 1999) so it is petrophysically important to include a facies which includes a mix of reef frame builders with detritus. If there is more than 25% detritus intermixed with reef framework organisms, then this facies is used to describe the rock. Usually the detritus is skeletal debris from the reef or reef dwelling organisms and in millimeter or smaller length fragments. Porosity types associated with this facies are moldic, interparticle, vuggy, and intraparticle.

Mud-dominated wackestone to packstones within the reef contain 10-30% detrital skeletal fragments. These grains range from mm to cm scale in long dimension. The common pore type in this facies is moldic. The molds can often be solution-enhanced and might be classified as a vug if no origin is known for the void space. The wackestones to packstones can occur anywhere within the reef, but are commonly found near the base interbedded with the reef framework, following the muddy bioherm facies.

The packstone to grainstone detrital facies within the reef is a grain supported facies. Grains in this facies can be either skeletal, grapestone, or of peloidal origin. This fabric has grains that are a millimeter or less in length, but can be as large as one

to two centimeters. These larger grains in the packstone to grainstone facies tend to occur near the base of the reef in the mud mound-reef transition zone. Moldic and interparticle porosity dominate this facies.

#### *Detrital Wackestone to Packstone*

The wackestone to packstone facies, with 10% or more of the rock fabric composed of skeletal grains, is not associated with reef growth. This facies occurs before, after, or between episodes of reef growth. It is a mud-dominated facies that occurs often at the end of the mud-mound stage and during the transition into reef growth. It is also sometimes seen occurring between the end of reef growth and the beginning of the supratidal island stage. The common pore type in this facies is moldic porosity. The molds can often be solution enhanced and might be classified as a vug if no origin is interpretable for the void space

#### *Detrital Packstone to Grainstone*

This facies, like the aforementioned facies, is not associated with the reef growth. This is a grain dominated fabric composed of skeletal, peloidal, or grapestone allochems. Upon termination of reef growth, there is a grainstone cap that usually occurs. Often, these grainstone caps are comprised of skeletal grains, although a few cores have shown the occurrence of peloids and grapestones. Moldic and interparticle porosity dominate this facies.

Grapestones may indicate a transition from the shelf, behind the reef, into the tidal flat environment.

#### *Mudstone*

The mudstone is not a frequently occurring facies within the cores and is not associated with the mud-mound stage. It is either laminated or rarely mottled by burrowing. The lack of peloids, burrows, or skeletal fragments suggest that this was a hypersaline environment, incapable of allowing organisms to flourish. These features lead to the interpretation that this facies formed in a restricted shelf

environment, likely behind the reef. Porosity and permeability in this facies is generally poor, generally limited to localized intercrystalline porosity associated with dolomitization.

### *Cyanobacterial Mats*

Most often, this facies occurs at the top of the reef sequences known as the “supratidal island stage.” It is easily recognized on gamma-ray logs as a high intensity reading compared to the facies below. This is due to the abrupt transition from pure carbonate to interbedded anhydrite with carbonate. Mudcracks and laminations are key sedimentary structures that help in addition to identifying this facies.

Subdivisions of this facies include ripped-up cyanobacterial mat intraclasts with a wackestone to packstone matrix, laminated cyanobacterial mat, cyanobacterial mat altered with evaporites, and evaporites interbedded with a mudstone. Even though there are several subdivisions, there appears to be no petrophysical significance between the various subfacies. The minor porosity that exists in this unit is fenestral porosity produced by the degassing of the cyanobacteria through the sediment.

### Sonic Velocity Characterization

Initial petrophysical characterization (sonic velocity analysis under confining pressures) show a clear pattern that is dependent upon facies and resulting pore architecture (see Figures 16-21). Primary facies is a key factor in the ultimate diagenetic modification of the rock and the resulting pore architecture. Facies with good porosity and permeability clearly show relatively slow velocity values as would be expected, and low porosity and permeability samples exhibit fast sonic velocity values, again as expected. What is significant is that some facies that have high porosity values, either measured directly or from wireline logs, also have very fast sonic velocity values. This is due to these facies having a pore architecture characterized by more localized pores (vugs, molds or fractures) that are not in communication, resulting in facies with good porosity but poor permeability (Figures 19-21).

Stable isotopic analyses (C/O) show that most of the reefs evaluated through Phase II have matrix values near Silurian seawater values, suggesting that the dolomite is early (and therefore formed as a result of either multiple episodes of isotopically similar waters, or one episode that dolomitized the entire reef – considered unlikely). Minor excursions of carbon (+) and oxygen (-) occur at a number of cycle boundaries (Figure 15). In general there is about a 1 per mil enrichment in C for dolomite relative to calcite. Under normal circumstances, diagenetic products resulting from the influence of meteoric fluids results in highly negative  $\delta$ -C values. Voice's (2005) summary of earlier Silurian isotopes show carbon values ranging from -1 to +2.5 per mil, so these are about the same. The slight enrichment of  $\delta$ -C, at the same time that  $\delta$ -O is depleted, was reported by Karen Cercone (1985) as possibly being due to anaerobic fermentation of organics related to organic rich layers deposited during the ensuing transgression.

#### ***Task 4.0 – Development of 3-D Geological Models and Assessment of Application Potential***

This work was scheduled to be accomplished during Phase III of the Project. Most of the effort on this task necessarily had to follow results of Phase I (Task 2) and Phase II results of Task 3. We acquired the Petrel 3-D modeling suite from Schlumberger (~\$1.2 MM donation) that was to be used in this Task, but further work was halted due to the stop work order at the end of Phase II.

#### ***Task 5.0 – Technology Transfer***

Technology transfer efforts (Task 5) was marked by formal presentations on the state and national levels as well as advertisement of the project's scope, anticipated results and funding agency on the WMU Department of Geosciences web site. During Year 2/Phase II, we presented two papers at the National AAPG Meeting in Houston, TX (see Appendix 3), 2 papers at the Midwest Regional PTTC workshop on carbonate



reservoirs, and 7 papers (3 professional and 4 student presentations) at the Eastern Section of AAPG in Buffalo. We also received an award, the Vincent E. Nelson Memorial Award for Best Poster presented at the 2005 ES AAPG Meeting (Sandomierski, Grammer and Harrison).

A summary of project presentations is provided in Appendix 4.

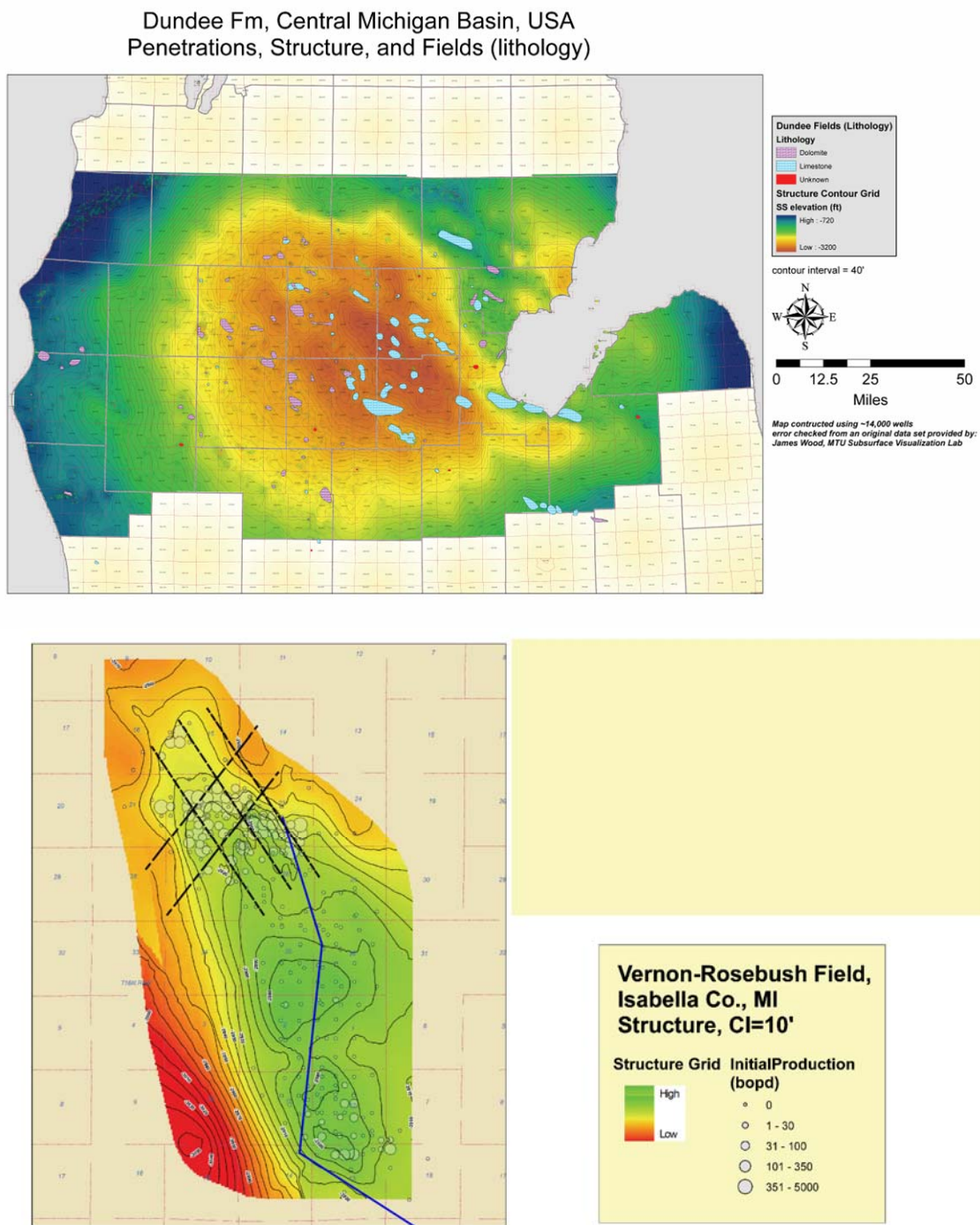


Figure 1. Structure contour map of the Devonian Dundee Formation (top) and details of one of the fields of interest.

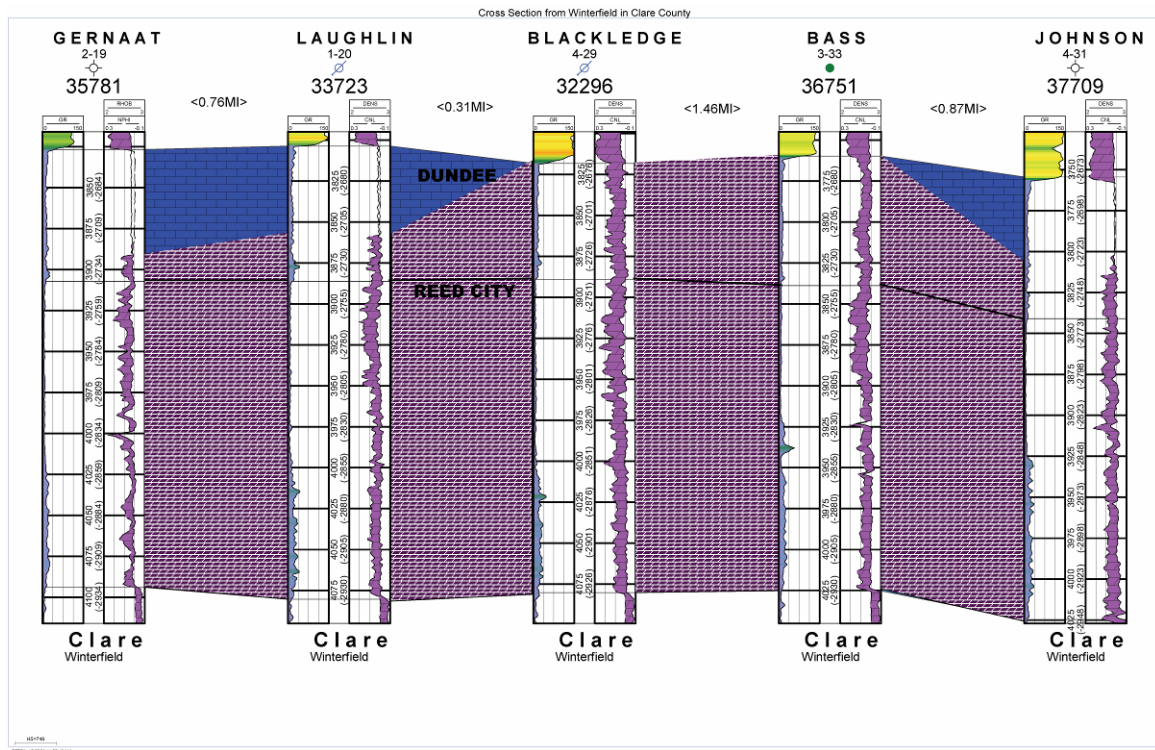
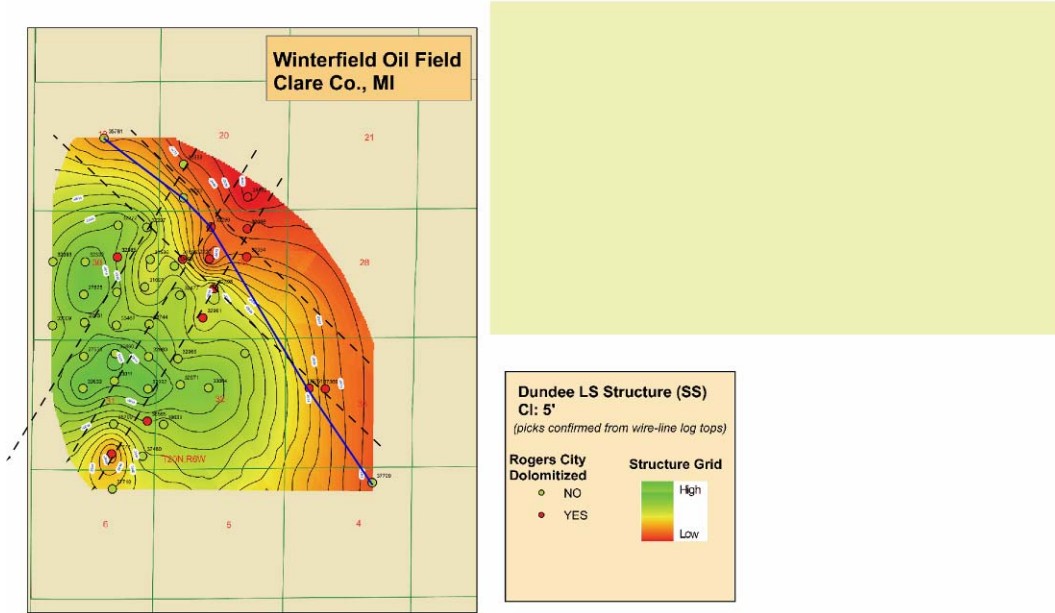


Figure 2-3. Structure contour map of the Devonian in Winterfield Oil Field with cross section showing pervasive regional scale dolomitization of the Reed City member of the Devonian Dundee.

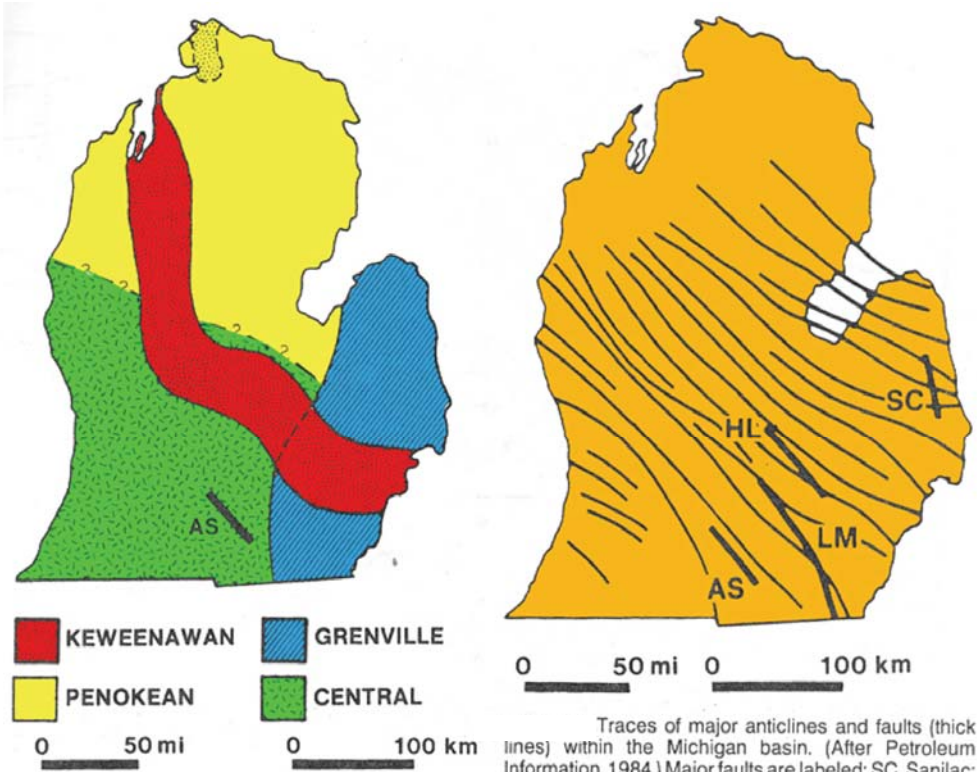


Figure 4. Provinces within the Precambrian basement of southern Michigan. (After Hinze et al., 1975). AS, Albion-Scipio field.

Traces of major anticlines and faults (thick lines) within the Michigan basin. (After Petroleum Information, 1984.) Major faults are labeled: SC, Sanilac; HL, Howell; LM, Lucas-Monroe; AS, Albion-Scipio.

Hurley and Budros, 1990

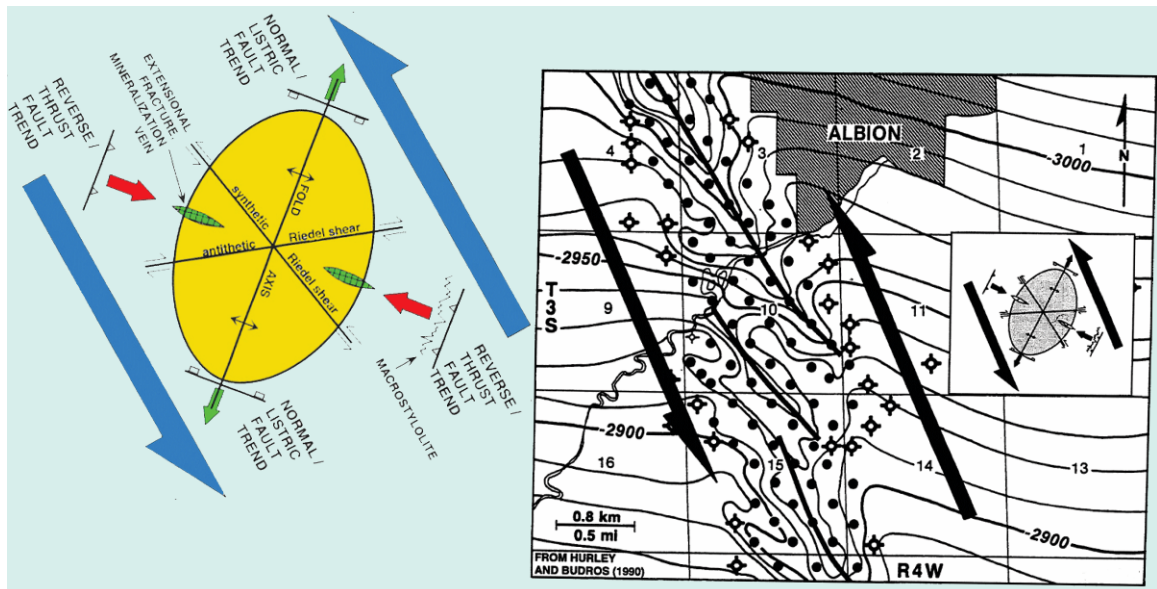


Figure 5. Riedel shear model for major fracture control at the Albion-Scipio fields in south-central Michigan (Trenton/Black River reservoirs).



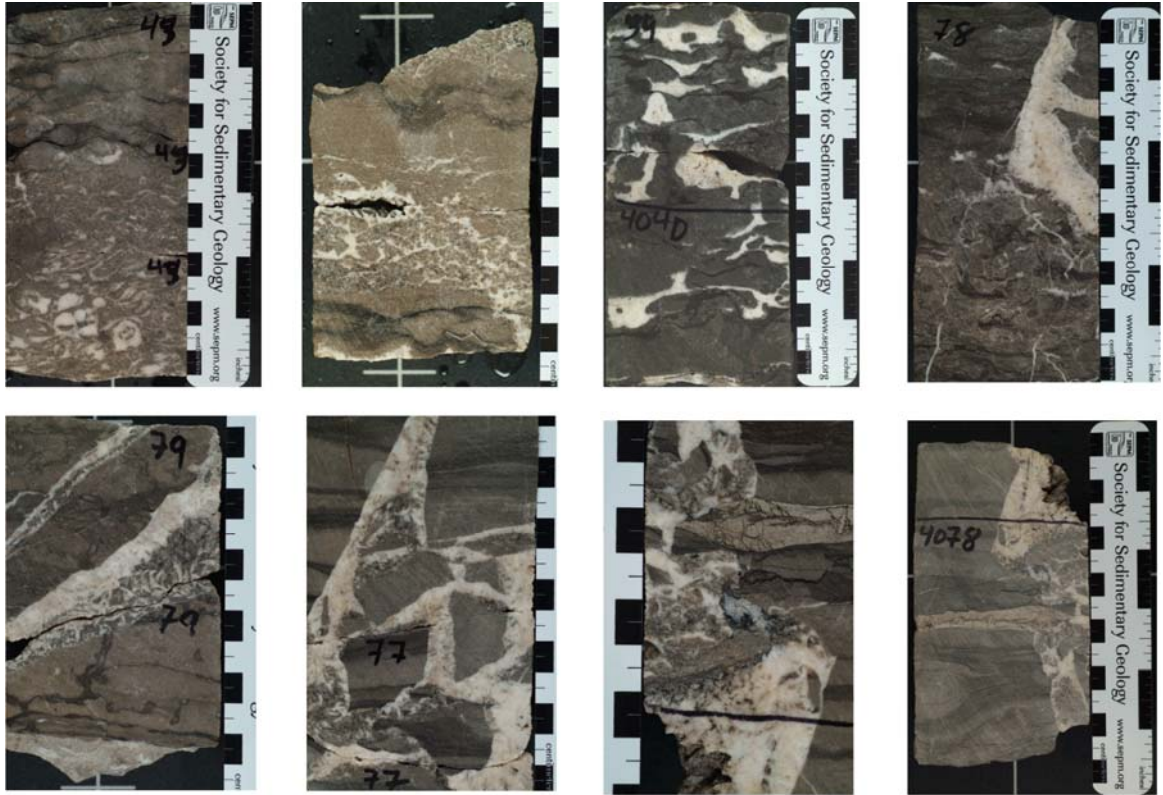
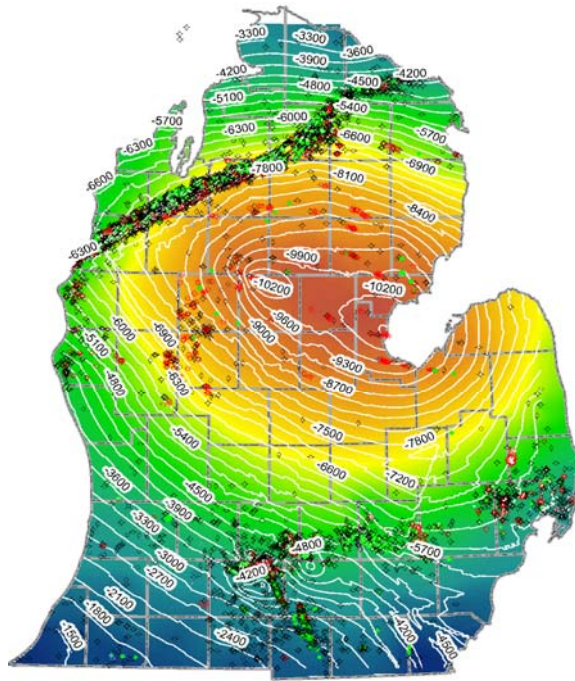


Figure 6. Hydrothermal dolomite filling fractures and primary porosity in Devonian Dundee and Trenton/Black River Formations.

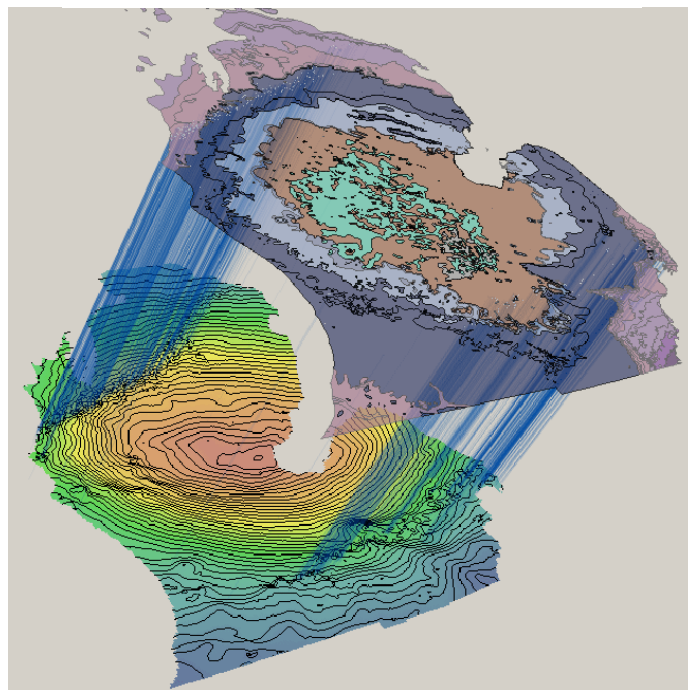
## Carbon and Oxygen Isotopic Composition of Saddle Dolomite: Selected Devonian Examples

| Source                          | $\delta^{18}\text{O}$ ‰ PDB | $\delta^{13}\text{C}$ ‰ PDB | Reference                 |
|---------------------------------|-----------------------------|-----------------------------|---------------------------|
| M. Dev., Manatoc, NWT           | -17.33 to -6.25             | -5.5 to -1.45               | Morrow et al, 1990        |
| M. Dev., Elk Point, N. Alb.     | -12 to -14                  | -1.0 to +2.0                | Dravis & Muir, 1992       |
| M. Dev., Pine Point, NWT        | -16.0 to -7.0               | -3.8 to +1.7                | Qing & Mountjoy, 1994     |
| Dev., Sidang-Burda, China       | -9.58 to -6.78              | -3.08 to -0.78              | Schneider et al, 1991     |
| U. Dev., Wabaman, Alb.          | -8.99 to -5.71              | -0.69 to +0.12              | Mountjoy & Dihardja, 1991 |
| U. Dev., Wabaman, Alb.          | -6.7 +/- 0.7                | 0.55 +/- 0.5                | Packard et al, 1989       |
| <b>Devonian, Michigan Basin</b> | <b>-8.2 to -10</b>          | <b>-0.6 to +1.34</b>        | <b>This Study</b>         |

Table 1. Stable isotopic values for Devonian hydrothermal dolomites in Canada and China. Note values from Devonian fit well within published range. Fluid inclusion data from the same Devonian samples show homogenization temperatures of 105-140°C, with an average of 122°C (N=38).



Brown Niagaran ("Niagaran Reefs", Middle Silurian) in the Lower Peninsula, MI. Structure depth (ss) interpolated from 9156 well penetrations.



Brown Niagaran surface structure model with Michigan subcrop map and fields

Figure 7. Maps showing structure contour of Brown Niagaran with well penetrations.

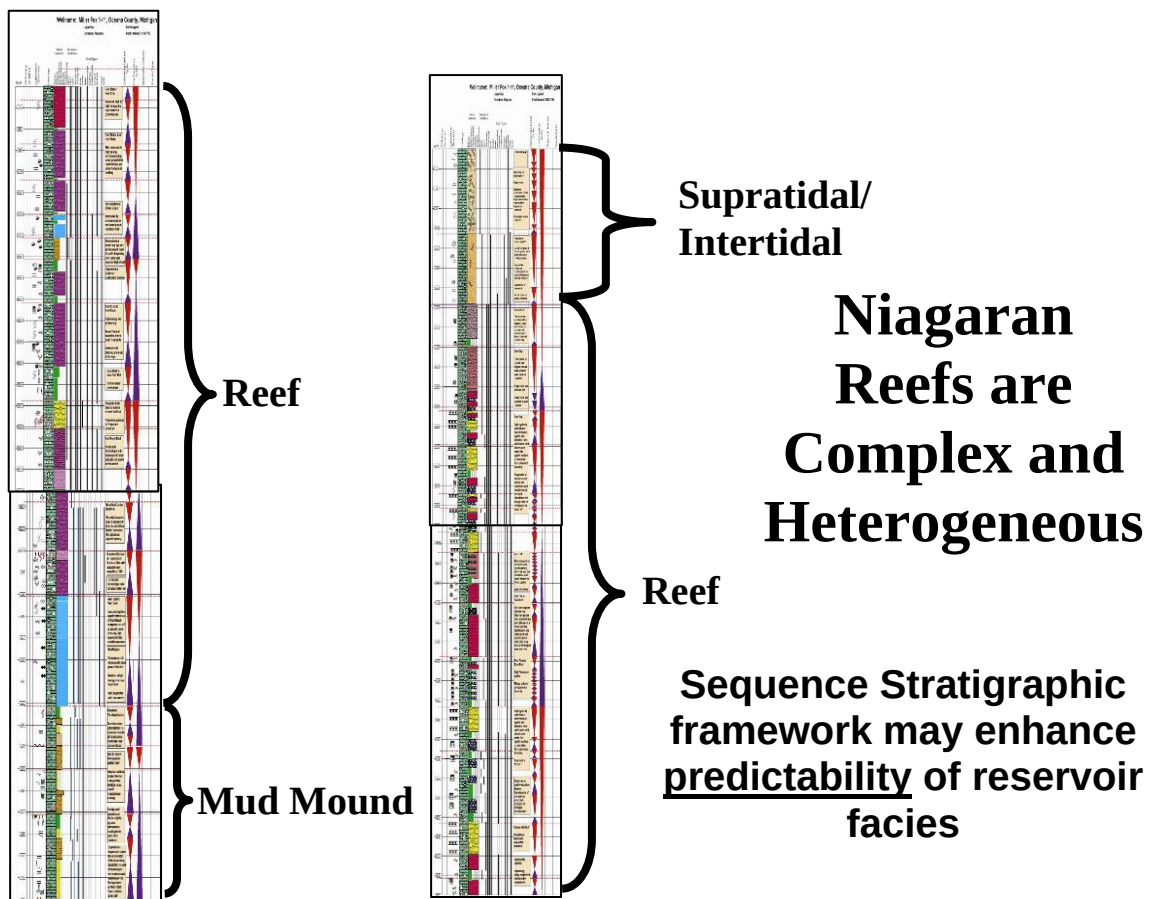
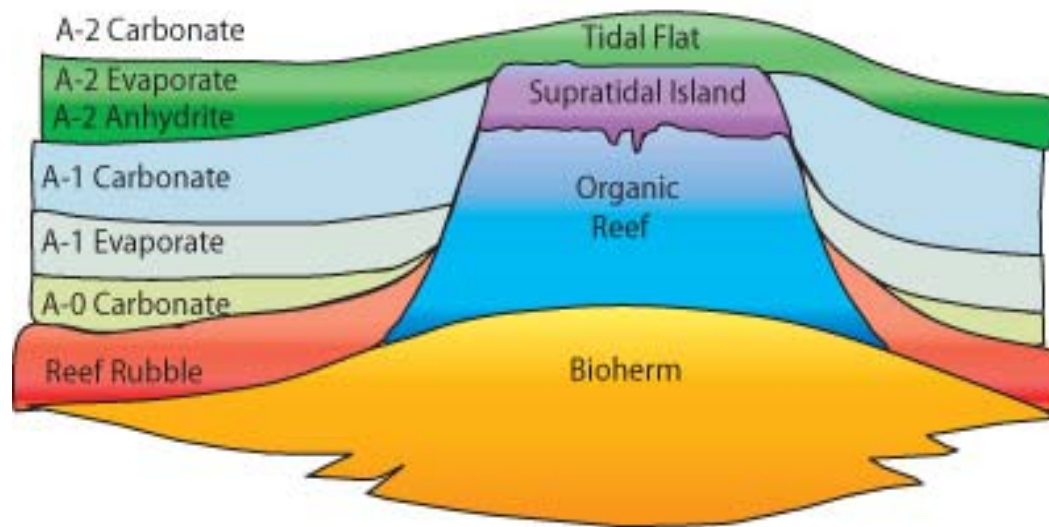


Figure 8. Schematic model for Niagaran reefs currently in use within the Michigan Basin (top) and detailed, high resolution facies analysis and sequence stratigraphic hierarchy established for the northern reef trend in work done to date.



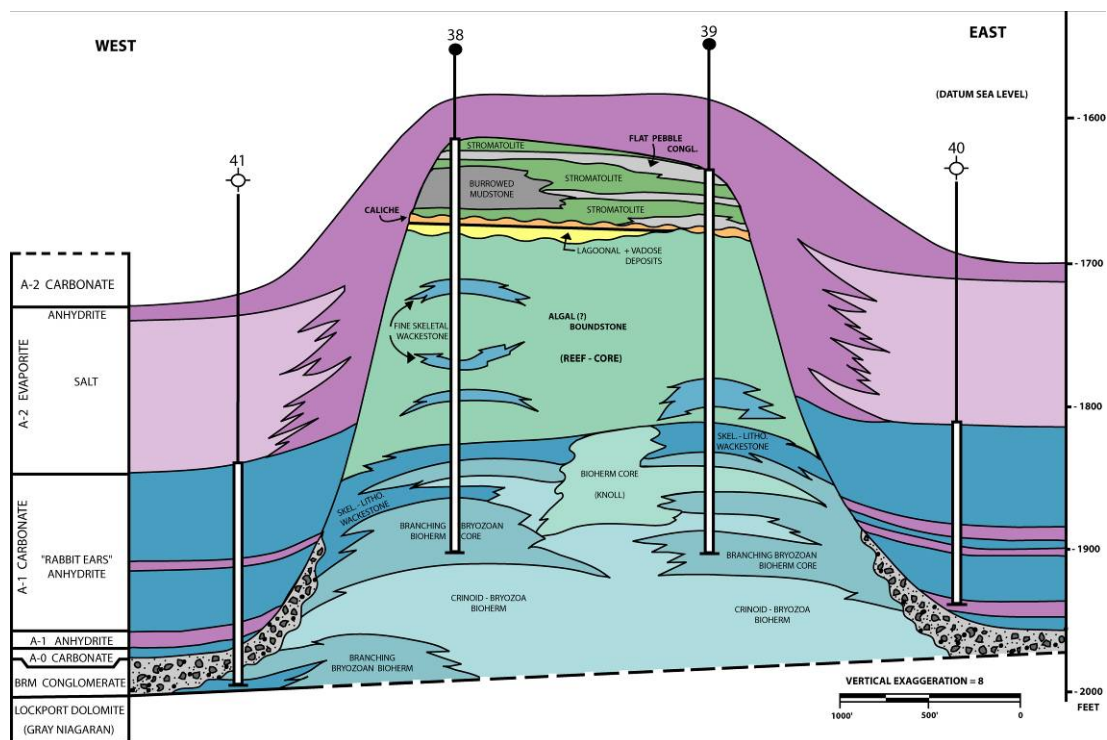


Figure 9. Schematic facies model of Belle River Mills reef showing evidence of lateral and vertical variability in facies (Gill, 1977). Detailed rock-based characterization of Niagaran reefs in this study illustrate that reservoir heterogeneity is much more complex, but that predictable patterns are revealed after constructing a sequence stratigraphic framework.

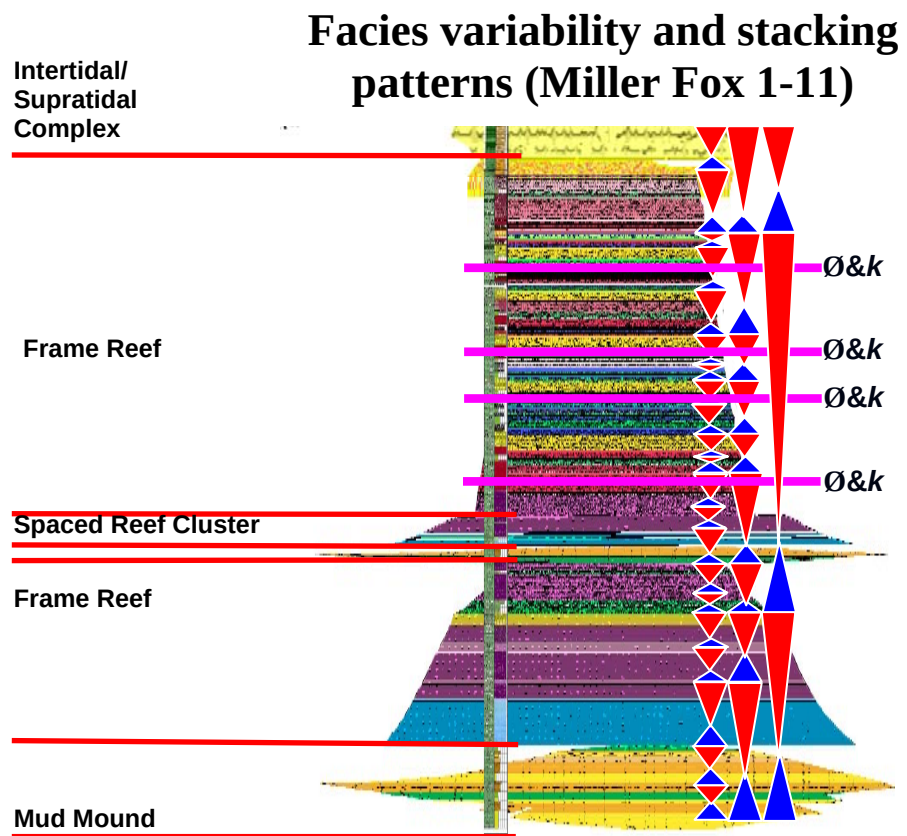
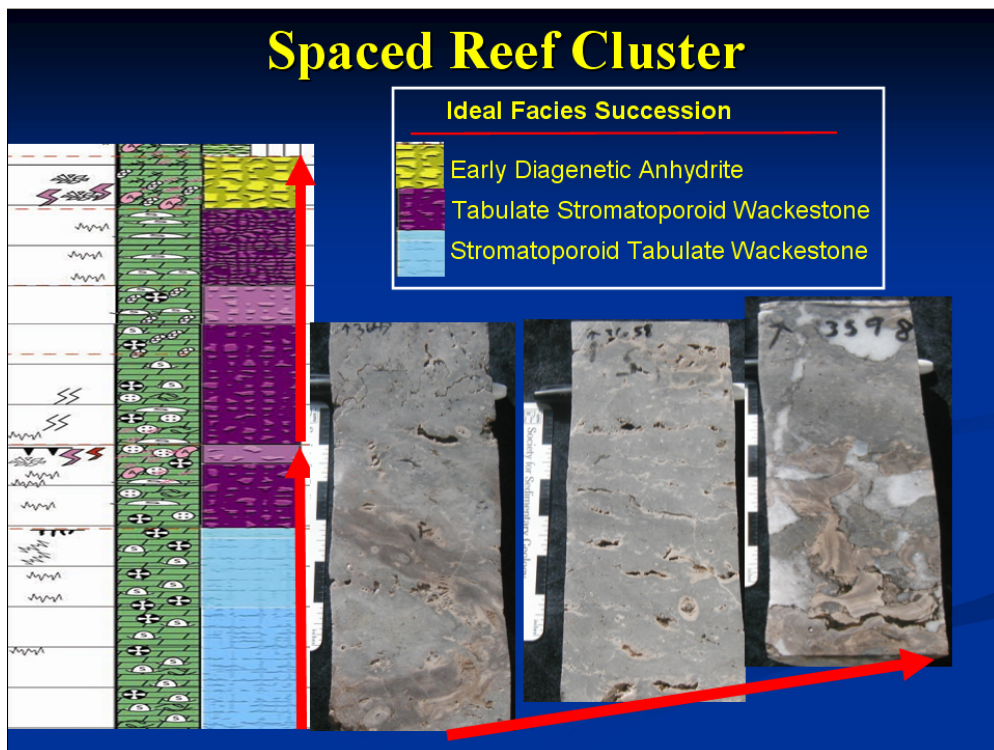
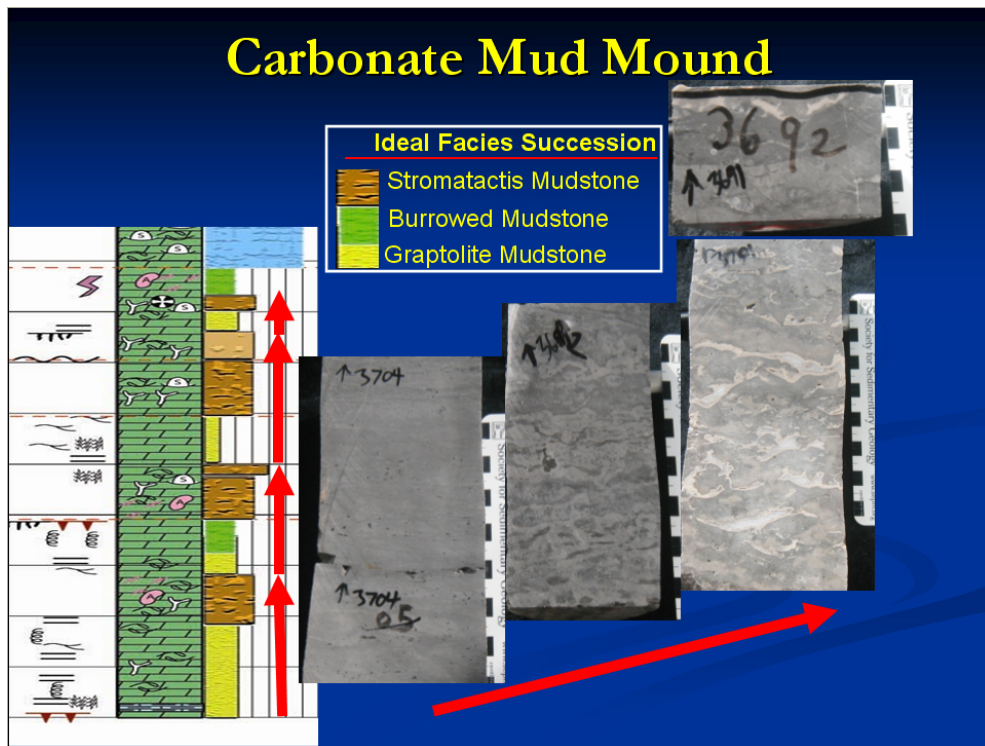
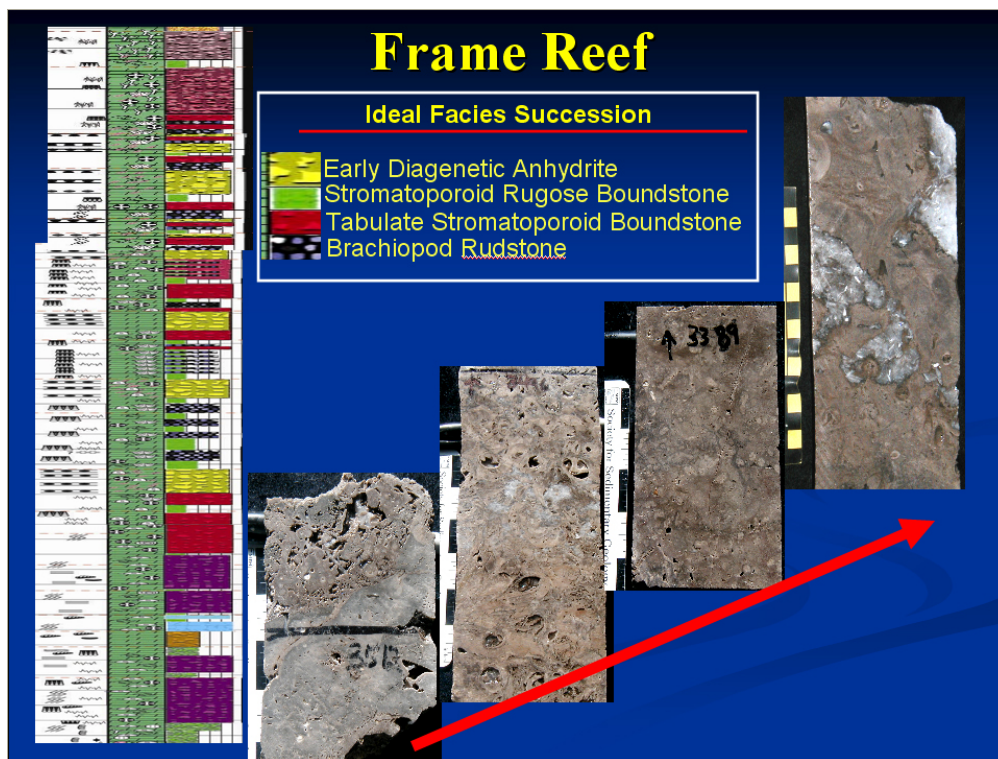


Figure 10. Schematic diagram for the 480 ft. Miller Fox 1-11 Niagaran reef showing the complex, but predictable facies succession and the sequence stratigraphic hierarchy established in this reef.



Figures 11 and 12. Examples of shallowing upward high frequency cycles that make up Niagaran reefs in this study.





Figures 13 and 14. Examples of shallowing upward high frequency cycles that make up Niagaran reefs in this study.

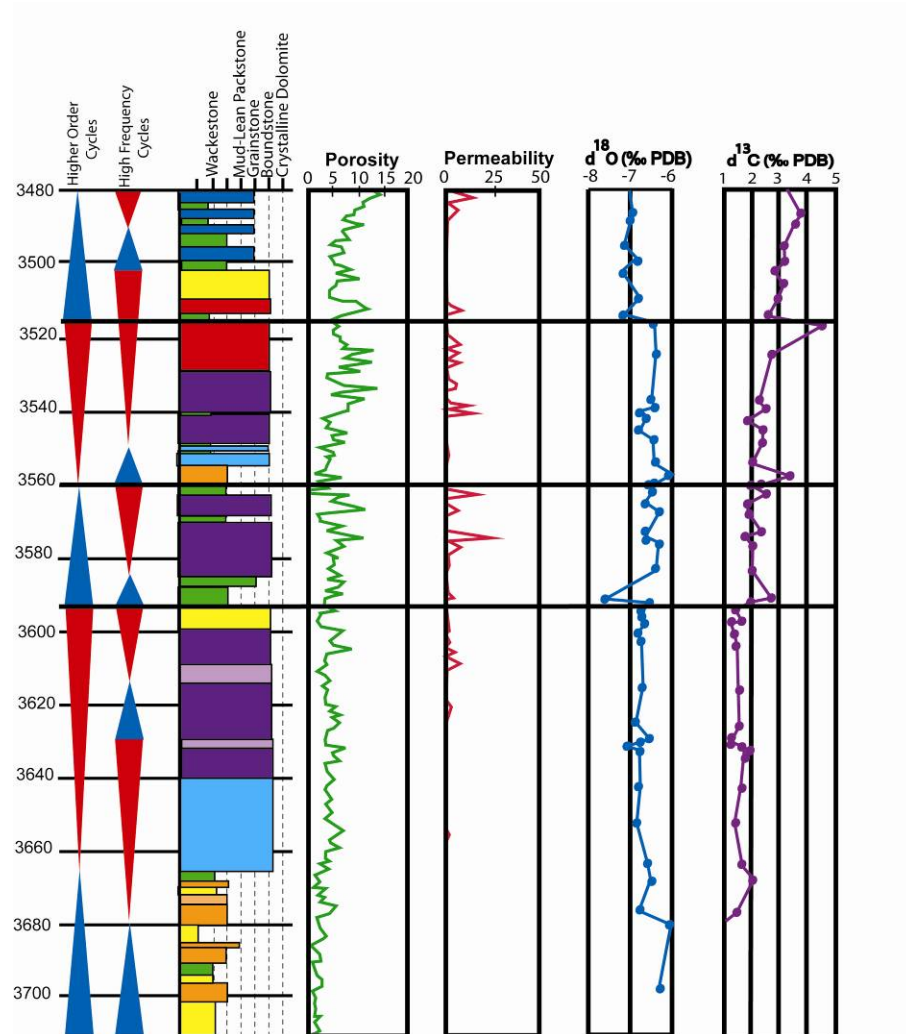
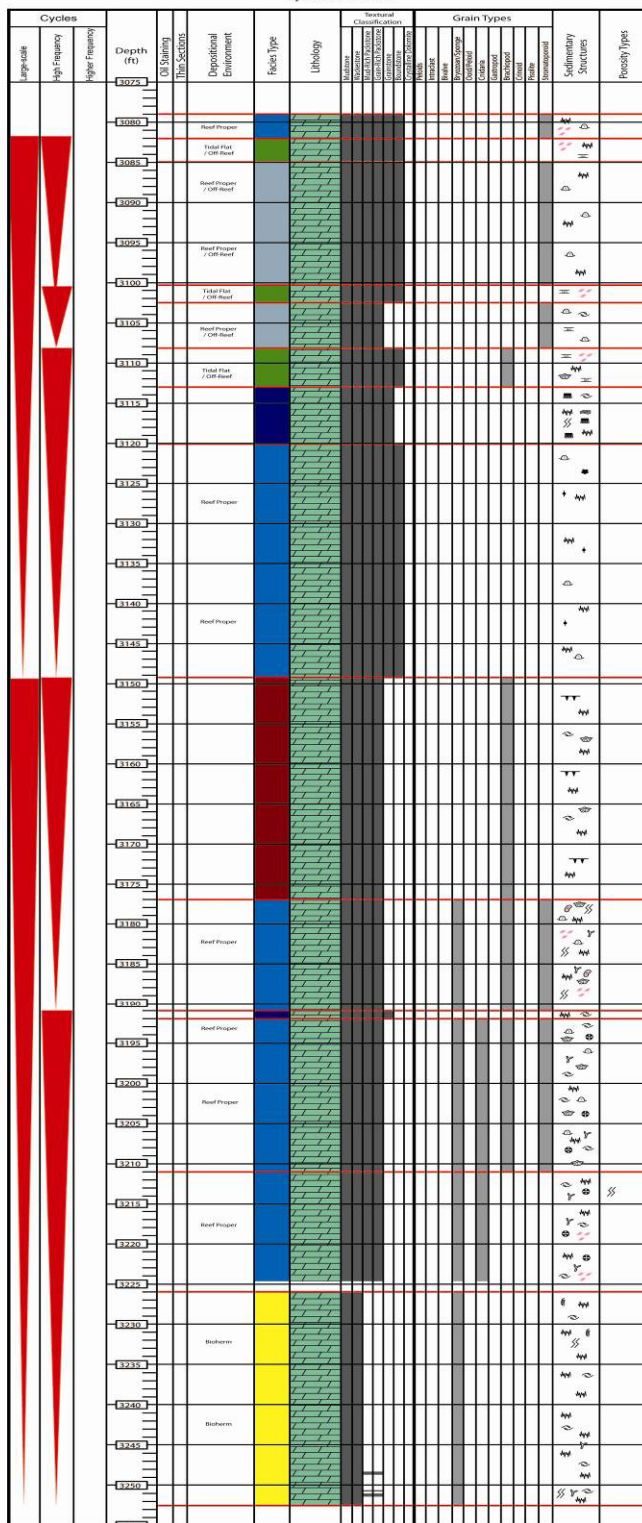


Figure 15a. Details of portion of Miller Fox 1-11 reef illustrating the complex variability in facies vertically, and the correlation between porosity and permeability spikes near the top (regressive portion) of many of the high frequency cycles.

By: Jessica L. Wold



#### FACIES SUMMARY

3079' – 3082' – Reef Core (Facies 4) Stromatoporeid Dominated Reef Interval  
3082' – 3100.25' – Reef Detritus (Facies 3) Stromatoporeid and Algal Debris  
3100.25' – 3102.5' – Algal Boundstone (Facies 8)  
3102.5' – 3108.1' – Reef Detritus (Facies 3) Stromatoporeid and Algal Debris  
3108.1' – 3113' – Algal Boundstone (Facies 8)  
3113' – 3120' – Peloidal Skeletal Grainstone (Facies 5) w/ Crossbedding  
3120' – 3149.2' – Reef Core (Facies 4) Stromatoporeid Dominated Reef Interval  
3149.2' – 3177' – Exposure Interval (Facies 10)  
3177' – 3191' – Reef Core (Facies 4) Stromatoporeid Dominated Reef Interval  
3191' – 3192' – Skeletal Grainstone to Packstone (Facies 5)  
3192' – 3211' – Reef Core (Facies 4) Stromatoporeid Dominated Reef Interval  
3211' – 3226' – Reef Core (Facies 4) Coral Dominated Reef Interval w/ Possible Microbial Influence  
3226' – 3252.5' – Bioherm (Facies 1) Skeletal Biomicrite (Mud Dominated)

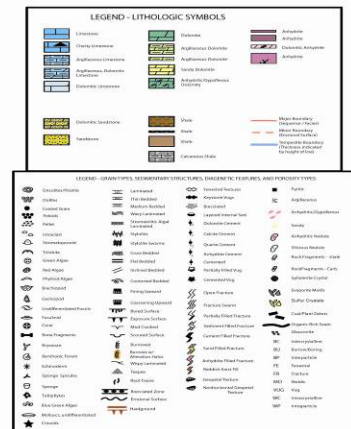
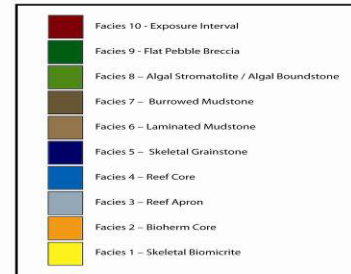


Figure 15b. Example of complex facies variability and stacking patterns in southern reef trend (Ray Reef Field).



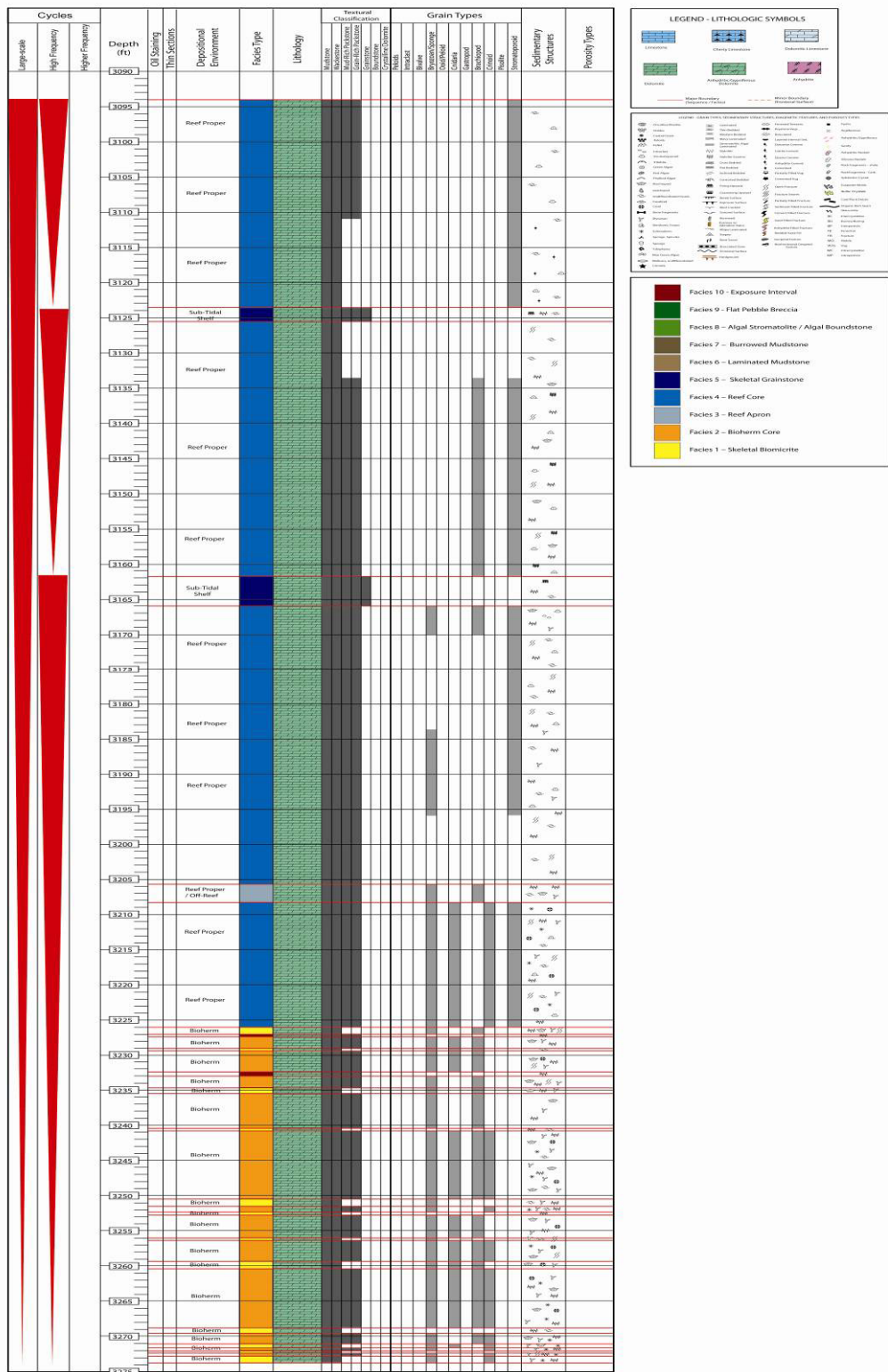


Figure 15c. Example of complex facies variability and stacking patterns in southern reef trend (Ray Reef Field).

Consumers Power Company Percy No. 2-2 Permit No. 25100, Macomb County, MI

Formations: Salina and Brown Niagaran (Guelph Formation) Depth Interval: 3198'-3252'

By: Jessica L. Wold

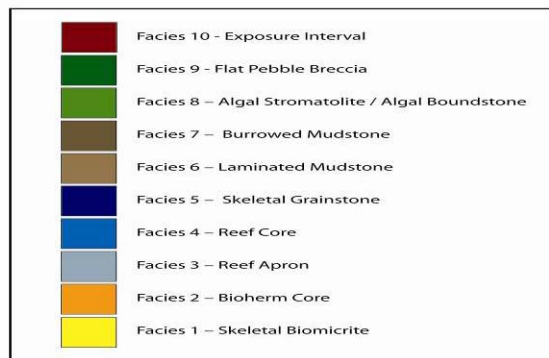
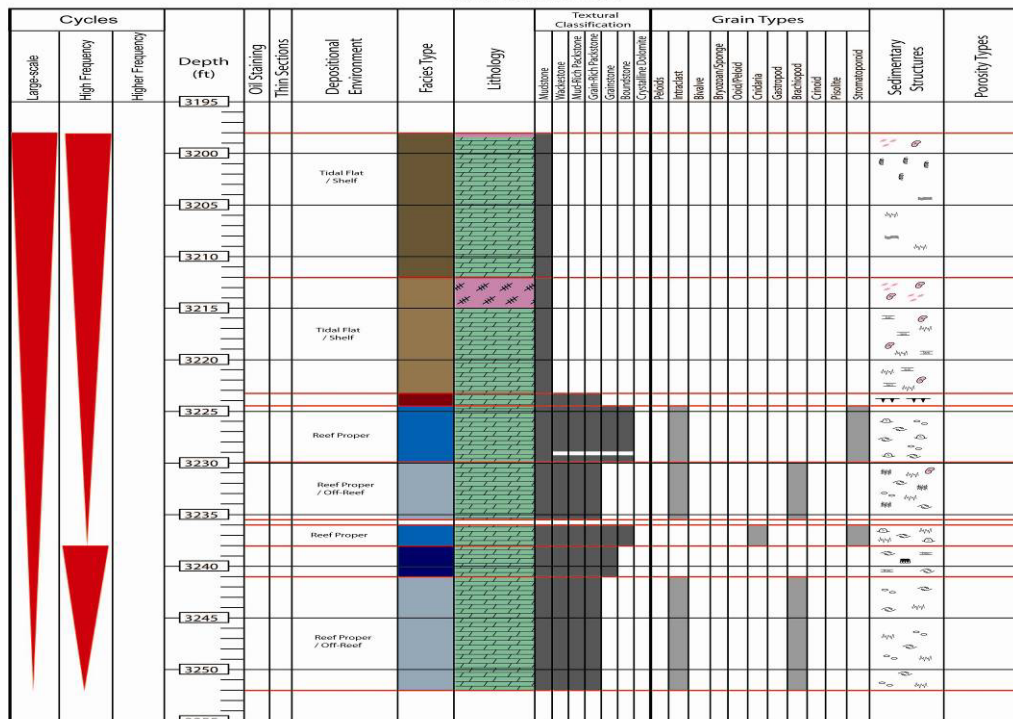
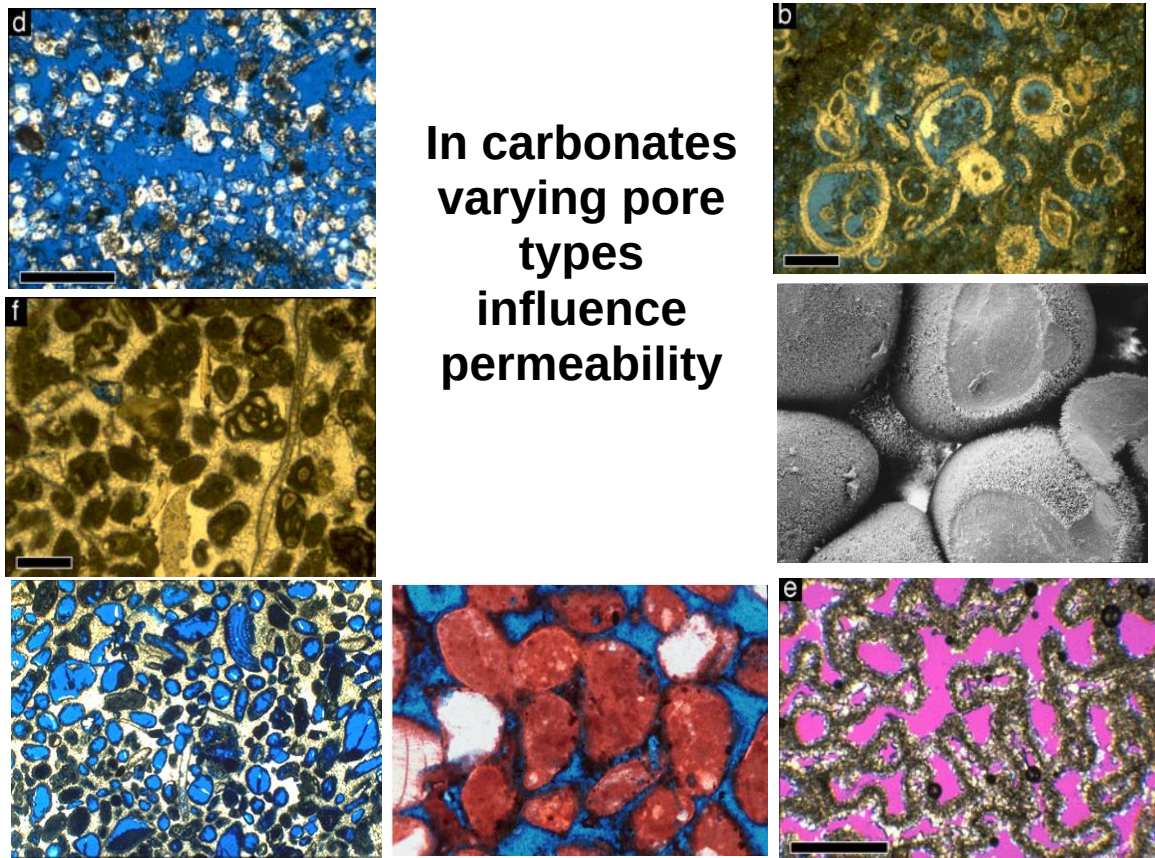


Figure 15d. Example of complex facies variability and stacking patterns in southern reef trend (Ray Reef Field).





Eberli, 2000

Figure 16. Examples of varying types of pore architectures common in carbonate rocks. Depending on the connectivity (i.e. permeability) of the pore network, carbonate rocks exhibit significant variability in sonic velocities.

# Velocity versus Porosity in Carbonates

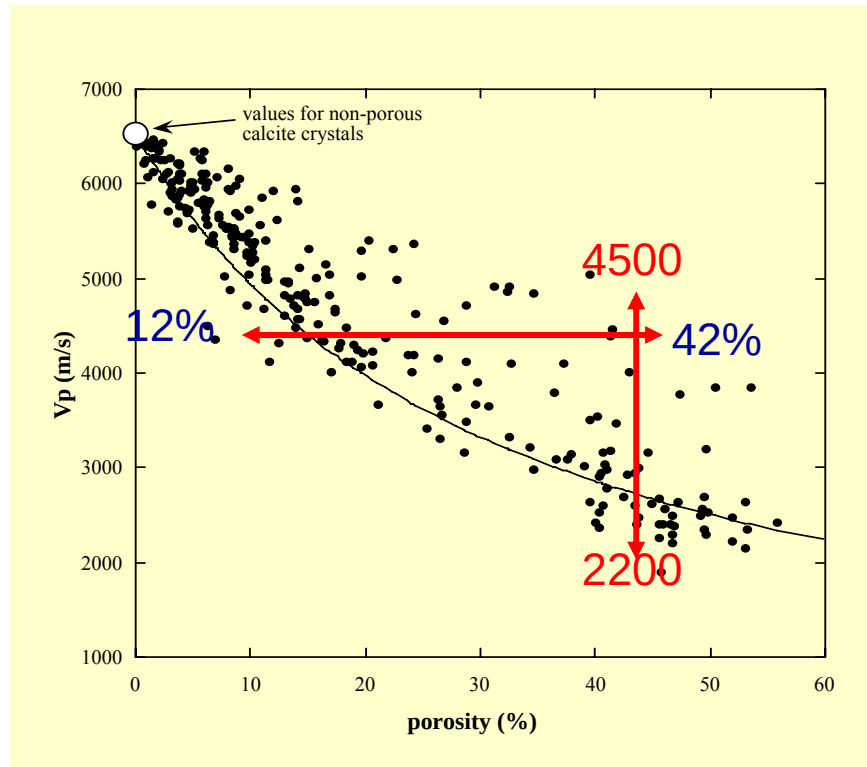


Figure 17. Plot illustrating variability in porosity, permeability and sonic velocity in carbonate rocks as a function of pore architecture (Eberli, 2004). Examples show how rocks with 42% porosity can have sonic velocities ranging from 2200 to 4500 m/s, or how rocks with an equivalent sonic velocity (in this case around 4500 m/s) may have porosities that range from 12-42%. This variability is a function of pore architecture which can be correlated back to primary depositional facies and positioning within a sequence stratigraphic framework.

## Miller Fox 1-11

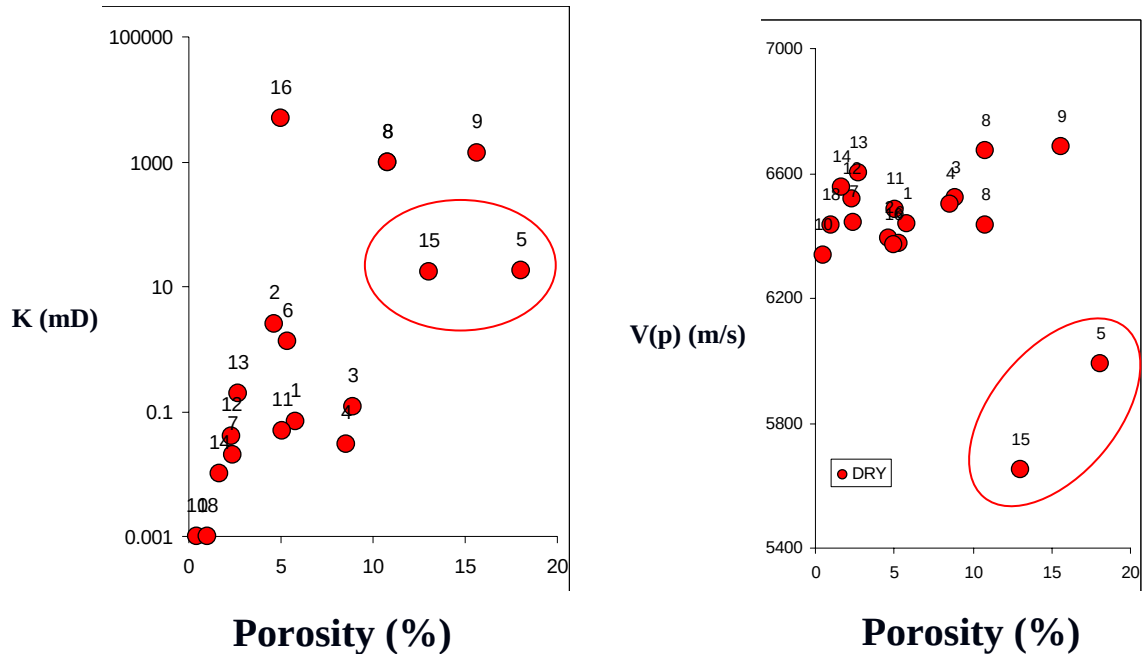
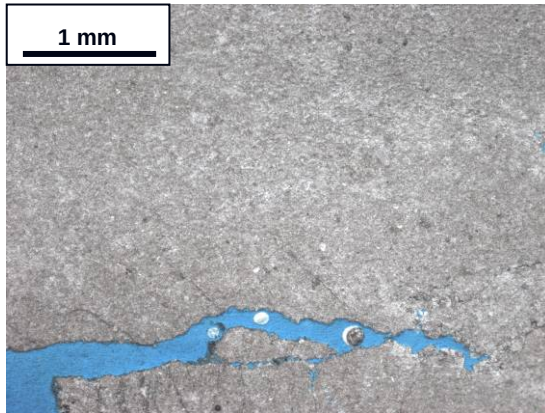


Figure 18. Porosity vs. P-wave velocity values for Niagaran reef facies. Cluster in upper left exhibits normal behavior (i.e. low porosity and high velocities) as does samples 5 and 15 (higher porosities with slower velocities). Velocity values were measured under confining pressures of 20-30 MPa, where 20 MPa equals about 1km of burial depth. Therefore, 30 MPa would equal approximately 1500m or 4920 feet which is consistent with the average burial depths for most Niagaran reefs in the Michigan Basin.



**Isolated vugs and local fractures with no matrix**

**3572 ft.**

**$\phi = 5.0\%$**

**$K = .05 \text{ mD}$**

**$V_p = 6480 \text{ m/s}$**

**Small (pin-point) vugs with minor matrix**

**3430 ft.**

**$\phi = 8.9\%$**

**$K = .12 \text{ mD}$**

**$V_p = 6400 \text{ m/s}$**

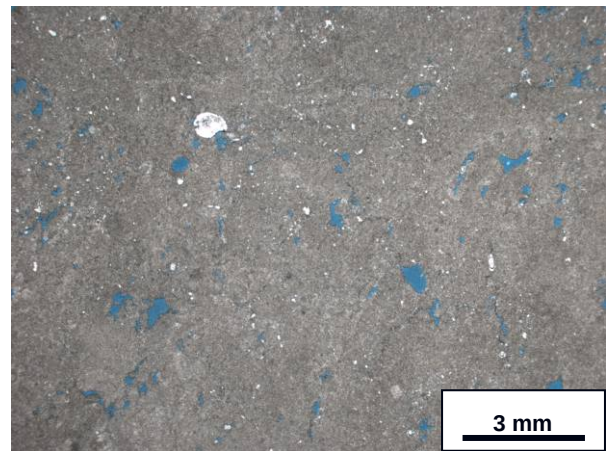
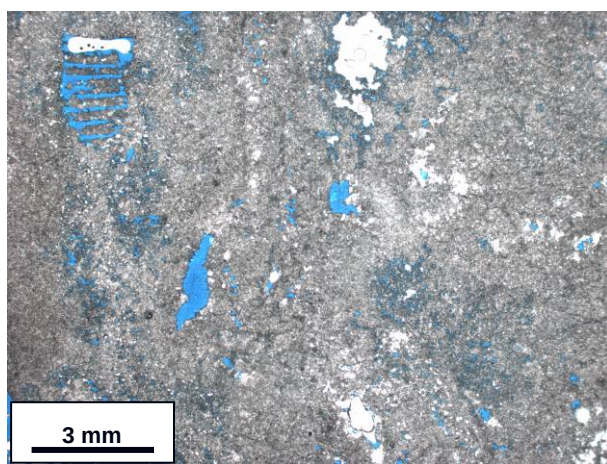


Figure 19. Thin section photomicrographs illustrating variability in porosity, permeability and sonic velocity dependent upon pore type and pore architecture.



**Large vugs + IX  
matrix**

**3480 ft.**

**$\phi = 18\%$**

**K = 17.8 mD**

**V<sub>p</sub> = 5900m/s**

**Large vugs + IX  
matrix**

**3631 ft.**

**$\phi = 13\%$**

**K = 17.3 mD**

**V<sub>p</sub> = 5630m/s**

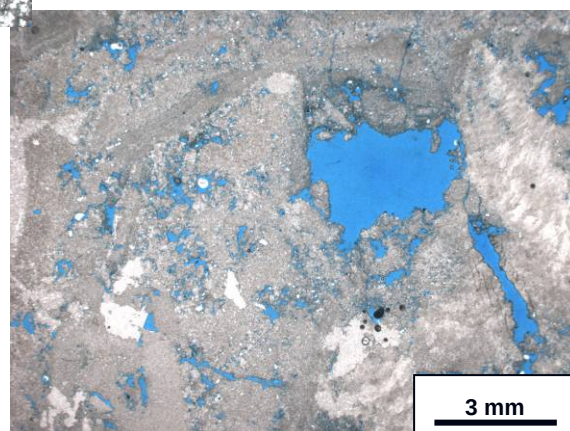
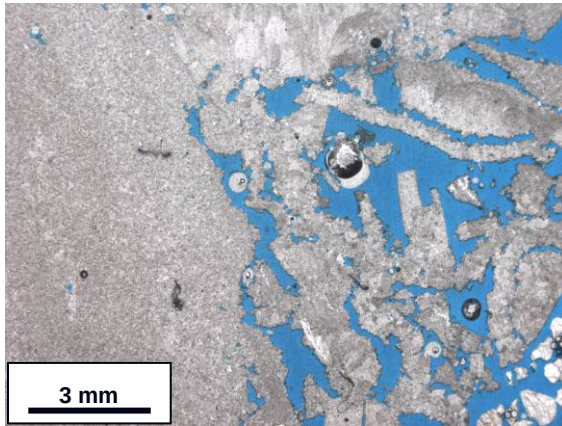


Figure 20. Thin section photomicrographs illustrating variability in porosity, permeability and sonic velocity dependent upon pore type and pore architecture.





**Large isolated vugs and fractures**  
**Low matrix porosity**

**3524 ft.**

**$\phi = 10.8\%$**

**K = 990 mD**

**V<sub>p</sub> = 6240m/s**

**Large isolated vugs and fractures**  
**Low matrix porosity**

**3540 ft.**

**$\phi = 15.6\%$**

**K = 1368 mD**

**V<sub>p</sub> = 6660m/s**

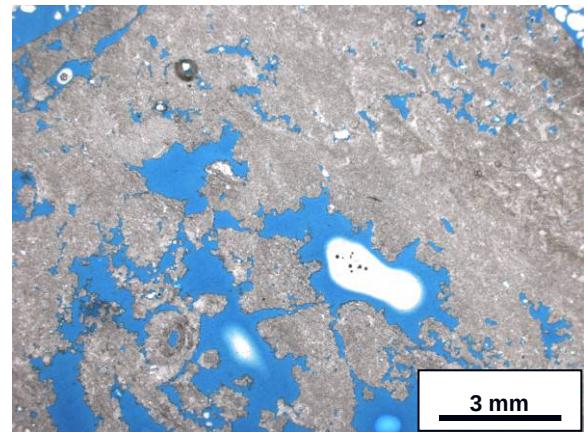


Figure 21. Thin section photomicrographs illustrating variability in porosity, permeability and sonic velocity dependent upon pore type and pore architecture.

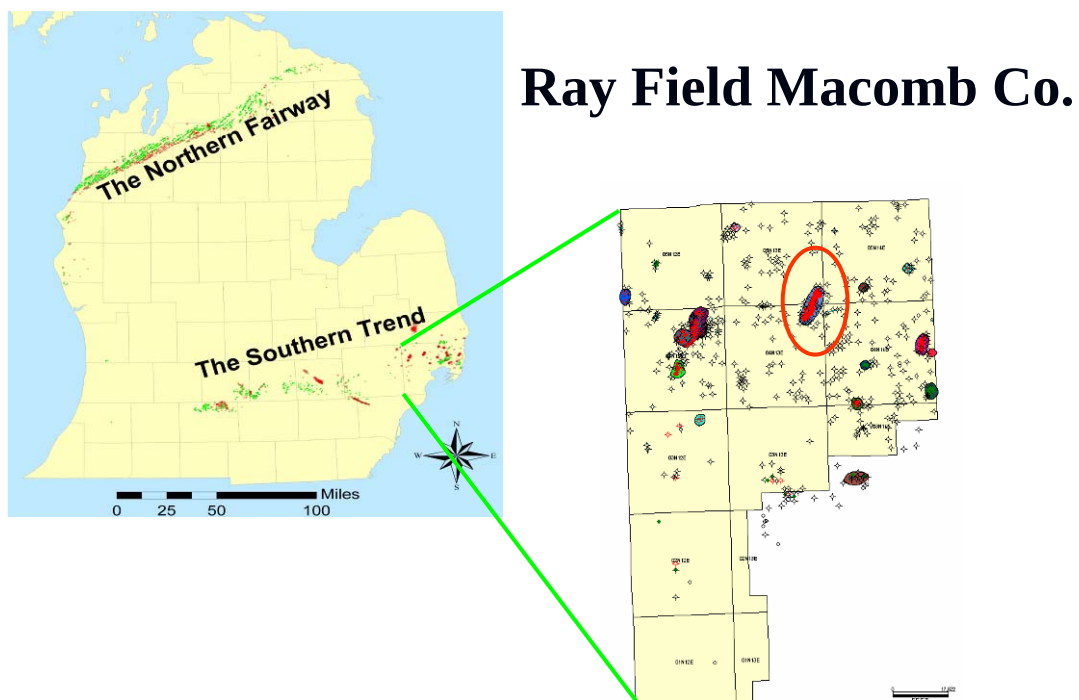
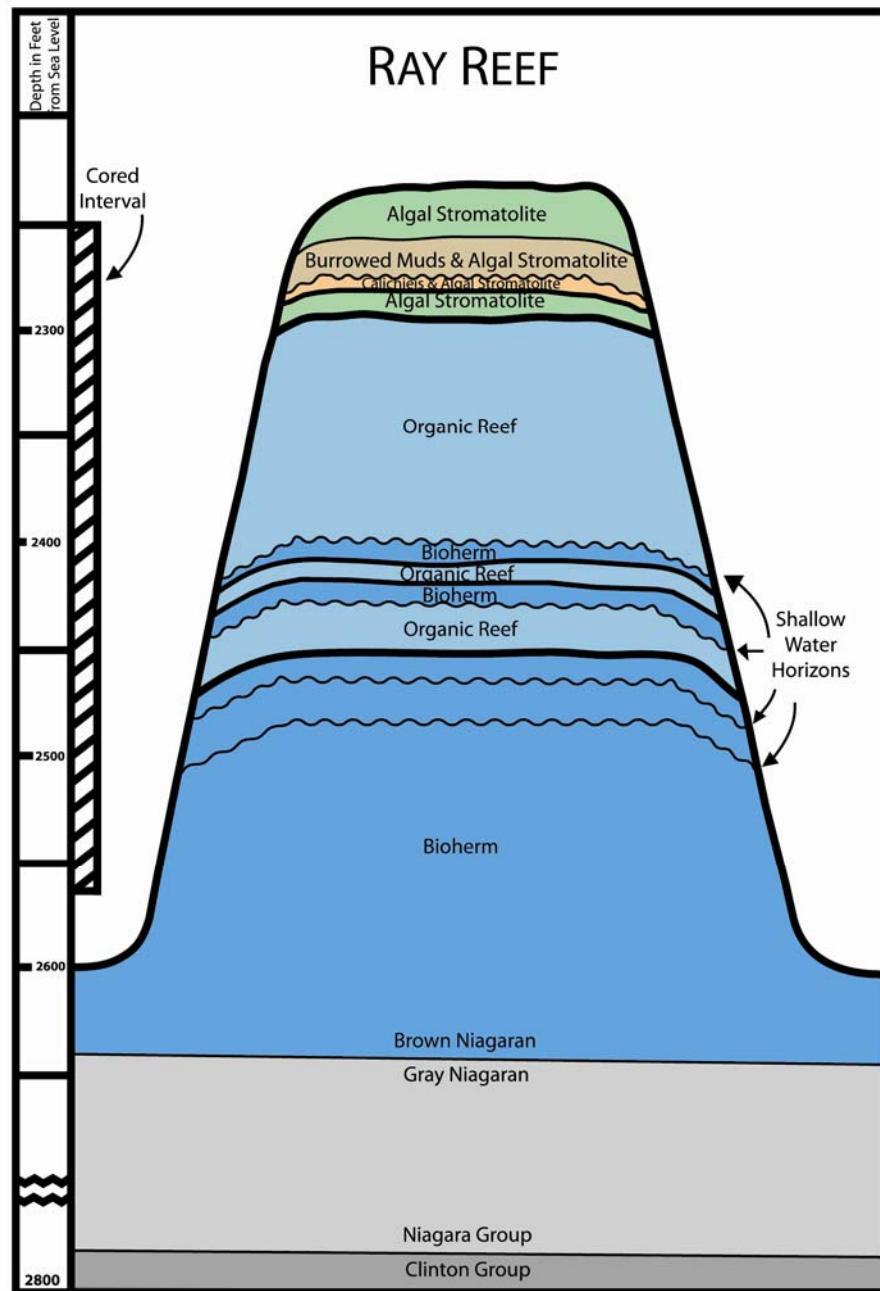


Figure 22. Location of Ray Reef field in the southern reef trend. Three graduate students are currently working on various aspects of reservoir characterization within this field, utilizing 18 cores for rock-based reservoir characterization and modeling.



Modified from Balogh (1981)

Figure 23. Schematic diagram showing general vertical variability in Ray Reef identified by Balogh (1981).



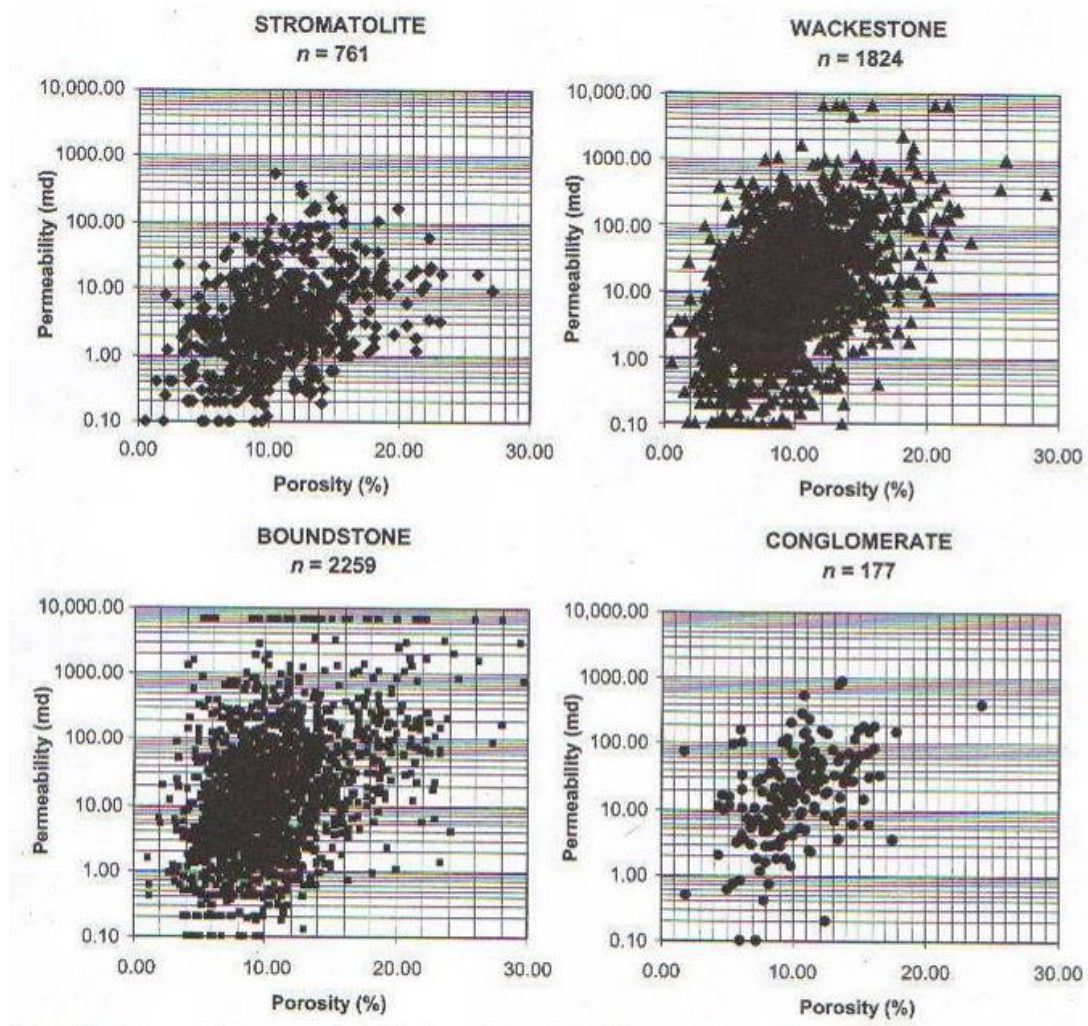


Figure 24. Core porosity and permeability from the Belle River Mills (southern reef trend) from Wylie and Wood, 2005, AAPG Bulletin, v. 89. The authors conclude that “no apparent trend exists between the core permeability and core porosity by rock type”, p. 420.

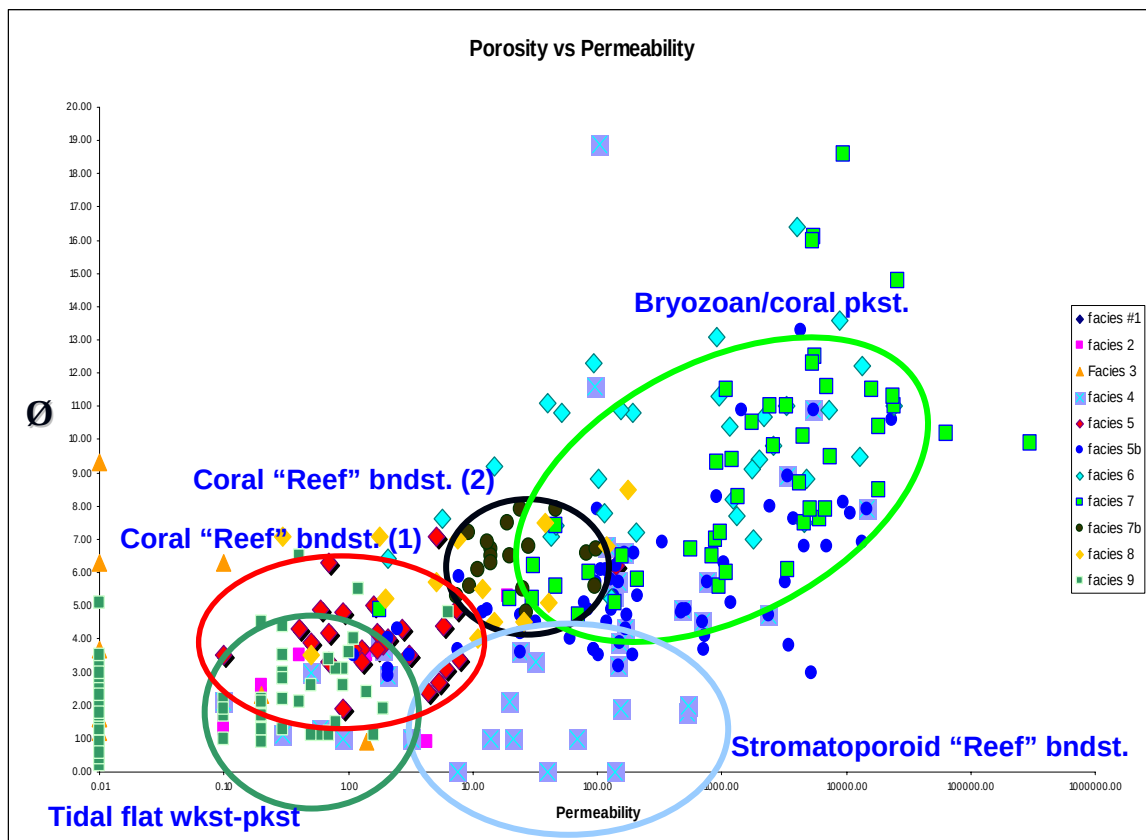
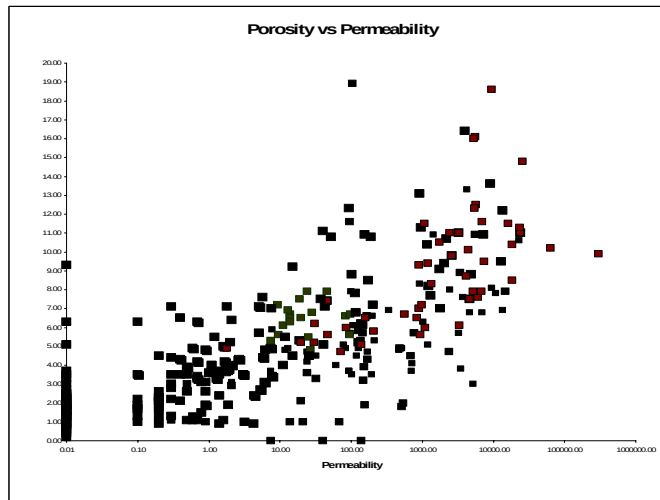


Figure 25a. Top figure show similar distribution of core porosity and permeability for the Miller Fox 1-11 as observed in the Belle River Mills field data published by Wylie and Wood (2005). Lower figure illustrates how when the facies are broken up into more detailed geological-based units, there is a distinct correlation between facies type and reservoir quality (porosity and permeability).

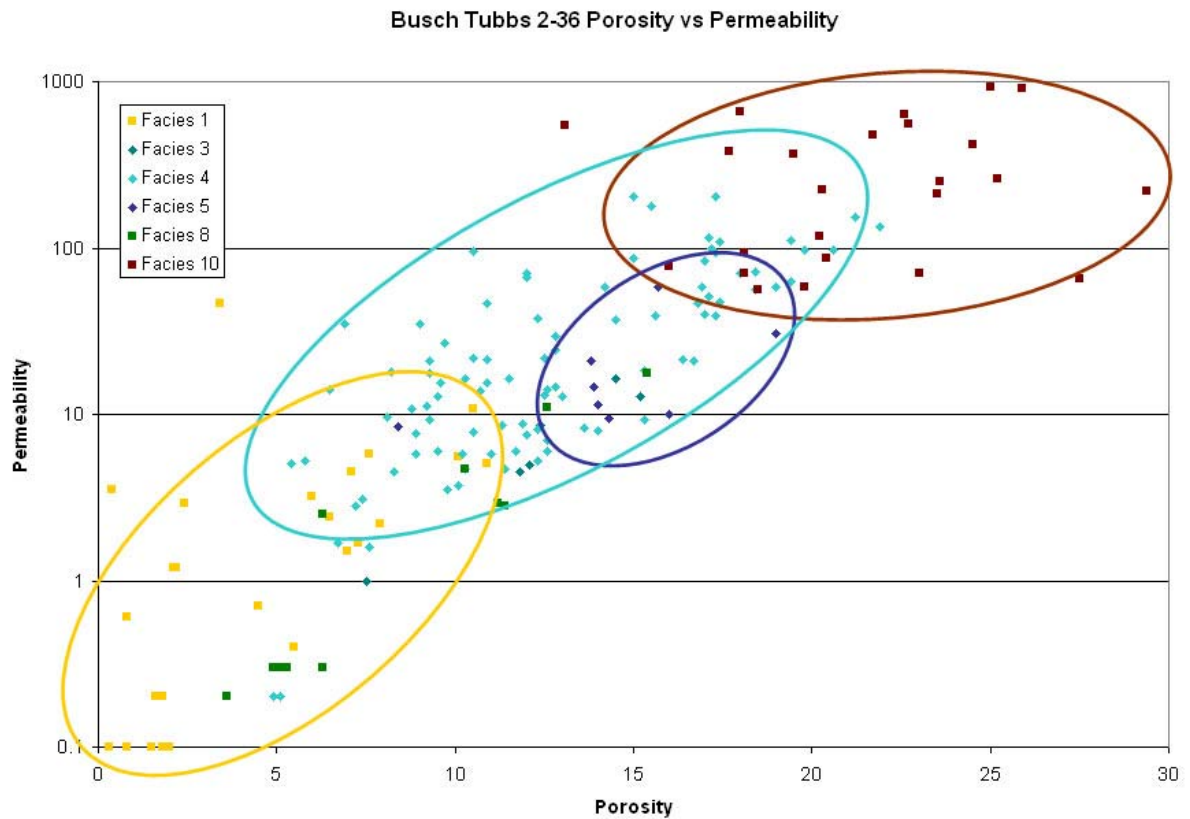


Figure 25b. Core porosity and permeability for the Busch Tubbs 2-36 in Ray Reef field (southern trend) illustrating a similar pattern to that observed in the northern trend (i.e. how when the facies are broken up into more detailed geological-based units, there is a distinct correlation between facies type and reservoir quality and therefore porosity and permeability).



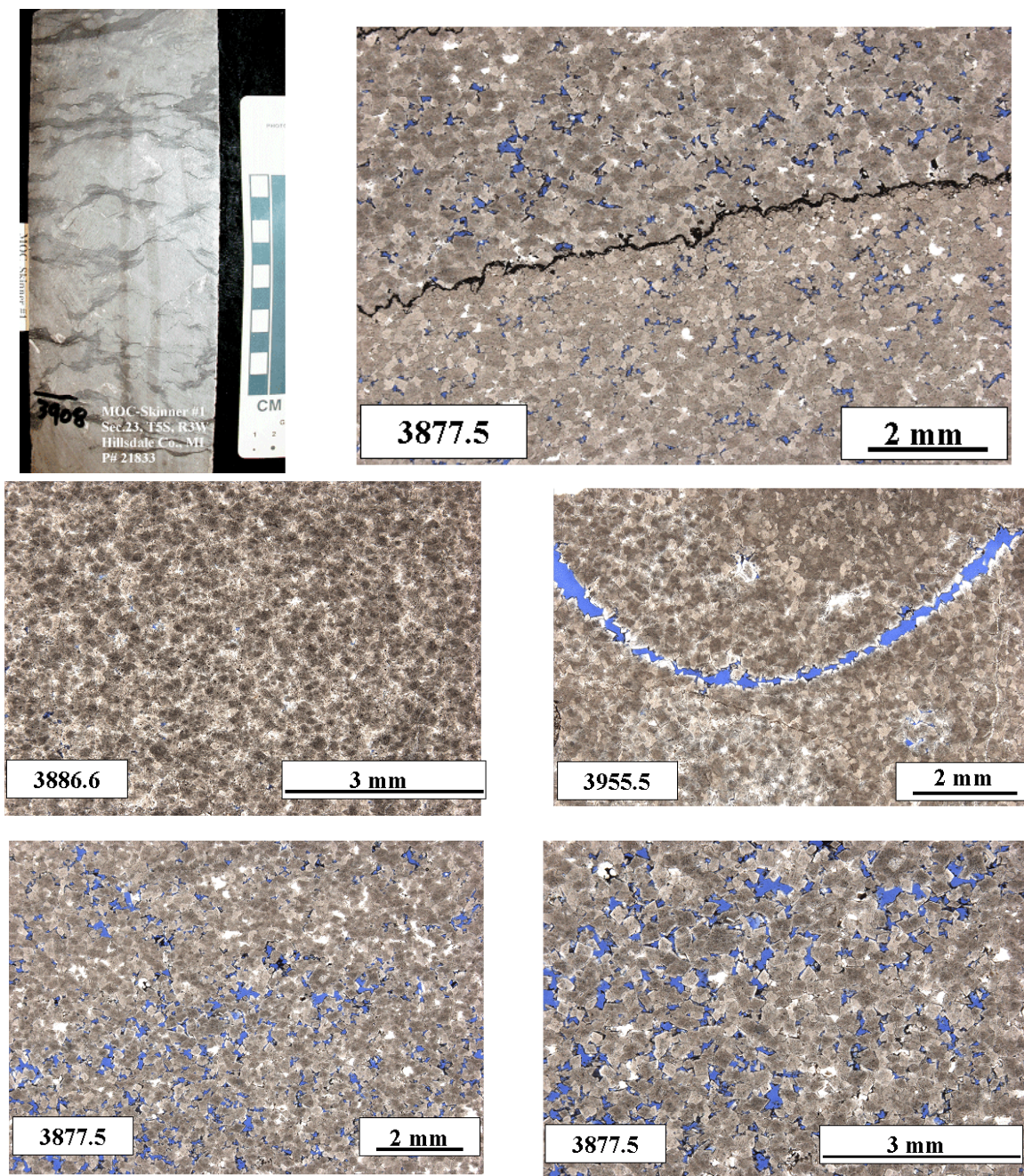


Figure 26. Core photo and thin section photomicrographs illustrating the variability in facies and pore systems in the Trenton/Black River formations.



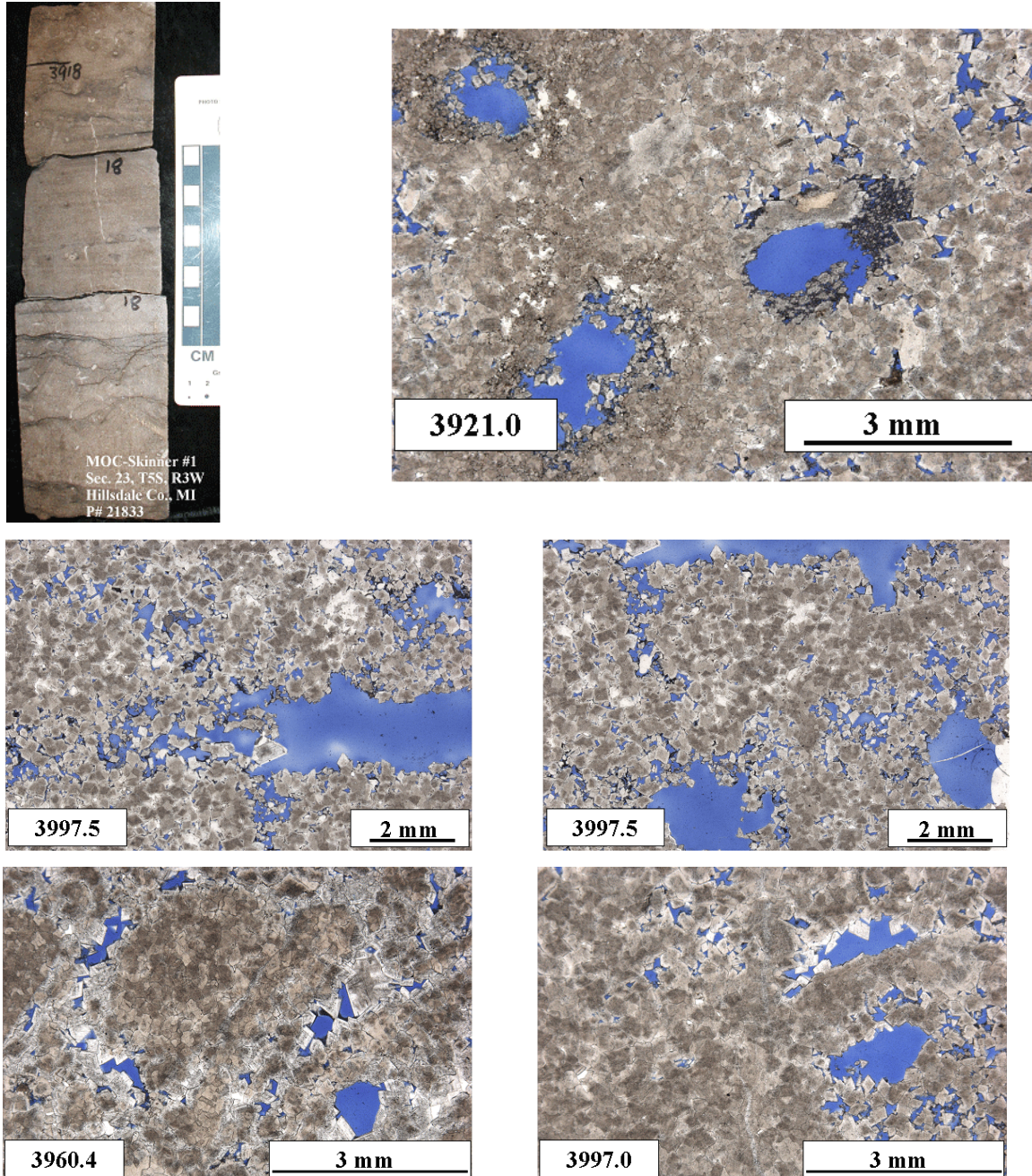


Figure 27. Core photo and thin section photomicrographs illustrating the variability in facies and pore systems in the Trenton/Black River formations.

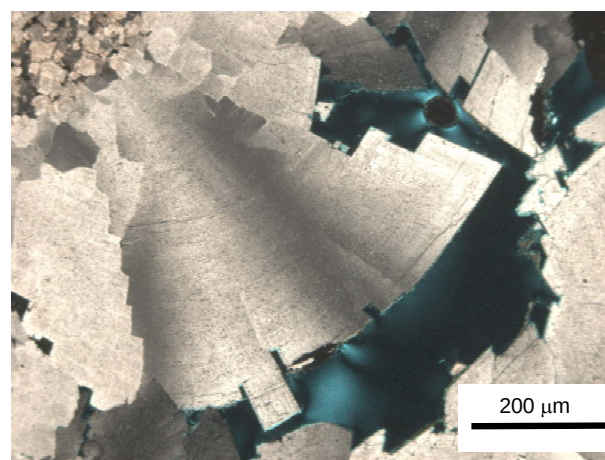
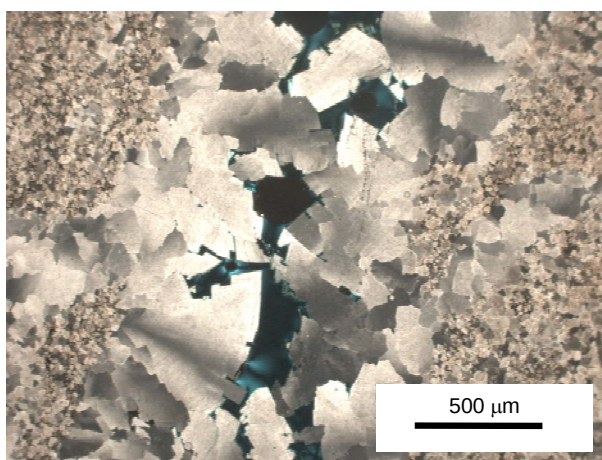
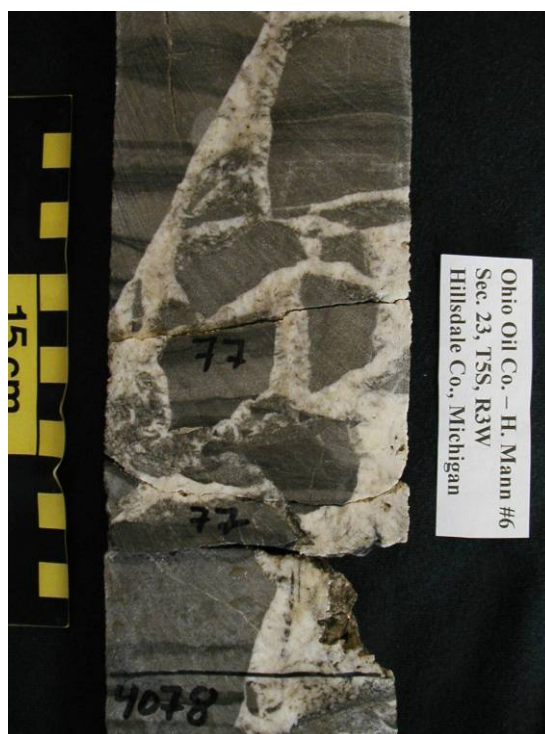


Figure 28. Slab photograph and thin section photomicrographs illustrating hydrothermal dolomite in the Trenton/Black River of Albion-Scipio Field. Note well-developed, classic baroque (saddle) dolomite crystals identified by their curved crystal lattice.



## DISCUSSION: PHASE I AND II - RESULTS FROM TASKS 2 AND 3

### ***Controls on Dolomitization in the Middle Devonian Dundee Formation - Oil Field Scale Structure and the Distribution of Log-Based Dolomite Lithofacies***

#### Introduction

The Middle Devonian Dundee Formation (Figure 29) is a prolific oil and gas producer, initially discovered in 1927, with cumulative oil production to date in excess of 350 MMBOE from over 130 fields in the Michigan Basin (Figure 30). Exploration and production drilling in the Dundee in the 1920's through the 1940's was conducted prior to the advent of modern drilling technology or acquisition of quantitative reservoir characterization data. Furthermore, many Dundee wells were "top set"; that is, drilled to within a few feet of the top of the producing horizon and completed for production with little or no sampling or logging of reservoir rock types. Oil and gas production is known from both primary limestone and secondary dolomite reservoirs in the Dundee.

Limited modern logs and rare core from more recent drilling activity in the Dundee provide an incomplete picture of important reservoir lithofacies, their distribution, and geological origin in Michigan. Geological models for the origin of prolific oil producing dolomite reservoir facies, most common in the central Michigan basin, are of particular interest. A better understanding of the origin, regional distribution, and reservoir scale characteristics of this dolomite reservoir facies should have significant impact on continued exploration for novel and untested exploration targets, and increase the effectiveness of secondary and tertiary recovery operations in the Basin in the Dundee Formation.

On the basis of unpublished work by numerous petroleum geologists in Michigan during the Dundee boom years of the 1930' and 1940's and more recent work, petroleum production is thought to occur from at least three different reservoir lithofacies types (Knapp, pers. comm., Fig. 31a and b):

- 1) Sedimentary Facies-controlled ("early diagenetic") dolomite reservoirs, dominantly in the western third of the central basin such as in the Reed City Member (e.g. Reed City Field).

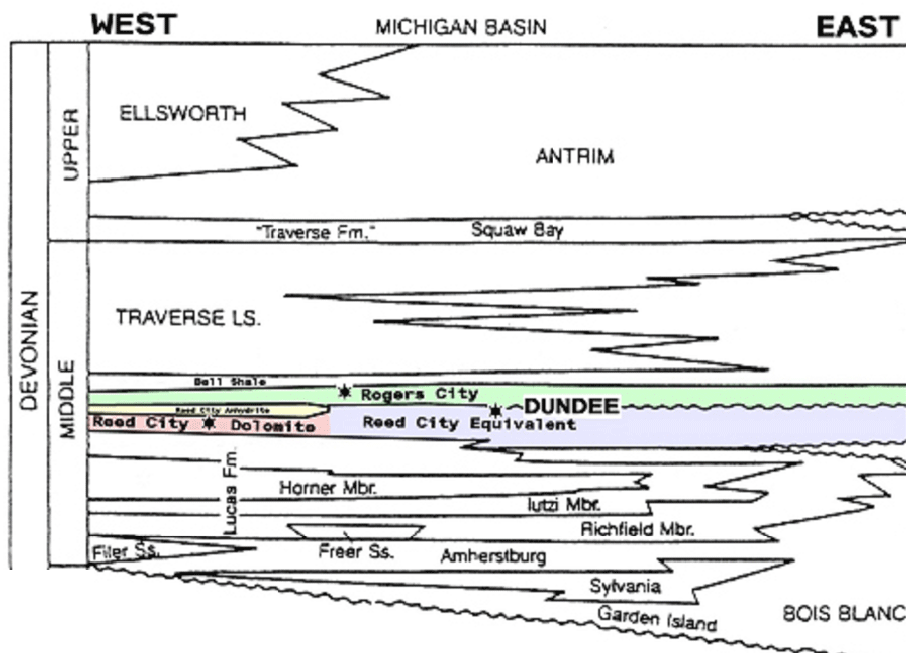


Figure 29. Devonian stratigraphy in the Michigan basin, from Gardener, 1971 (Drafted by Eric Taylor)

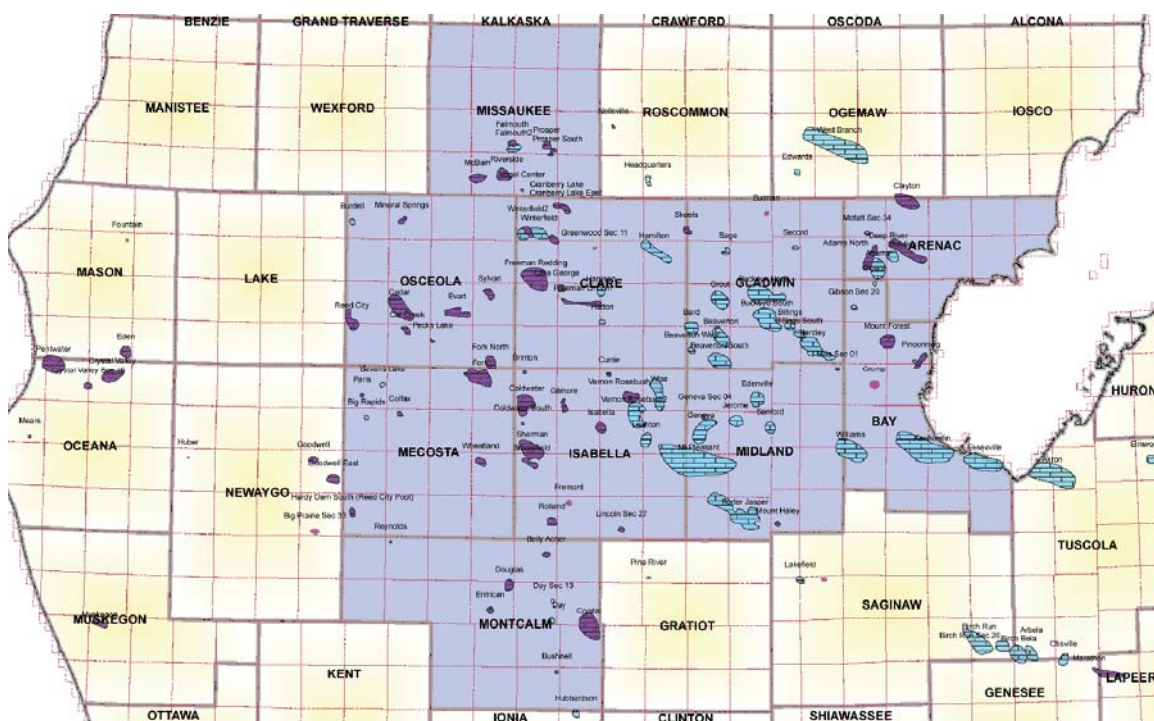


Figure 30. Dundee Formation fields in Michigan. Probable producing lithology indicated by dolomite and limestone symbols



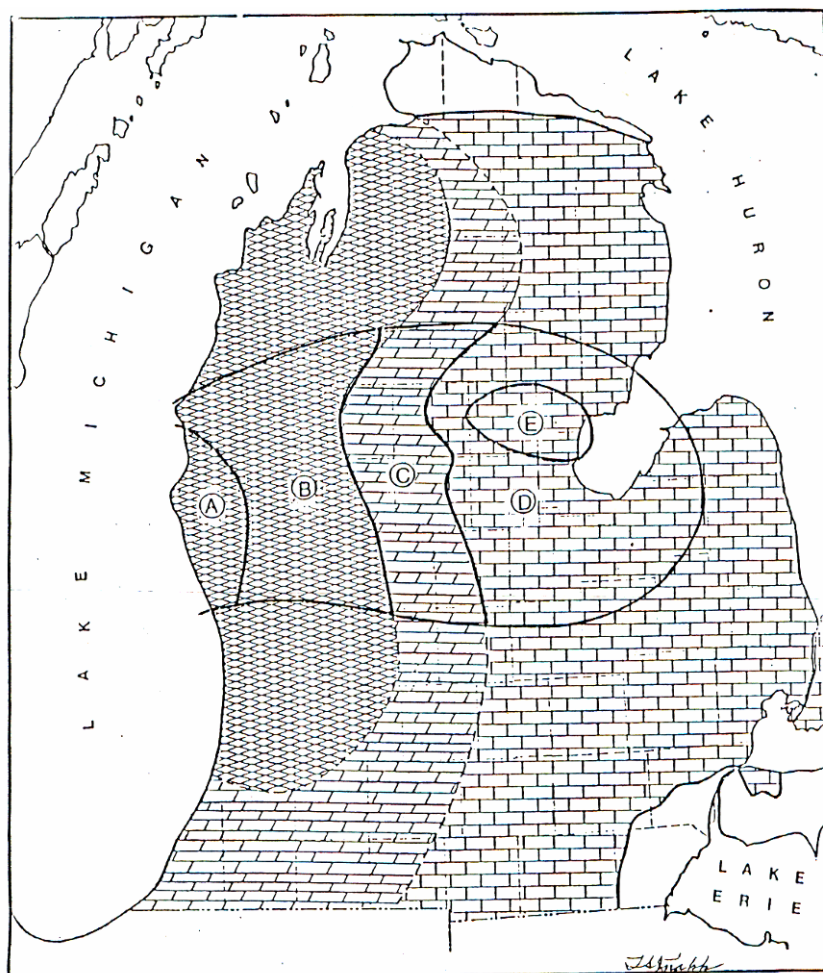


Figure 31a.  
Generalized  
lithofacies and  
spatial distribution of  
reservoir types in the  
Dundee Formation,  
from Tom Knapp,  
personal  
communication

Figure 6. Lithofacies map of Dundee formation:

|  |                                   |
|--|-----------------------------------|
|  | Predominantly limestone           |
|  | Predominantly evaporitic dolomite |
|  | Evaporitic dolomite and anhydrite |

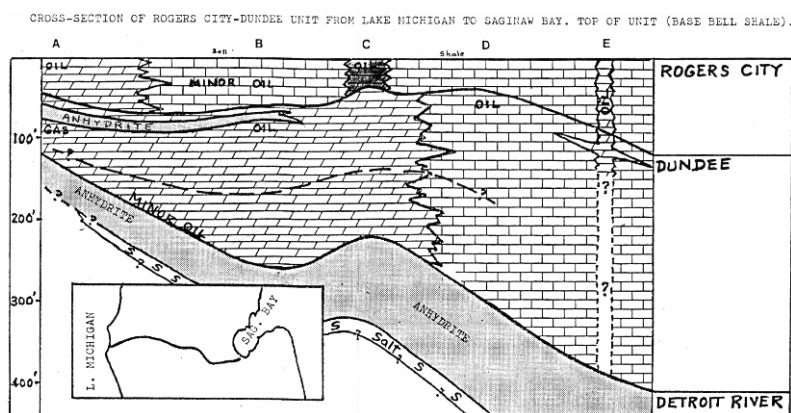


Figure 31b. Generalized  
lithofacies and spatial  
distribution of reservoir  
types from Tom Knapp,  
personal communication.  
"Dundee" unit refers to  
Reed City Member of this  
report.

- A. Rogers City "primary" dolomite. Ex: Pentwater Field - 6.7 million bbl. oil  
Dundee "primary" dolomite. Ex: Pentwater Field - 1.0 billion CF gas
- B. Rogers City limestone. Ex: Reed City Field - minor oil  
Dundee (Reed City) "primary" dolomite. Ex: Reed City Field - 42.0 million bbl. oil
- C. Rogers City "secondary" dolomite. Ex: Coldwater Field - 22.0 million bbl. oil
- D. Dundee limestone. Ex: Porter Field - 49.7 million bbl. oil
- E. Rogers City "secondary" (rift) dolomite. Ex: Deep River Field - 26.9 million bbl. oil  
Dundee limestone. Ex: Sterling Field - 0.43 million bbl. oil

- 2) Sedimentary Facies-controlled limestone reservoirs, mainly in the eastern third of the central basin in the Reed City "equivalent" Member (e.g. South Buckeye, Mt. Pleasant, and West Branch fields).
- 3) Dolomite reservoirs of controversial origin in the upper Dundee/Rogers City Member predominantly in the central basin (e.g. Vernon Field), but also noteworthy both to the far west (e.g. Pentwater field) and east (e.g. Deep River Field). Some fields of this type have been referred to as "dolomite chimneys" due to linear, fracture-related field geometry.

#### Geological Background - Dundee Formation

The Dundee Formation in the Michigan Basin consists of two subsurface members, the Reed City and overlying Rogers City members (Gardner, 1974, see Figure 29). A diverse lithologic assemblage of predominantly fossiliferous and grainy carbonate rocks of the Reed City member overlies dolomicrite, anhydrite and salt of the Lucas formation, deposited in sabkha, peritidal, and restricted lagoon environments (Gardner, 1974, Figure 29). The Reed City Member is most distinct in the western parts of the basin where it consists of restricted marine, peritidal facies, including a prominent anhydrite unit informally called the Reed City anhydrite near the top of the member. The primary depositional facies in the Reed City member basin-wide consists of a shallow marine shelf carbonate assemblage including, grainy carbonate, stromatoporoid reef, and peritidal to supratidal/evaporitic facies that generally shoal upwards to the Rogers City contact (Gardner, 1974; Montgomery, 1986; Curren and Hurley, 1992, Montgomery, and others, 1998). More open marine limestone facies (Reed City "equivalent") are predominant in the eastern basin, while more restricted, dolomitized and evaporite-bearing facies (Reed City Member) occur to the west (Gardner, 1974, Figure 32) suggesting that the Reed City was deposited on a carbonate ramp that transgressed the basin from east to west. Pervasive alteration of grainy and fossiliferous primary limestone facies to dolomite occurs in the Reed City member throughout most of the western parts of the Michigan Basin. The Reed City member comprises a complex primary facies

mosaic that is not well known due to the lack of outcrop and subsurface core material in the basin.

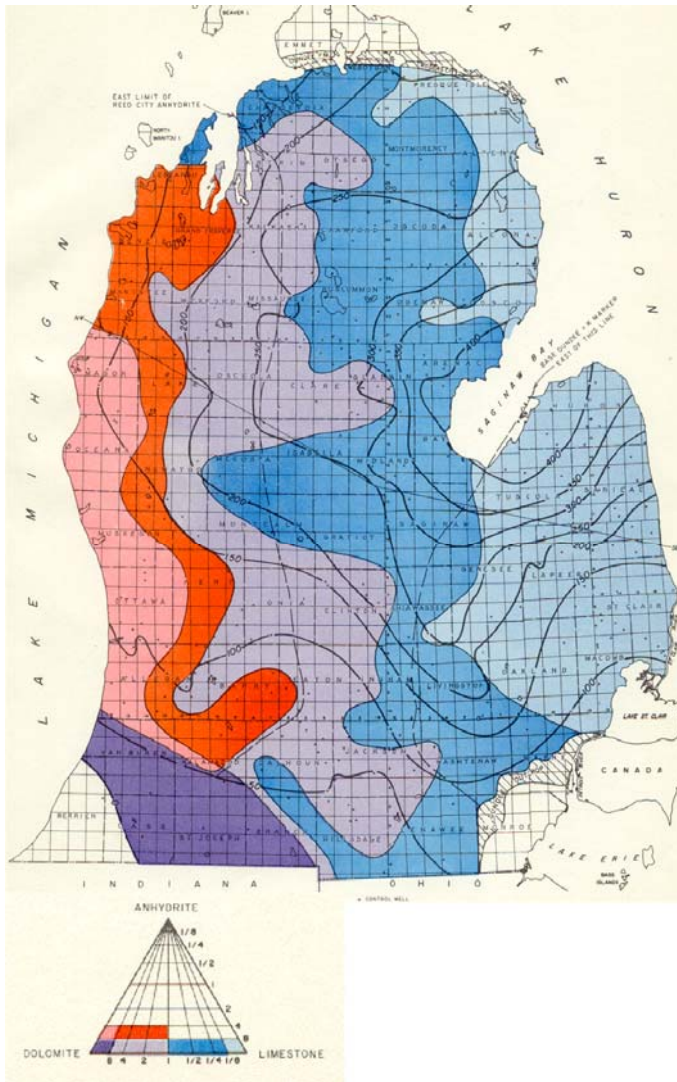


Figure 32. Dundee Formation (Reed City Member) lithofacies and isopach map from Gardner, 1974.

The Rogers City Member overlies various rock types of the Reed City Member at a generally sharp, probable marine flooding surface (as determined in core, Curran and Hurley, 1992) that marks an apparent rapid marine transgression. This contact is not easily recognized in logs, especially in the east, and its origin may vary throughout the basin. Primary depositional facies in the Rogers City, although incompletely known due to limited core, are generally lithologically homogeneous and consist of mostly open marine nodular lime wackestone to mudstone. Biostromal buildups and spatially-related fossiliferous grainstone-packstone deposits in the upper Reed City-Rogers City interval found in several oil fields in the eastern basin, suggest possible syn-depositional structural relief on the sea floor and resulting shoal water facies in some parts of the Michigan Basin during the transition from the upper Reed City equivalent to the Rogers City member (Montgomery, 1986).

#### Dolomite Reservoirs in the Dundee Formation

Some of the most productive (initial production {IP} of 2000-9000 BOPD) reservoirs in the Dundee are found in dolomite facies in the central and western parts of the basin. Some of the largest fields include the Reed City Field (42.9 MMBO); Deep River Field (27.2 MMBO); Coldwater Field (22.3 MMBO); Freeman-Redding Field (17 MMBO); and North Adams Field (9.5 MMBO). Dolomite reservoirs in the Reed City Member are thought by some basin geologists to originate as "early diagenetic" or "facies related" dolomite that is spatially related to the stratigraphic distribution of the Reed City Anhydrite (see Figure 31b and 32) and formed through seepage reflux mechanisms (Jones and Xiao, 2005, Figure 33). This is likely the case in several fields in the western basin (Reed City, most notably). Application of a seepage reflux model to the distribution of dolomite reservoirs in the central basin, however, is strongly dependant on an inferred pinch-out of the Rogers City Member over a proposed "shell bank" or shoal water bathymetric feature that existed in the central basin during the transition between Reed City and Rogers City time (Figure 34). A pinch out of the Rogers City member is interpreted to exist over this "shell bank", and magnesium-rich saline fluids are thought

to have migrated basin-ward and up-section, dolomitizing porous primary limestone facies in the Reed City Member that extended to the top of Dundee Formation at the base of the Bell Shale.

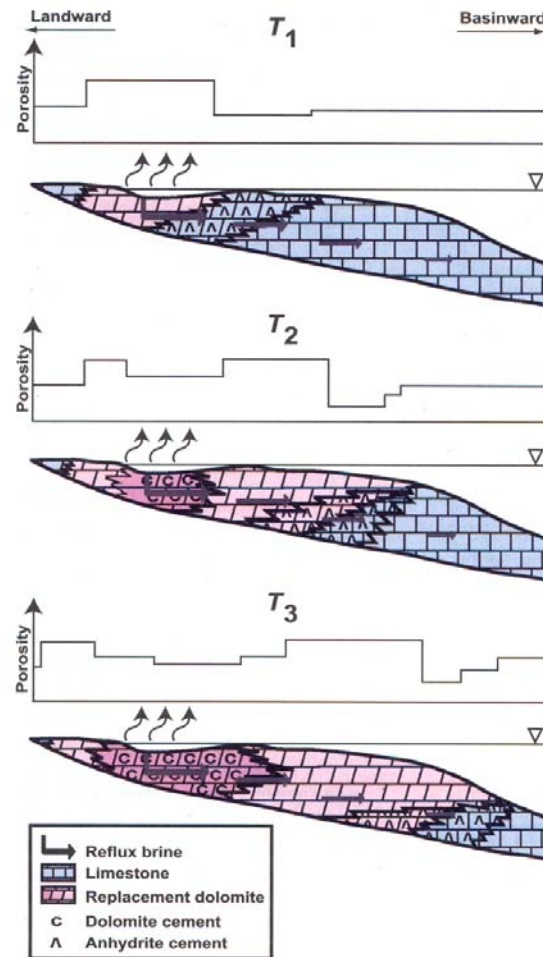


Figure 33. Model for lithofacies distribution in a reflux system, from Jones and Xiao, 2005.

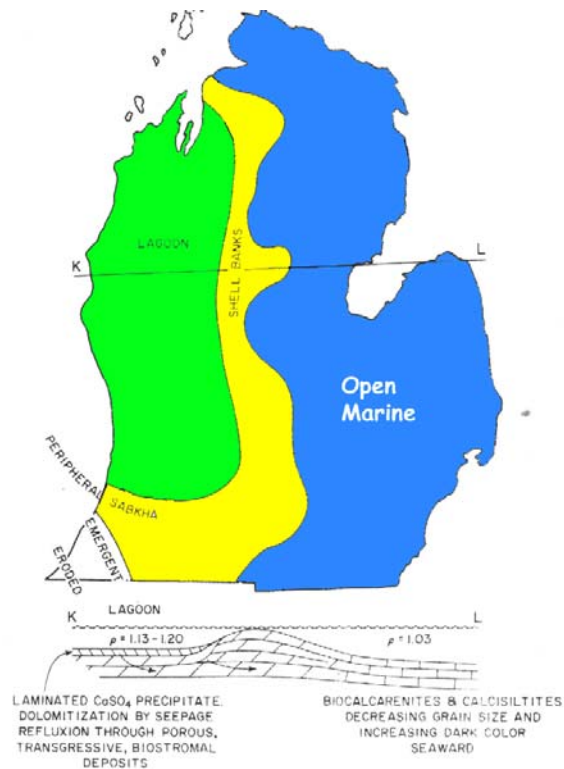


Figure 34. Paleogeographic map and cross section during regressive, Reed City member time, from Gardner, 1974. Note the inferred paleo-bathymetric high in the central basin that is interpreted by many basin geologists to be responsible for pinch-out of the overlying Reed City Member in this area. It is important to note, however, that this “interpretation” has not been substantiated in the literature but is more of a general impression in the basin.

An alternative model for dolomitization of the upper Dundee, Rogers City member in the central basin has been suggested as resulting from fracture-related mechanisms and hydrothermal alteration (see model by Strecker and others, 2005 after Boreen and Davis, 2001, Figure 35). This is a much more feasible hydrodynamic model for dolomitization in the central basin if the upper Dundee originally comprised Rogers City member limestone because primary porosity in this predominantly lime mudstone to wackestone unit would preclude flow of significant dolomitizing fluids through primary permeability conduits. It is a widespread industry perception that such fracture mechanisms are the probable origin of linear “dolomite chimney” fields in the eastern Michigan Basin (e.g. Deep River, Pinconning, and North Adams fields in Arenac and Bay counties, Wood and Harrison, 1999), although this inference is based primarily on anecdotal drillers reports, mud logs and the distinctive linear geometry of the developed fields.

The importance of distinguishing mechanisms for dolomitization in Dundee Formation reservoirs is fundamental to maximizing production of hydrocarbons from this interval. Regional flow systems that delivered dolomitizing fluids to the Dundee, eastward of the probable source of these fluids in the western basin, would result in dolomitized reservoirs that may have significant lateral continuity dependant mainly on the lateral continuity of facies controlled, primary fluid flow conduits. In sharp contrast is the abrupt lateral discontinuity that should exist between primary limestone and dolomite as a result of fracture-controlled delivery of hydrothermal dolomitizing fluids. These distinct mechanisms for dolomitization would result in fundamentally different timing of reservoir and trap development, oil migration pathways, and reservoir geometry relative to structural features.

#### Study Methodology and Objectives

In order to investigate the geological origins and controls on the occurrence of dolomite reservoirs in the Dundee Formation in Michigan, we compiled available digital subsurface geological data (mostly from the Michigan Department of Environmental Quality, Geological Survey Division, MDEQ-GSD) including formation tops, wire-line



logs, and driller's reports. Where appropriate we compiled these data into tabular spatial databases. These spatial databases were used to construct Geographic Information Systems files (both ArcGIS and Petra software),

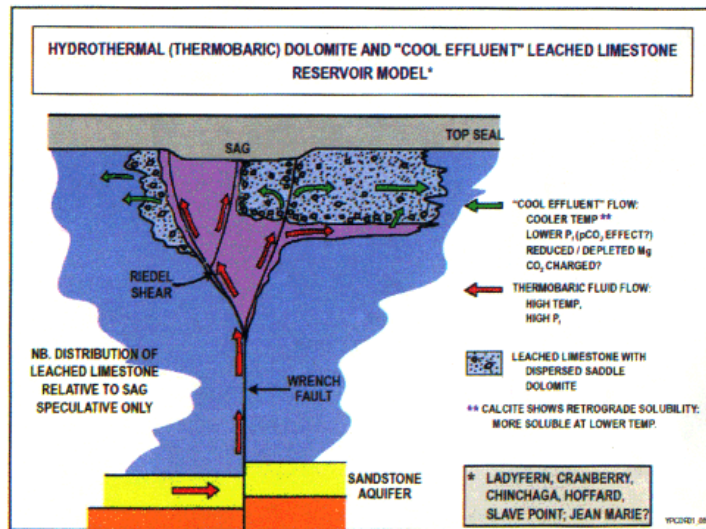


Figure 35. Generalized geometry and lithofacies model for fracture related hydrothermal dolomite reservoirs, from Strecker and others, 2005



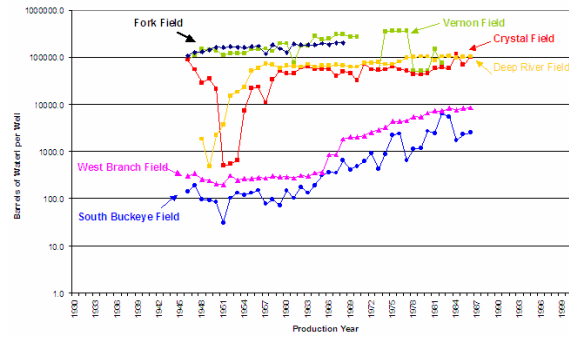
as well as maps and cross sections of important geological properties in the Dundee - including the spatial distribution of dolomite versus limestone in the Dundee Formation relative to structural features and oil field occurrences in the Michigan Basin. Modern wireline logs in digital format were analyzed from over 400 wells. Quality controlled Dundee Formation tops from a data base with more than 25,000 wells (data base originated from J. R. Wood, MTU Subsurface Visualization Lab) were used in the structural mapping. The current availability of large institutional digital subsurface databases, modern digital well logs, readily accessible computational power, and appropriate software provides the opportunity to evaluate correlations amongst general structural and lithologic trends in the Dundee from a wide range of data sources. A limited number of modern litho-density well logs from across the basin provide an important source of information available for investigation of lithology in the Dundee Formation relative to spatial location and structural features in the Michigan Basin subsurface.

#### Dundee Field Water Production Characteristics

Field production characteristics in Dundee Formation fields (Figure 36a and b) define at least two distinct drive mechanisms basin-wide on the basis of water production and pressure decline: 1) bottom water and 2) gas expansion. Figure 36a shows per well water production from representative fields with two distinct trends of 1) relatively high water production per well from inferred bottom water drive dolomite fields (Fork, Vernon, Crystal; central basin dolomite fields, and Deep River; an eastern basin dolomite chimney field) versus 2) relatively low water production from probable gas expansion drive limestone fields (West Branch and South Buckeye; eastern basin limestone fields). Pressure decline is substantially greater in the gas expansion fields and initial bottom hole pressures are generally preserved in the inferred bottom water drive, dolomite fields. A similar breakout of field drive mechanisms is suggested by percent water cut plot (Figure 36b). The increase in water cut later in the production history of the eastern limestone fields is, in part, influenced by secondary recovery water flood projects. Facies related fields (both limestone and dolomite) in the Reed City member typically possess gas

expansion type drive while upper Dundee/Rogers City dolomite fields possess bottom water

A.



B.

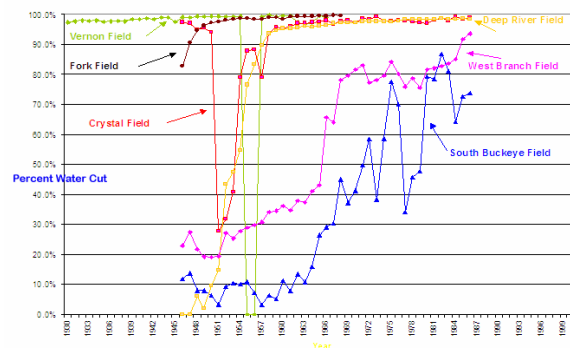


Figure 36a and b. Water production characteristics of Dundee field types.

drives that apparently tap a regional aquifer of substantially greater volume than any individual field.

#### Fracture Related Hydrothermal Reservoirs in Michigan

The significance of fracture-related mechanisms in the origin of important hydrocarbon reservoirs in Michigan is virtually undisputed. Fields in the Ordovician Trenton/Black River formation in Michigan, most notably the Albion-Scipio Field, are classic examples of geometrically complex dolomite reservoirs effectively modeled by the hydrothermal dolomite reservoir (HTDR) concept (Figure 37). Application of models for reservoirs of this generic type in other Michigan formations is controversial but of great current interest for both exploration and enhanced recovery in the petroleum industry.

Structural analysis of Michigan Trenton Black River (Hurley and Budros, 1990) and (more recently) Dundee Formation Fields (Prouty, 1988; Wood, 2003; and Budros, 2004; and others) suggests a relationship between probable reactivated basement wrench faults, anticlines with steep margins, and oil field occurrences. Riedel shear deformation mechanisms including complex flower structure fracture patterns are suggested as important components in the development of these dolomitized fields. The transport of dolomitizing hydrothermal fluids delivered to generally low permeability, primary limestone facies in the Rogers City Member in particular, is thought to result from flow through fractures associated with periodically reactivated wrench faults. Recent petrologic study of central basin, fractured upper Dundee/Rogers City lithofacies (Luczaj, 2001), suggests temperatures of saddle dolomite formation in excess of 120°C in several central basin wells, which is well above ambient burial temperatures.

#### Distribution of Wire-line Log Based Lithofacies in the Dundee Formation

Lithofacies in the Dundee Formation were investigated using an industry standard "quick-look" overlay methodology and digital litho-density wire-line logs. When Neutron porosity and Bulk Density logs are overlain on a common, limestone equivalent porosity scale, changes in lithology can be inferred with depth (Figure 38). Shale, tight and porous

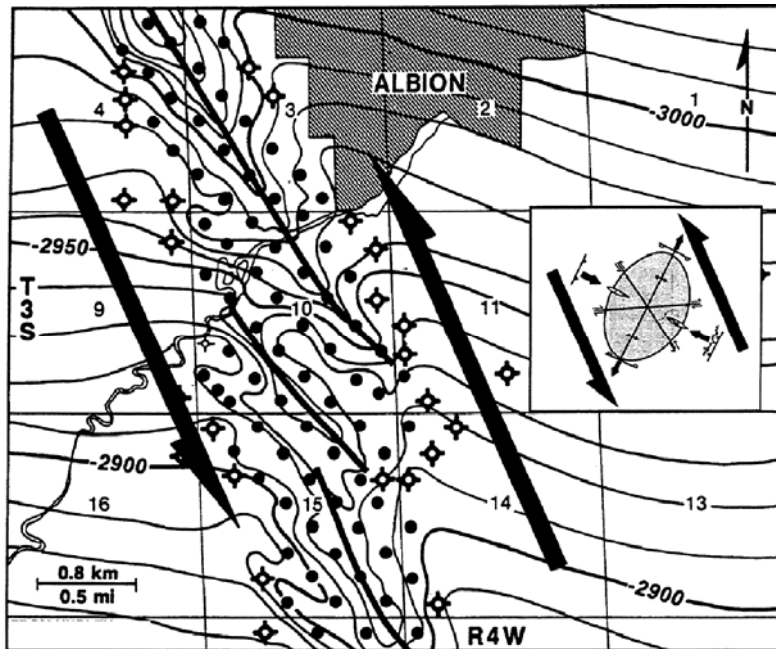


Figure 37. Model for Riedel shear control on the Albion-Scipio fractured dolomite field, Michigan basin, from Hurley and Budros, 1990.

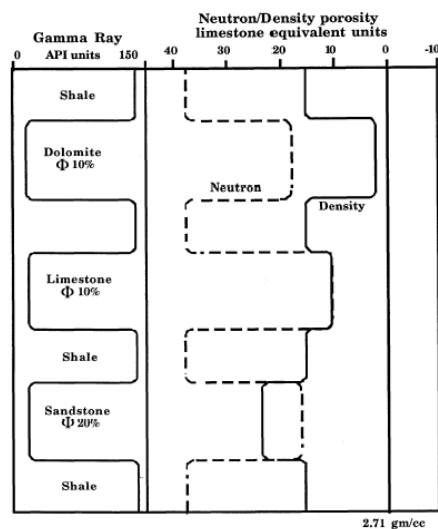


Figure 38. Hypothetical neutron-density overlay patterns for simple log-based lithofacies. The overlay uses a common calibration to an equivalent limestone porosity scale. (From Doveton, 1986).

limestone, dolomite, and anhydrite are relatively confidently identified using this "quick look" overlay method and log-based lithofacies in the Dundee Formation can be interpreted. Since log-based lithofacies are dependant on bulk density properties it is not possible to distinguish dolomite facies with different textural properties or geological origins including overprinted dolomitization.

A wide range of dolomite versus limestone successions are observed throughout the basin (figures 39a-f; in both producing and dry holes) including six distinctive assemblages:

1. No dolomite in the Dundee in the eastern basin (Gladwin Co., Figure 39a; lithofacies assemblage 1)
2. Complete dolomitization of Reed City Member (and associated Reed City "Anhydrite") with no dolomite in the Rogers City member; western-most central basin, (Mason Co., Figure 39b; lithofacies assemblage 2)
3. Complete dolomitization of both Dundee members in the central basin (Isabella Co., Figure 39c; lithofacies assemblage 3)
4. Partial/minor dolomitization of the Reed City (and associated Reed City Anhydrite) and no dolomite in the Rogers City west-central basin (Mecosta Co. Figure 39d; lithofacies assemblage 4)
5. Partial dolomitization (bottom up) of the Reed City and no dolomite in the Rogers City in the central basin (Isabella Co., Figure 39e; lithofacies assemblage 5)
6. Partial dolomitization in the Reed City/Rogers City undivided (top down) and minor associated Reed City Anhydrite in the northwestern central basin (Missaukee Co., Figure 39f; lithofacies assemblage 6).

#### Regional Dundee Structure Mapping and Log-based Lithofacies Distribution

Top Dundee structure was mapped using an extensive tops data base compiled from data made available by James Wood, Michigan Tech, Subsurface Visualization Lab. Ten central Michigan Basin counties were each individually analyzed using geostatistical methodology and industry standard ArcGIS software. Structure contour and grid maps were created for each county through a quality control procedure involving iterative error

analysis. Apparently spurious data points were eliminated from the tops data set by county until root mean square error (RMSE) of measured versus predicted tops in that county was less than 20 ft (the displayed contour interval). Some analyses produced RMSE well below 20' (Figure 40). A ten county composite Dundee top structure prediction map was then produced (Figure 41) that shows a strong preferred northwest-southeast grain and a less pronounced, essentially conjugate, northeast-southwest grain.

The distribution of productive, Dundee dolomite fields in the central basin is typically associated with structural trends with a predominant  $310^{\circ}$  -  $130^{\circ}$  and a conjugate  $40^{\circ}$  -  $220^{\circ}$  orientation. Areas marked by a convergence of these structural grains typically coincide with dolomitized Dundee fields. Small-scale spatial variation and complex geometric patterns of dolomitization in several counties supports local rather than regional dolomitization in the upper Dundee due to fracture-related fluid migration pathways (e.g. Figure 42). Dolomitization patterns in the lower Dundee, Reed City Member have wider spatial distribution but may represent a complex interplay between primary facies controlled dolomitizing fluid conduits and fracture related conduits. If the geometrically complex dolomitization in the upper parts of the Dundee occurs in what was regional tight primary limestone of the Rogers City, this relationship is almost certainly the result of fracture related hydrothermal dolomitization associated with geometrically complex matrix fracturing.

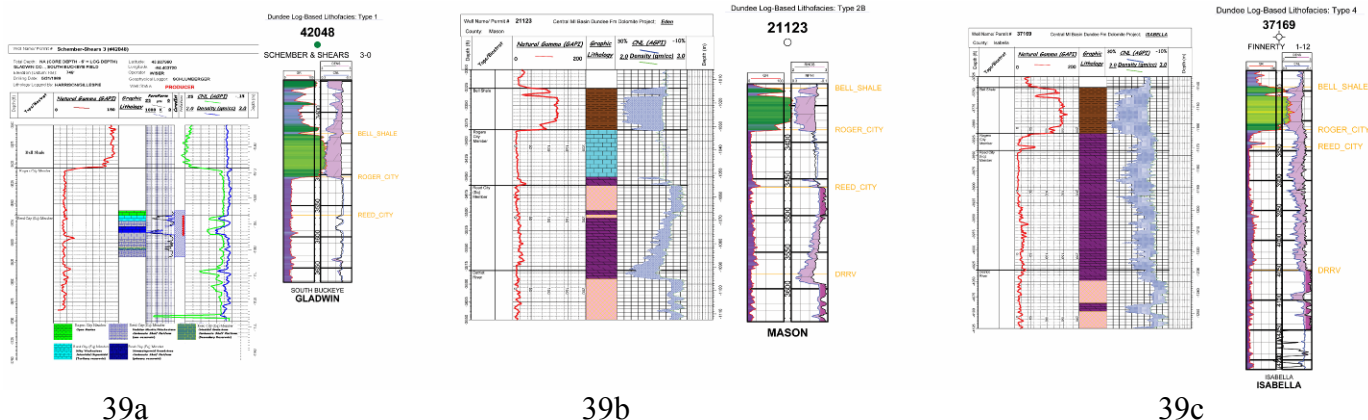


Figure 39a,b, and c. Litho/density log-based Dundee Formation lithofacies assemblages 1, 2, and 3 respectively. See text for discussion.

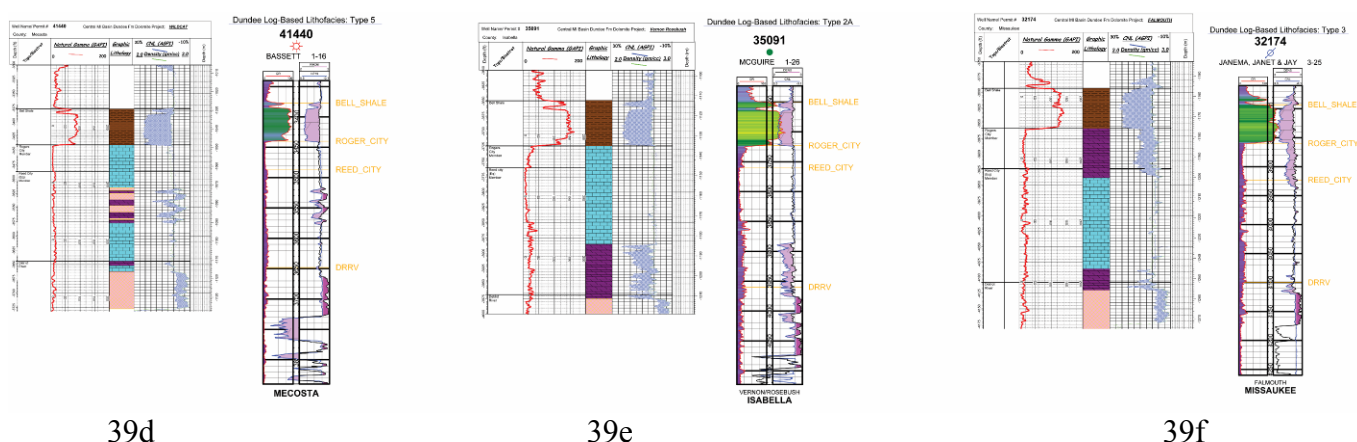


Figure 39d,e, and f. Litho/density log-based Dundee Formation lithofacies assemblages 4, 5, and 6 respectively. See text for discussion.

### Field Scale Structure Mapping and Log-based Lithofacies

Field scale structural mapping of top Dundee with high quality, wire-line log controlled well data indicates a geometrically complex spatial correlation between subtle structure and reservoir facies variations in the Upper Dundee/Rogers City Member. High resolution structure contour mapping (5'-10' contour interval) based on high quality top and lithofacies picks, suggests top Dundee surface irregularities that are best interpreted as faults with small throw of generally less than tens of feet in two Dundee fields, Winterfield (Clare Co., Figure 43a) and Vernon-Rosebush (Isabella Co, Figure 43a). In

the Winterfield field a transition from dolomitized upper Dundee/Rogers City to undolomitized upper Dundee occurs within less than 0.3 mi. The alignment of wells with dolomitized upper Dundee/Rogers City is in accordance with a  $40^{\circ}$ -  $220^{\circ}$  orientation superimposed on an overall  $310^{\circ}$  -  $130^{\circ}$  trend for the field. A nearby extension of the Winterfield field (not shown) with a linear,  $310^{\circ}$  -  $130^{\circ}$  field orientation and probable fracture-related Dundee production (Chittick, 1996).

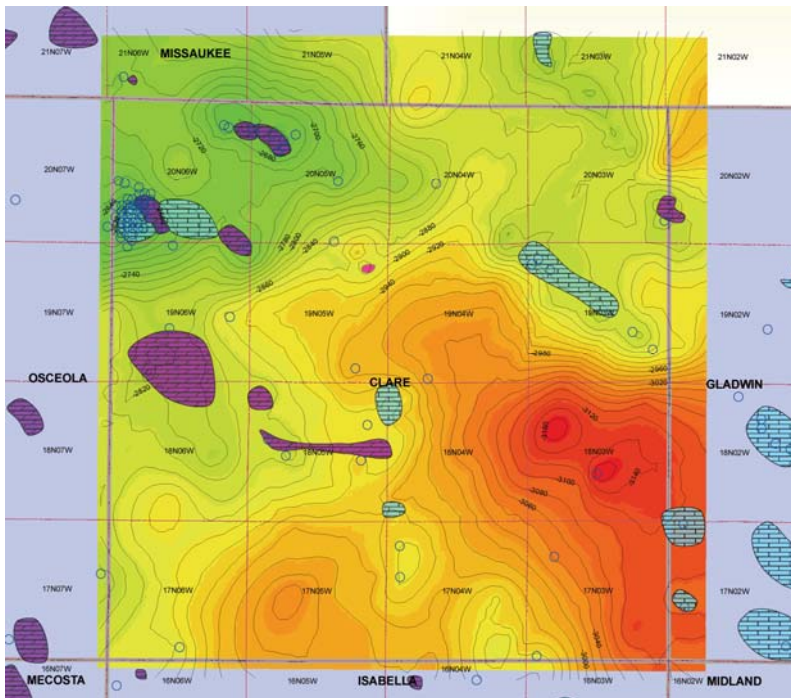


Figure 40. Example of central Michigan basin county structure map on top Dundee Formation with superimposed Dundee fields and inferred reservoir lithofacies.



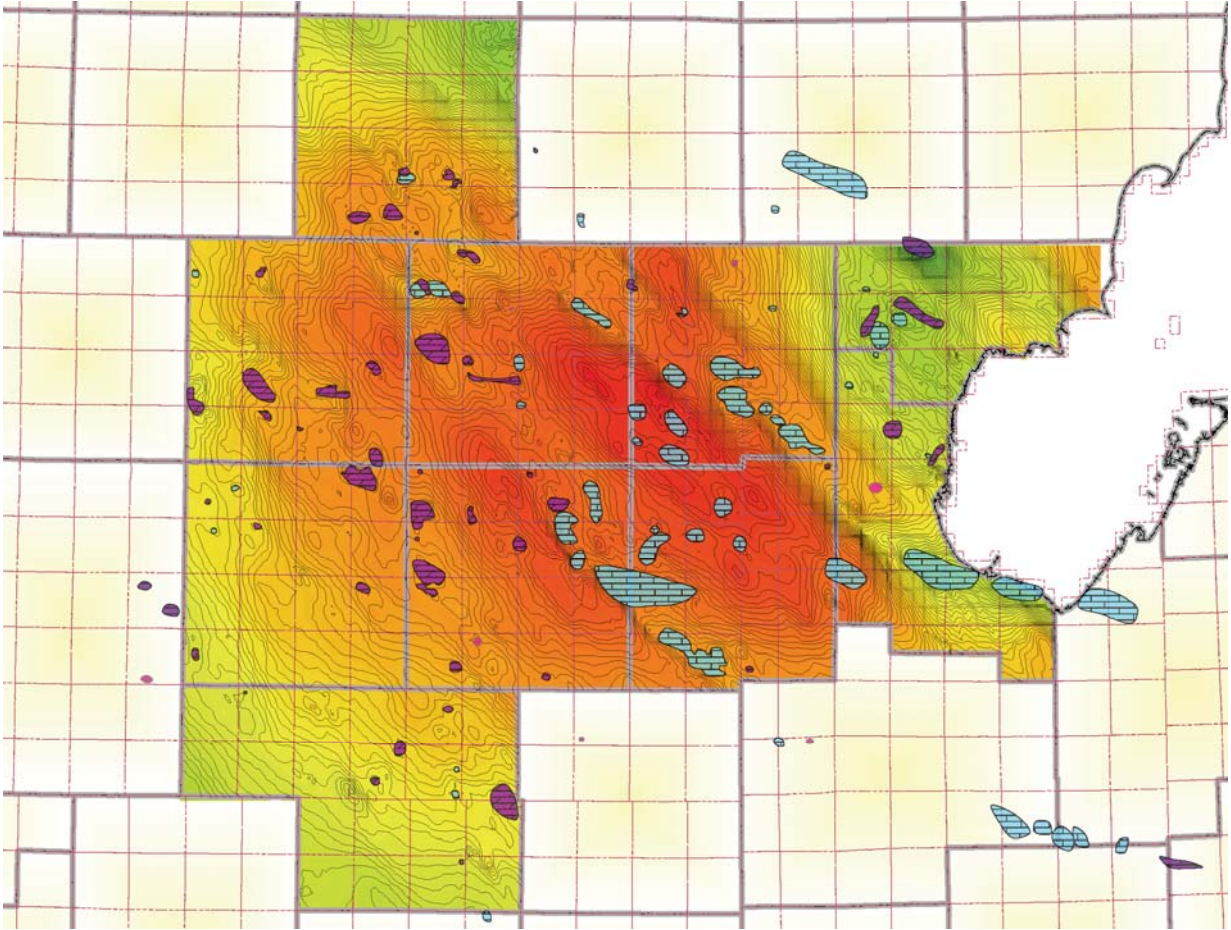


Figure 41. Michigan central basin 10 counties structure map on top Dundee Formation with superimposed Dundee fields.

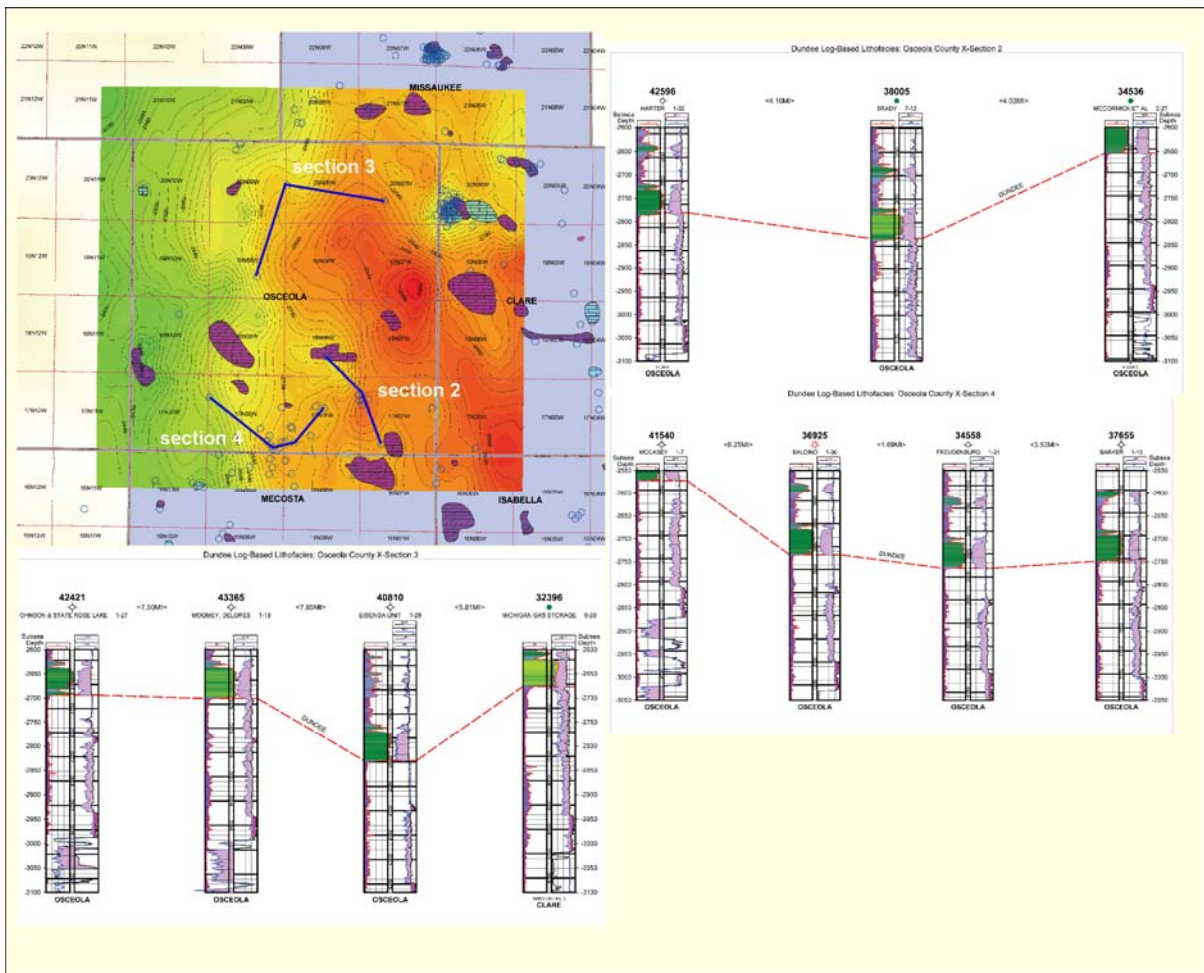


Figure 42. Osceola County structure map on top Dundee and litho-density “quick look” lithofacies assemblage cross-section. Small-scale spatial variation and complex geometric patterns of dolomitization supports local rather than regional dolomitization in the upper Dundee/Rogers City due to fracture related fluid migration pathways.

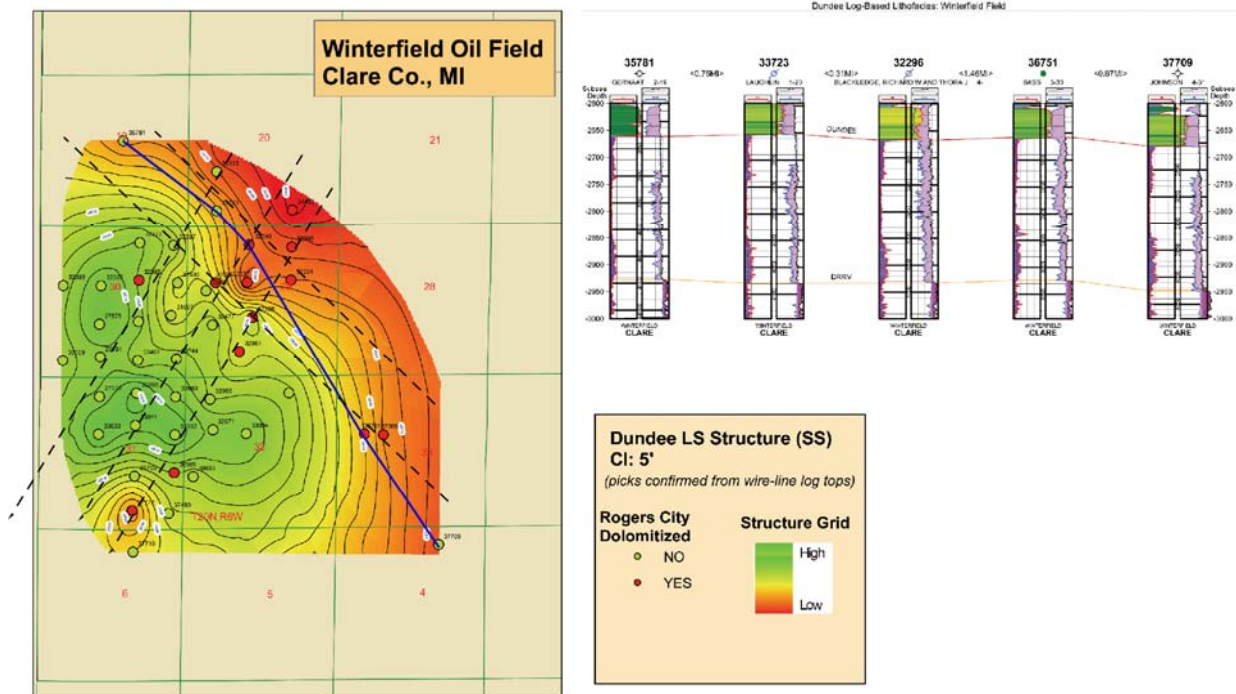


Figure 43a. High resolution (5' contour interval) structure contour map of the Winterfield field, Clare Co. Note small spatial scale variation in upper Dundee dolomite distribution associated with interpreted small throw displacement faults (dashed lines) with  $\sim 310^\circ$ - $130^\circ$  and  $40^\circ$ - $220^\circ$  orientation.

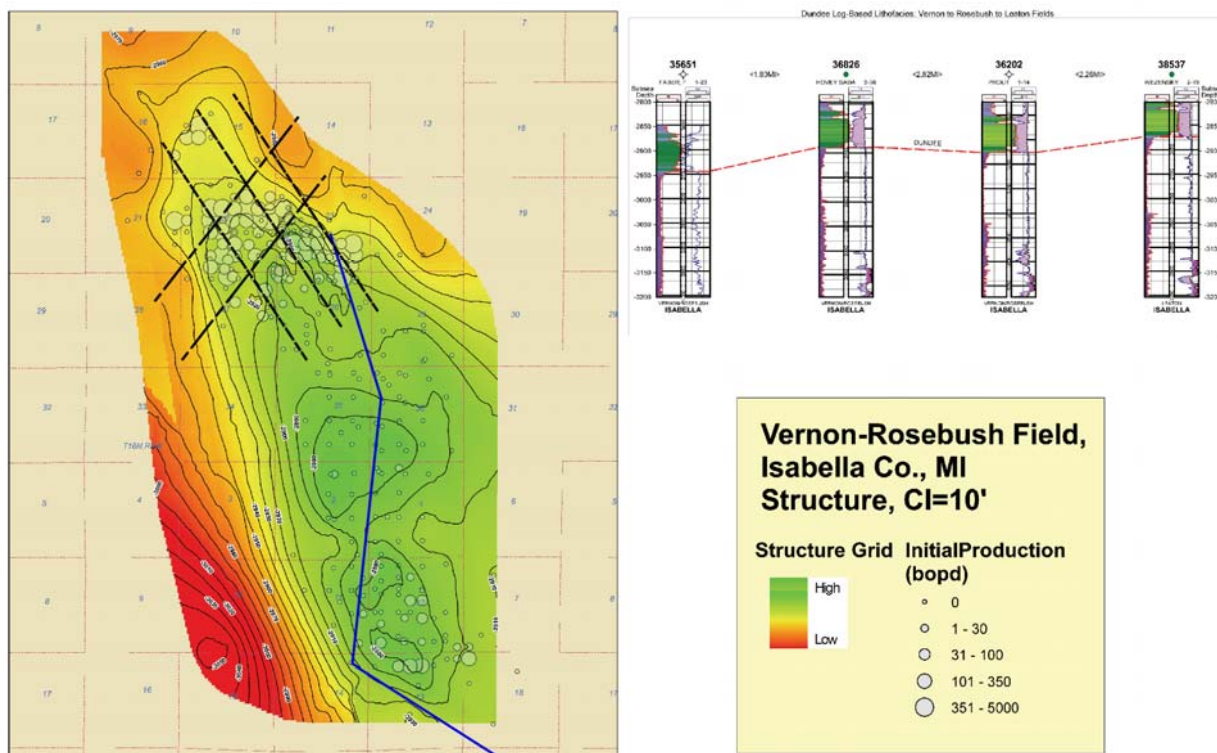


Figure 43b. High resolution (10' contour interval) structure contour map of the Vernon-Rosebush field, Isabella Co. High initial production in wells in the Vernon (northwest, down structure) portion of the field coincide with interpreted small throw displacement faults (dashed lines) with  $\sim 310^{\circ}$ - $130^{\circ}$  and  $40^{\circ}$ - $220^{\circ}$  orientation. One litho/density well log in the Vernon area (Faber well) suggests complete dolomitization of the entire Dundee section while wells to the southeast (Rosebush area) are mostly limestone coincident with relatively simple, open structural style.



A similar, relationship between small scale structure and the inferred distribution of Dundee dolomite reservoirs is interpreted in the Vernon-Rosebush field of Isabella Co. Small scale structural deformation of the top Dundee surface is mapped in the north-northwest extension of the Vernon-Rosebush structure (Figure 43b). In the down dip north and west portion of the Vernon-Rosebush field, sparse log control can be interpreted to indicate complete dolomitization of the Dundee associated with high initial oil production rates. The IP's (to several thousand BOPD) are comparable to many central basin Dundee fields that are probably fracture-related. Less than 2 miles to the south and east, which is up structure, the Dundee contains limestone from bottom to top.

Interpreted faults and related fractures apparently propagated to the Dundee-Bell Shale contact in places throughout the central basin (and apparently elsewhere in the basin) and may have provided geometrically complex secondary conduits locally for dolomitizing fluids that permeated upwards through the otherwise regional tight limestone of the upper Dundee/Rogers City.

#### Implications for Petroleum Geology in Michigan and other U.S. Hydrocarbon Basins

Our mapping efforts have important implications for both new exploration plays and improved enhanced recovery methods in the Dundee and Ordovician Trenton/Black River "plays" in Michigan – i.e. the interpreted fracture-related dolomitization control on the distribution of hydrocarbon reservoirs. In an exploration context, high-resolution structure mapping using quality-controlled well data should provide leads to convergence zones of fault/fracture trends that are not necessarily related to structural elevation. Acquisition of high-resolution seismic data in areas with prospective structural grain may provide decreased risk for fractured Dundee or Trenton/Black River exploration drilling.

Application of fracture models to reservoir characterization in secondary and tertiary recovery projects in existing fractured Dundee or Trenton/Black River fields, may result in substantial additional recovery from fields that typically had low (<30%) primary recovery factors. Careful consideration of fracture orientations and water coning problems should decrease risk in enhanced recovery activities.

Undoubtedly more complex, hybrid reservoir types exist in dolomitized lower Dundee/Reed City Member lithofacies in the central basin. This is anticipated as a result of complex, early fluid flow through primary limestone pore conduits within a reflux system, in addition to fracture generated pathways in fault/fracture convergence zones.

### ***Silurian (Niagaran) - Petrophysical Facies and Image Analysis of Pore Networks***

Classification of petrophysically-significant facies and characterization of pore networks utilizing image analysis techniques can provide an important tie between sonic velocity values and permeability in carbonate rocks. Most of this work was scheduled to be performed in Year 3 of the originally funded project, and as such, only a general introduction is presented here.

#### **Petrophysically Significant Lithofacies**

From basic core analysis, six petrophysically significant facies have been chosen based on rock fabric and related pore architecture versus depositional environment. These six facies are:

**P-1: Muddy Bioherm**

**P-2 and P-3: Reef Core (framework reef and internal reef detritus)**

**P-4: Capping Skeletal Wackestones, Packstones, and Grainstones**

**P-5: Laminated Mudstones**

**P-6: Cyanobacterial Mats**

#### **Muddy Bioherm (P-1)**

This is a mud dominated facies often associated at the initiation of reef growth in the “mud-mound” stage. This facies can be further divided into two lithofacies; a styolitic

mudstone with lithoclasts and <10% grains and another that is a mudstone to wackestone containing stromatactis. Porosity and permeability within the muddy bioherm is relatively low compared to the other facies. The little porosity that exists is due primarily to molds and intercrystalline pore types. Minor solution enhancement along stylolites and microfractures produce slightly higher porosity values.

A subset of the mud-rich facies is a stylolitic mudstone with lithoclasts and minor skeletal grains that is likely a part of the Lockport formation, below the actual Pinnacle reef. The stylolites are wispy, indicative of the primarily mudstone matrix. The lithoclasts add to the nodular look of this facies. Gill (1977) suggested that the elliptical shape of nodules and the presence of dark argillaceous material around the nodules were a result of compactional forces resulting from the burial of heterogeneous sediment. He recognizes this fabric in the Belle River Mills field in St. Clair County. Most Niagaran reef cores do not reach down to the Lockport Formation and thus it is only observable in a few wells.

A mudstone to wackestone lithofacies containing stromatactis marks the gradual transition from off reef to the biohermal core. This facies contains more skeletal grains than the aforementioned mudstone. The stromatactis feature is characterized by a flat bottom with an irregular upper surface, creating a void that is often filled with cement or internal sediment. The origin of stromatactis is still problematic. Bathurst (1980) suggested that these features in carbonate mud mounds are a result of cement and sediment fill of cavities which have developed between submarine-cemented crusts. Recently, however, it has been suggested that it is actually a type of fenestral porosity caused by rapid, uninterrupted sedimentation and the subsequent decay of organics that

leave a characteristic pore shape that may be later filled with cements (Hladil, 2005). Nonetheless, several studies have indicated stromatactis is a well known feature of carbonate mud mounds from around the world (Krause et. al, 2004).

### **Reef Core (P-2 and P-3)**

This facies is characterized by large skeletal organisms, little mud, and cavities filled with skeletal debris. This facies is quite often interbedded with skeletal wackestones, packstones, and grainstones. Based upon their coexistence with reef framework (vertically integrated), these facies are interpreted as skeletal detritus that occurs within cavities of the framework reef, and as such are differentiated from the wackestone to grainstones that occur at the top of a reefal succession. The dominant pore types in the reef core facies include vugs, molds, and intraparticle pores. Anhydrite and salt occlude pores in some reefs.

A lithofacies of **reef framework (P-2)** is used when the rock is primarily composed of reef building organisms, such as stromatoporoids, tabulate corals, and algae (Gill, 1975 and 1977) or microbialites. Framebuilders in growth position within reefs typically only make up about 30% of the reef of the actual reef core, with the rest of the reef composed of detritus (Gill, 1975; Wood, 1999). These organisms produced the wave-resistant framework of the reefs. The characteristics of this facies are vuggy porosity, cm-dm scale reef cavities, cavity fills of cement and/or internal sediment, and intraparticle porosity if corals are present. In addition, there is little to no mud in this facies except inside cavities.



The **reef framework with detritus (P-3)** facies consists of reef framework with abundant detritus. Forty to ninety percent of the rock volume of a reef typically consists of rubble, sediment, and voids (Wood, 1999) so it is important petrophysically to include a facies which includes a mix of reef frame builders with detritus. This facies designation was used when there is more than 25% detritus intermixed with reef framework organisms. The detritus consists of sand to silt sized skeletal debris from the reef framework or associated reef dwelling organisms. Pore types associated with this facies are moldic, interparticle, vuggy, and intraparticle.

The P-3 facies has tentatively been subdivided into a mud rich facies (wackestone to mud rich packstone) and a grain rich facies (mud lean packstones and grainstones). The mud dominated wackestones to packstones within the reef contain approximately 10-30% skeletal grains that are generally sand to silt sized, but locally range up to cm scale. The most common pore types observed in this facies are moldic and vuggy pores. The molds can often be solution-enhanced and might be classified as a vug if the origin of the void space cannot be determined. The wackestones to packstones can occur anywhere within the reef, but are commonly found near the base, interbedded with the reef framework, and following the muddy bioherm facies stratigraphically.

The mud-lean packstone to grainstone within the reef is a grain supported facies. Allochems consist of skeletal, grapestone, or peloidal grains. Grain size varies from sand to silt sized, but can be as large as one to two centimeters. These larger grains tend to occur near the base of the reef in the mud mound-reef transition zone. Moldic and interparticle porosity dominate this facies.

#### **Capping Skeletal Wackestone to Grainstone (P-4)**

The P-4 wackestone to packstone facies occurs stratigraphically either at the base of reefs or as a capping unit and is therefore interpreted as not being associated with reef growth. Muddier facies (wackestones) occur often at the end of the mud-mound stage and during the transition into reef growth and may mark a significant flooding interval. The common pore types in this facies include molds and solution-enhanced molds or vugs.

#### *Packstone to Grainstone*

This facies, like the aforementioned facies, is not associated with the reef growth but interpreted as a grainstone shoal on top of the reef. Compositionally this is a grain dominated facies composed of skeletal, peloidal, or grapestone grains. Most often, these grainstone caps are comprised of skeletal grains, although a few cores have shown the occurrence of peloids and grapestones. Grapestones may indicate a transition from the shelf, behind the reef, into the tidal flat environment. Moldic and interparticle porosity dominate this facies.

#### **Laminated Mudstone (P-5)**

This facies consists of laminated to locally burrowed mudstones with rare skeletal fragments. The lack of bioturbation is indicative of a restricted environment hostile to benthic infauna (hypersaline and/or low oxygen levels). Porosity and permeability is consistently poor with minor intercrystalline porosity associated with the dolomitized matrix.

## **Cyanobacterial Mats (P-6)**

Most often, this facies occurs at the top of the reef sequences and is regionally known as the “supratidal island stage.” It is easily recognized on gamma-ray logs as a high intensity reading compared to the facies below (due to increased organic material) and by density contrasts related to the abrupt transition from pure carbonate to interbedded anhydrite with carbonate. Mudcracks and laminations are key sedimentary structures that help in addition to identifying this facies in core.

Variations within the facies include ripped up cyanobacterial mat with a wackestone to packstone matrix, laminated cyanobacterial mat, cyanobacterial mat altered with evaporites, and evaporites interbedded with a mudstone. Even though there are several subdivisions, there appears to be no petrophysical significance between the various units. Minor fenestral porosity, produced by the decay and degassing of cyanobacteria and other organics through the sediment, is present in this facies.

### Image Analysis

Porosity in reservoir rocks consists of pore types whose size and shape are controlled by the depositional fabric and post-depositional processes (McCreesh et al., 1991). Most of the image analysis studies currently in the literature have been performed on sandstone reservoirs (Stout, 1964; Ehrlich et al., 1991). This is due in large part to the complexity of pore geometries and pore architecture in carbonate rocks relative to other sedimentary rocks (Anselmetti et al., 1998). This complexity can be attributed to the high diagenetic potential of carbonate rocks. Physical properties (e.g. sonic velocity) in carbonates are a function not only of the total amount of porosity, but the pore geometries and pore architecture as well (Anselmetti et al., 1998).

In fluid reservoirs, permeability depends on the three-dimensional connectivity of

the pore network (Ehrlich et al., 1984). While viewing the three-dimensional aspects of a pore network is limited to analytical techniques such as CT scans, it has been shown that a two-dimensional slice, or thin section, has a predictable relationship to the three-dimensional network it was extracted from (Ehrlich. 1984). As such, to further evaluate the pore network in these rocks, 23 thin sections were analyzed using various image analysis techniques utilizing the software program ImagePro Plus (Figure 44).

Images of the thin sections were obtained with a Leica M240 Petrographic microscope at 8x magnification with a Leica DC480 12V Camera. Two images were analyzed per thin section; one of the upper portion and one of the lower portion of the thin section. Other studies (Anselmetti et al., 1998; Ehrlich et al., 1991) suggest that several images should be taken at several different magnifications, but for the purpose of this study, the macroporosity was of main interest and could be analyzed accurately at the 8x magnification.

Thin section images were then imported into the Image-Pro Plus program. Color cube based color segmentation was used to separate the pore space from the solid space. Other studies have binarized pore phases and matrix using blue and gray tones (Anselmetti et al., 1998), but have also suggested that picking colors by color cube color segmentation is also effective, albeit with slightly reduced accuracy relative to the binarized technique. Common parameters such as pore size, pore shape, and abundance was calculated from the program. Of these parameters, the pore shape/roughness parameter, combined with the distribution of pore sized within a rock, provides the most information about the three-dimensional pore network.

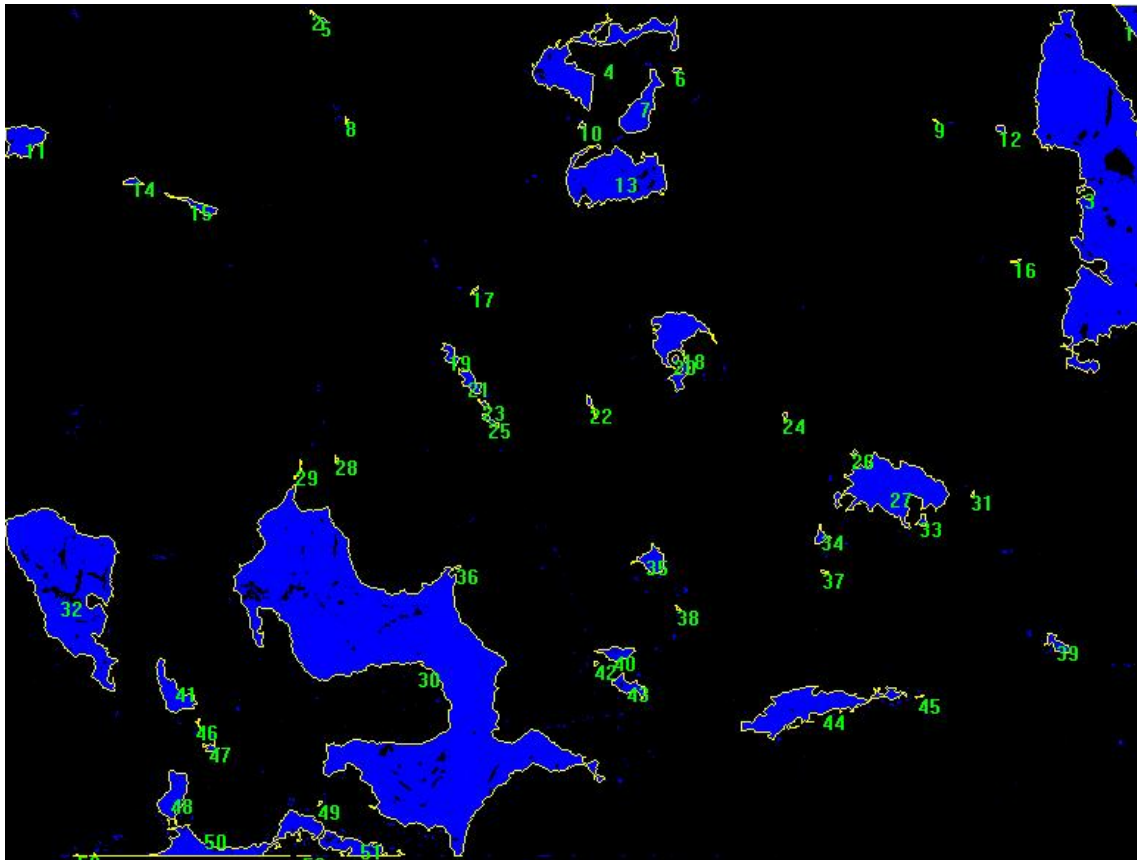


Figure 44. Photomicrograph illustrating pore geometries as highlighted in image analysis. Various calculations of pore size, roughness, length/width etc can be calculated with Image Pro Plus, allowing for characterization of pore architectures and comparisons with permeability values. Much of this work was scheduled to take place during Year 3 of the project.

The roundness parameter from the image analysis program is a ratio of the pore perimeter to the pore area:

$$\text{Roundness} = \text{Perimeter}^2 / (4 * \pi * \text{Area})$$

However, Anselmetti et al. (1998) suggest using a similar roundness/shape parameter:

$$\gamma = \text{Perimeter} / (2 * \sqrt{(\pi * \text{Area})})$$

For the purpose of this study the gamma ( $\gamma$ ) value is primarily used to describe the pore shape/roughness. For pores that yield a value closest to 1 (the lowest ratio), the more rounded the pore is, and values higher than 1 indicate a more elongated or irregular shaped pore. An interparticle pore between perfectly spherical grains will have a  $\gamma$  value of 1.9 whereas cracks may have values greater than 5 (Anselmetti et al., 1998). The more branching pores, the more likely they are to form a connected pore network (Anselmetti et al., 1998).

Thin sections from all 5 wells were grouped by facies. Plots of pore size and gamma were then made to evaluate the pore shape and size distribution. In addition, plots were made of pore area and roundness to compare the results of the two different equations used. These plots were then used to determine the cause of the variable permeabilities that occur within each facies.

#### Initial Image Analysis Results (By Facies)

In general, the reef core (P-2), reef core with detritus (P-3) and the capping grainstone intervals (P-4) exhibit the best porosity and related permeability. The gamma

value in these facies tends to reflect more irregularly shaped pores as opposed to rounded pores. Some of the grainstones on top of the reef interval exhibit the best reservoir properties; porosity is high and the pores are irregular, but still are dominated by moldic pores. Some of the porosity and permeability variability within the facies can also be attributed to microporosity in the fine crystalline dolomite matrix. This explains some of the more mud dominated fabrics having high permeability but low porosity. In order to accurately characterize the microporosity, analysis with a scanning electron microscope (SEM) would be needed as was planned for Year 3 of the project. Initial results are summarized in Figures 45-58.

#### **Facies P-2: Reef Core**

Three main petrophysical differences that exist in this facies (from looking at whole core data initially)

##### **(1) High Porosity and High Permeability**

- Miller-Fox has porosity from 2 to 15% with permeability from 0.2 to 10,000 md for this facies
- Umlauf has porosity ranging from 6 to 17% with permeability from 1 to 1,000 md for this facies

##### **(2) Marginal Porosity and Marginal Permeability**

- Charlton (northern trend) has porosity ranging from 5 to 20% with permeability ranging from 0.5 to 80 md
- Fugere (southern trend) has porosity ranging from 1 to 7% with permeability from about 0.5 to 90 md

##### **(3) Low Porosity and Low Permeability (mostly salt occluded pores)**

- Highlander (southern trend) has porosity from 0 to 2.5% with permeability around 1 md
- The Miller-Fox and the Highlander were chosen for image analysis because they represented the most diversity in the facies
- Image analysis of the Miller-Fox showed this facies to have porosity ranging from 2.3 – 1.1%
- Image analysis of the Highlander showed this facies to have a porosity range from 4.3 to 5.1%
- The majority of the pores are small mesopores (Choquette and Pray, 1970). The main pore types are fracture, vuggy, and moldic
- Pores 150 microns or larger, in diameter, tend to increase in branching – these tend to be the fractures and solution enhanced vugs
- Pores less than 150 microns, in diameter, tend to take on a more rounded appearance and are pin-point vugs and moldic in origin
- Miller-Fox pores less than 150 microns actually are more branching probably because this pore type is intercrystalline
- Gamma (roundness) values for this facies can range from 1.3 to 1.5, making this a more permeable facies in some areas
- What makes this facies more permeable can be the dolomitization of the marine cemented reef, creating intercrystalline porosity, the abundance of detrital material, and the presence of fractures (either through burial and/or due to the brittle nature of the marine cement and early diagenetic fracturing).

### **Facies P-3: Reef Core with Detritus**

Three main petrophysical differences that exist in this facies (from the initial evaluation of whole core data)



### (1) High Porosity and High Permeability

- Miller-Fox: Porosity ranges from 3 to 15% with Permeability ranging from 0.1 to 100,000 md
- State Charlton (northern trend): Porosity is from 5 to 15% and Permeability ranges from 0.1 to 100 md for facies 2B
- Umlauf: Porosity ranges from 2 to 10% and Permeability ranges from 0.2 to 100 md for facies 2B

### (2) Marginal Porosity and Marginal Permeability

- Fugere: Porosity ranges from 3 to 10% and Permeability ranges from 0.5 to 11 md for facies 2B

### (3) Low Porosity and Low Permeability

- Highlander: Porosity ranges from 0 to 3% with Permeability ranging from 0.8 to 5 md for facies 2B. Porosity is occluded by salt

The focus to date has been on the high and marginal porosity values because they are the most frequently occurring values in the cores.

### *Marginal Porosity and Permeability*

- Image analysis calculates a porosity of 1.8 – 4.2% in the Charlton well
- Image analysis calculates a porosity of 2.7 – 2.75% in the Fugere well
- Image analysis calculates a porosity of 3.2 – 5.6% in the Miller-Fox well
- 75-90% of the pores are well rounded
- 10-25% of the pores are branching
- 60-70% of the pores for a given sample are 100 microns or smaller
- Average Gamma for the samples is about 1.4 to 1.6, so the pores are irregular in shape

- This facies is very heterogeneous due to the reef core AND detritus – the more detritus, the more variable pore types exist, resulting in more branching and interconnected pores with a higher permeability
- The Charlton thin-sections have detritus and reef framework with fracture, interparticle, moldic, and pin-point vuggy porosity which all adds to a more interconnected pore network

#### *Good Porosity and Permeability*

- Whole core data from the State Charlton show a porosity ranging from 5 to 20% with permeability ranging from 0.1 to 100 md
- Whole core data for the Miller-fox 1-11 shows porosity ranging from 5 to 10% and permeability ranging from 10 – 10,000 md
- The State Highlander has a porosity of about 0.5% and 1 md permeability – since this is averaged of 5 foot intervals, this looks biased based on the properties of the surrounding rock types
- Image analysis porosity for the Charlton well is 8.7 – 9.4%
- Image analysis porosity for the Highlander well is 10.2 – 13.2%
- Average Gamma is 1.4
- Pores are sub-rounded to angular– abundant moldic and vuggy porosity
- Larger pores (with an area of 50,000  $\mu\text{m}^2$  or larger) are more branching because it looks like several pores were solution enhanced to form the vugular shapes
- Only a small percentage of the pores are this size and shape though
- Good permeability is due in large part to intercrystalline matrix microporosity

#### **P-4: Packstone to Grainstone (>1 mm)**

- Whole core analysis for Umlauf shows porosity from 4 – 6% with about 8 md

permeability

- Image analysis for Umlauf shows a porosity of 10% and a gamma value of 1.2
- Pores are rounded, not branching, yielding low permeability values
- Intercrystalline matrix porosity from the dolomite may enhance the permeability values if present
- The predominant pore type is moldic
- This facies is only locally present in the cores, as the capping packstones to grainstones usually occur with millimeter or less fragments. The fragments in this facies are 1 mm or larger

**P-4a: Packstone to grainstone with small (mm or less) size particles**

- Whole core analysis for the State Charlton shows porosity ranging from 5 to 20% with permeabilities ranging from 1 to 100 md
- Whole core analysis for the Fugere shows porosity ranging from 3 to 7% with permeability ranging from 1 to 100 md
- Whole core analysis for Umlauf shows porosity ranging from 15 – 20% with permeability of around 100 md
- Whole core analysis for the Miller-Fox shows porosity ranging from 0.1 – 5% with permeability values less than 10 md
- This facies in the Miller-Fox is actually salt occluded
- The state Charlton was used for image analysis
- Image analysis for the Charlton showed a porosity of 21.5 – 29% with a gamma value of 1.4-1.5
- These appear to be moldic pores that were solution enhanced, allowing for more interconnected branching geometries

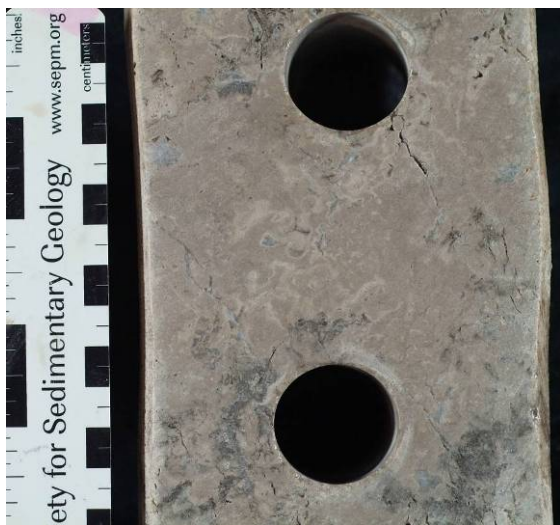
### Sonic Velocity

Sixteen (16) core plugs from the Miller-Fox were analyzed at the University of Miami for sonic velocity. Six (6) of these plugs were also evaluated using image analysis. Additional analyses from the Miller Fox and other reef cores were planned for Year 3 of the project as originally defined. However, the facies characteristics (rock fabric and pore geometry) of the Miller-Fox are similar to that of the other wells from other locations in the basin and therefore the sonic velocity values retrieved for the Miller-Fox 1-11 are probably a good first order characterization of the same facies from other wells. Once the acoustic properties of the plugs are determined, the velocities can be correlated to the sonic logs. The pore architecture and related permeability will hypothetically show an inverse relationship with sonic velocity values. The seal and reservoir facies then can be predicted within the established sequence stratigraphic framework.

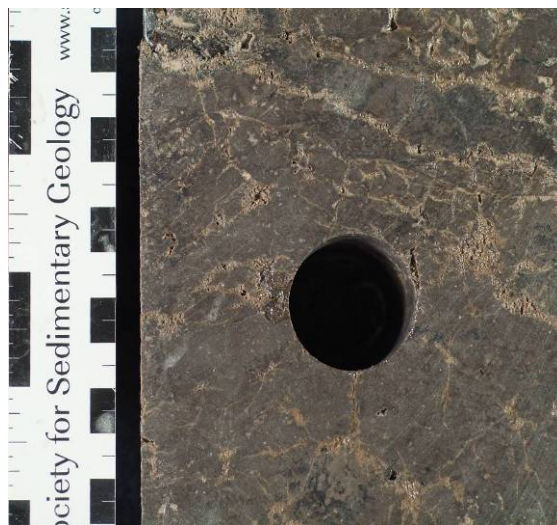
Modifications of rock due to cementation and dissolution alter the physical properties in rock, resulting in a dynamic relationship between depositional facies and diagenesis recorded by physical parameters such as porosity, permeability, and sonic velocity (Grammer et al., 2004). This relationship and the variability caused by the depositional and diagenetic fabrics of carbonates makes predicting physical properties, such as velocity and porosity, more difficult than in siliciclastic sediments (Anselmetti and Eberli, 1999). Early marine cements can decrease porosity and add rigidity to younger rocks, resulting in an increase in velocity much more than that of sediments responding only to compaction (Grammer et al., 2004). The main factor in controlling the

sonic velocity in rocks is porosity; however, the pore architecture is equally important in the resultant velocity (Eberli et. al., 2003). Graphs of porosity vs. velocity of various pore types have an exponential best fit curve with scattering that reflects pore type and its resultant elastic property (Grammer et al., 2004). Moldic porosity in rocks exists within a stiff frame and provides rigidity in a rock that result in high velocity. Fabric destructive dolomitization results in a rock containing intercrystalline porosity with low rigidity as well as low velocity (Grammer et al., 2004).

Wireline logs are the most powerful tool used in predicting the downhole lithology from physical properties because cores are not the most cost efficient. The knowledge of the porosity-velocity correlation in carbonates can be used to improve wireline log interpretation by being able to predict parameters such as pore type, permeability trends, and diagenetic fabrics in addition to the parameters that are measured with the wireline tool (Anselmetti and Eberli, 1999).



Miller-Fox 1-11 (3495 ft.)



Highlander (3990 ft.)

Figure 45. Core photos of petrophysically significant facies P-2.

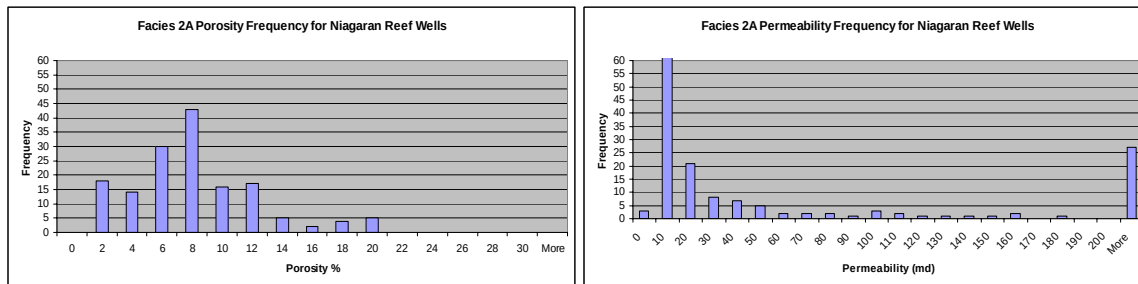


Figure 46a. Whole core porosity and permeability frequency for P-2 for all Niagaran cores examined to date for petrophysical facies P-2.

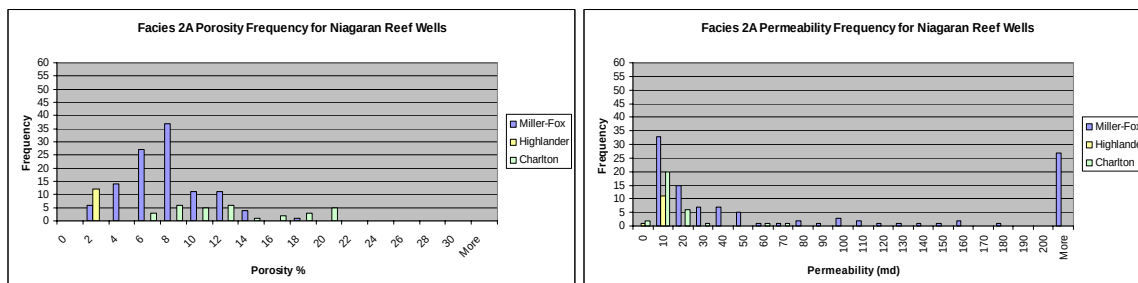
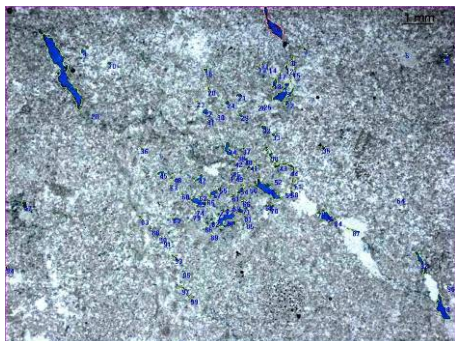
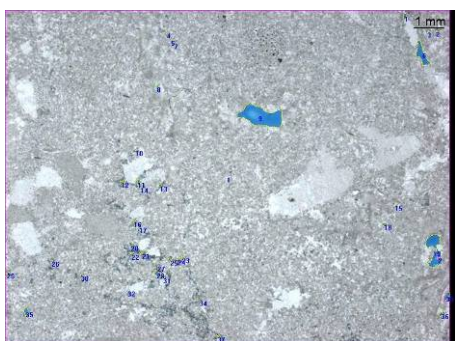


Figure 46b. Whole core porosity and permeability frequency by well for Niagaran cores examined to date for petrophysical facies P-2.



Miller-Fox 1-11 (3495 ft.)  
Porosity: top 2.3%, bottom 1.1%



Highlander (3990 ft.)  
Porosity: top 5.1%, bottom 4.3%

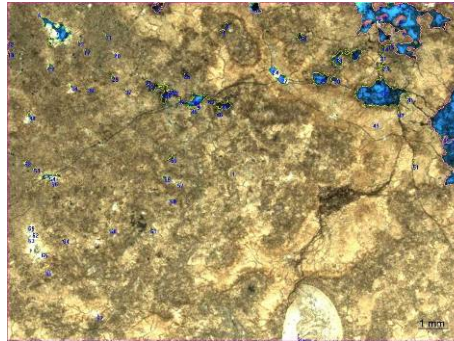


Figure 47. Thin section photomicrographs (8x magnification) with porosity values from image analysis calculations for petrophysical facies P-2.



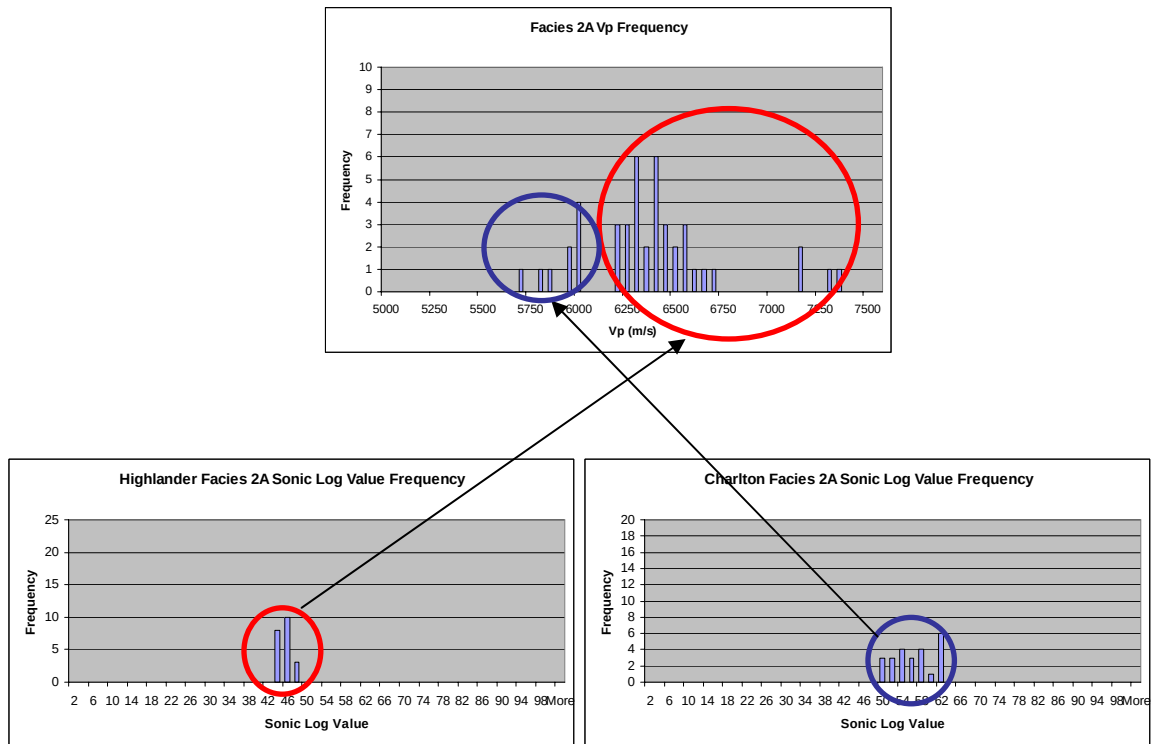


Figure 48. Correlation of laboratory measured sonic velocities to sonic log values in Petrophysical Facies P-2. In this sample there is a measured gamma value of 1.3.

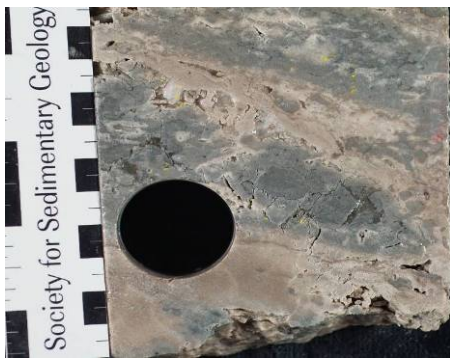


Figure 49. Core photographs from Petrophysical facies P-3. Top left: Fugere (4335 ft.); top right: Charlton (4921 ft.); bottom: Miller Fox 1-11 (3611 ft.)

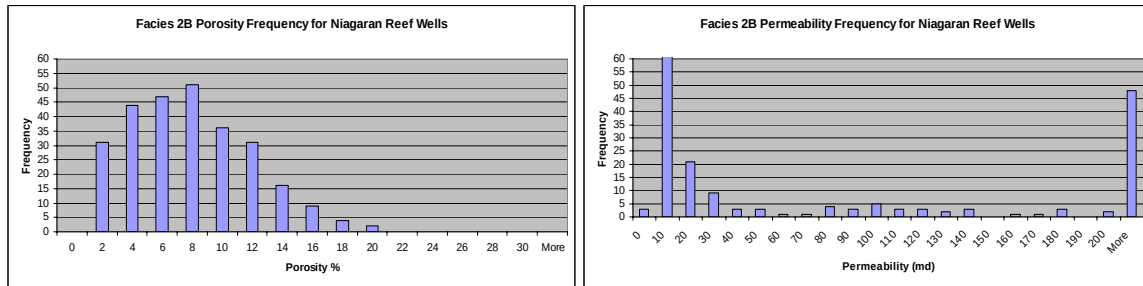


Figure 50a. Porosity and permeability frequency for all Niagaran cores examined to date for petrophysical facies P-3.

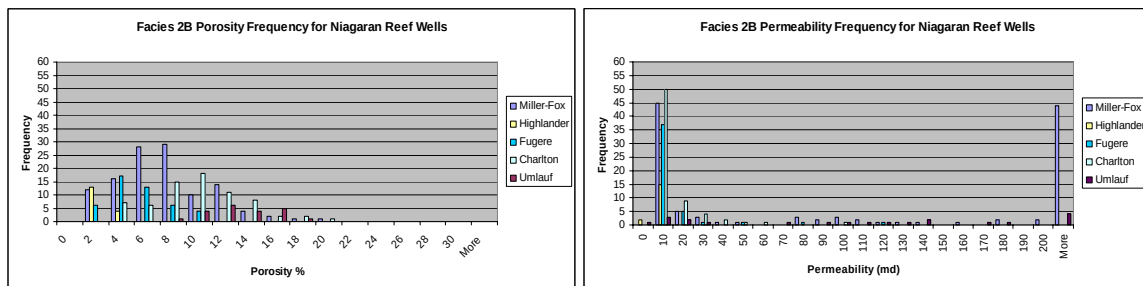


Figure 50b. Porosity and permeability frequency by well for all Niagaran cores examined to date for petrophysical facies P-3.

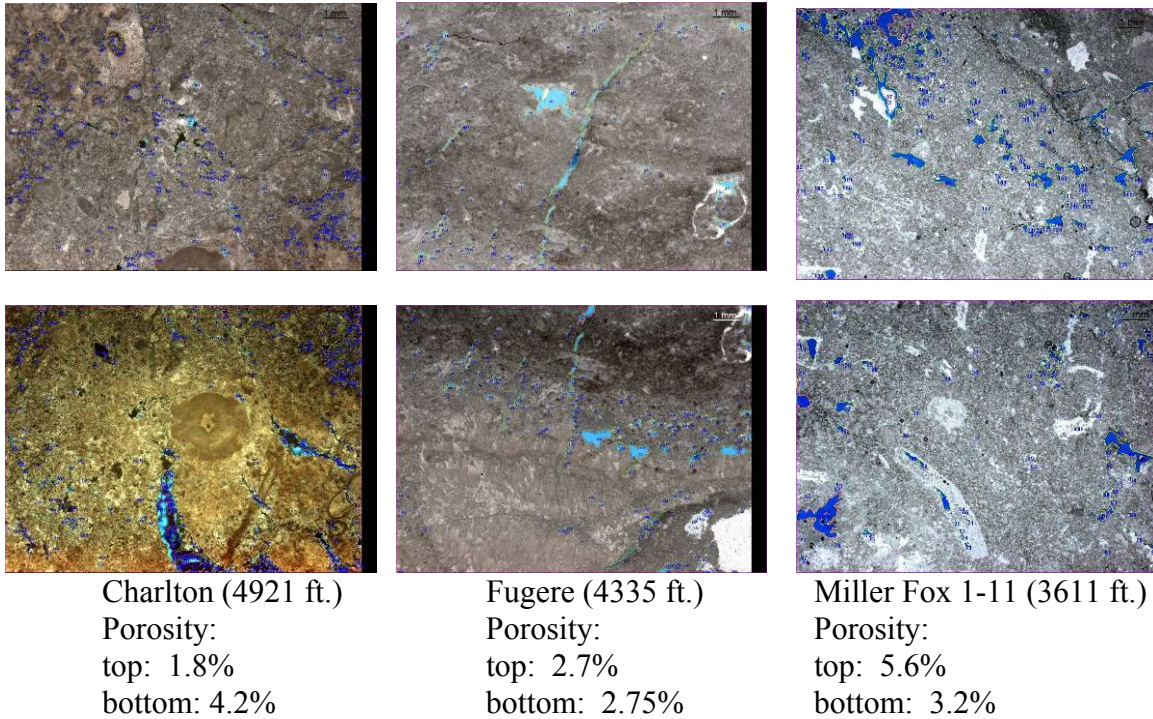


Figure 51. Thin section photomicrographs (8x magnification) with porosity values from image analysis calculations for petrophysical facies P-3.

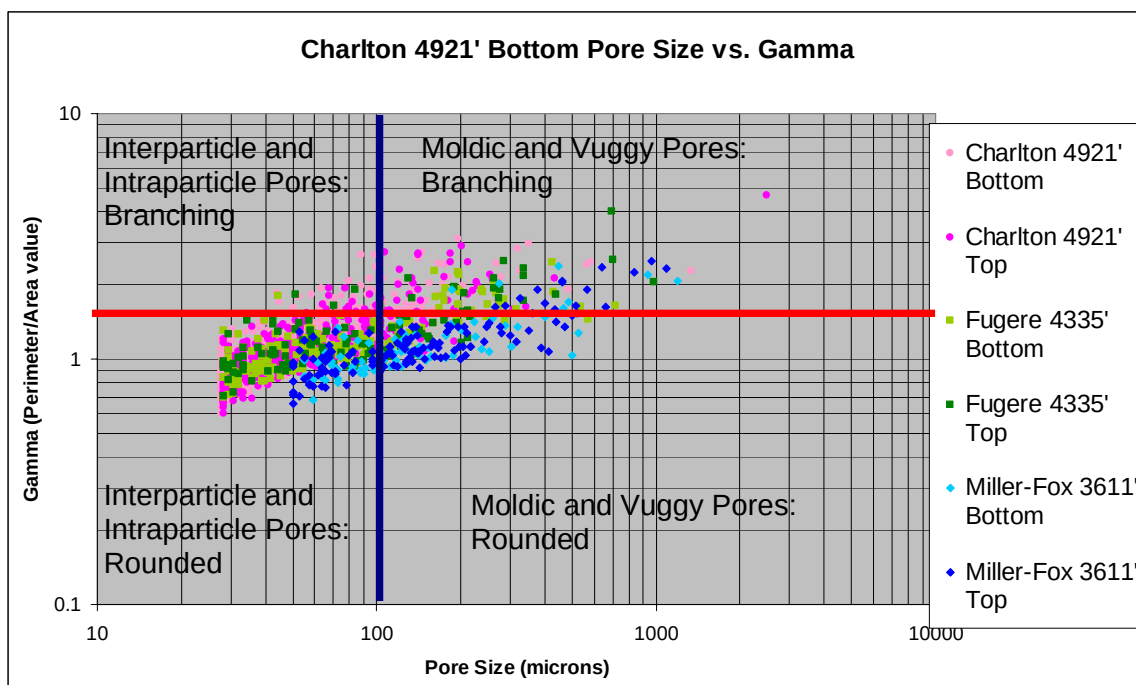


Figure 52. Graph of pore size versus “gamma” and variation in pore shapes.

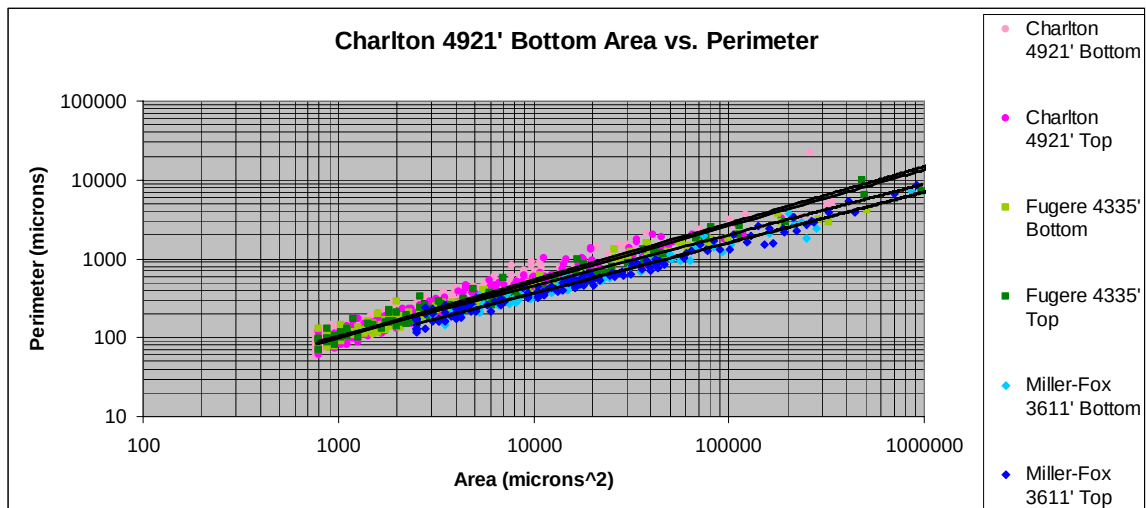


Figure 53. Graph correlating pore area to pore perimeter. The good fit to the trend line indicates that most pores are well rounded and not irregularly shaped (branching).

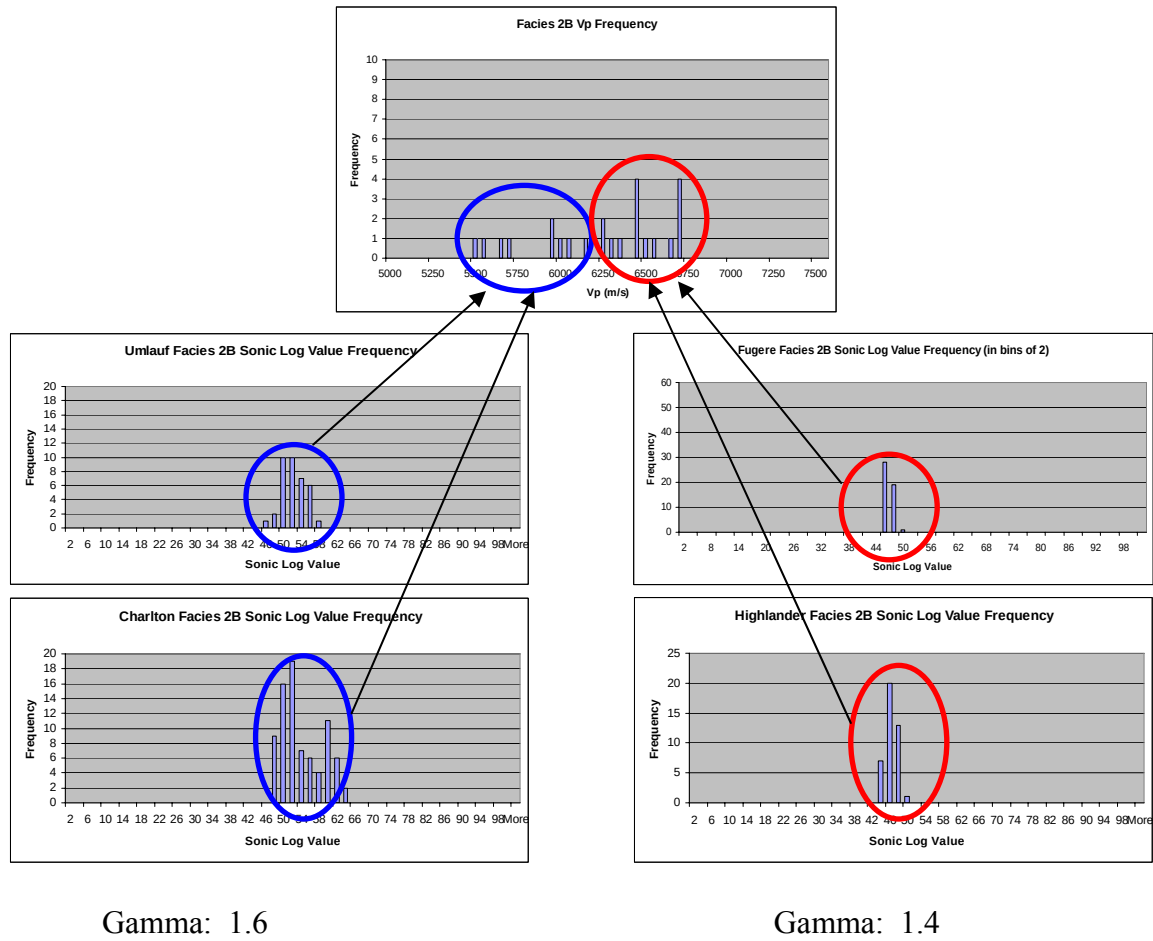


Figure 54. Correlation of laboratory measured sonic velocities to sonic log values in Petrophysical Facies P-3. In this sample there is a measured gamma value of 1.3.





Figure 55. Core photograph from petrophysical facies P-4 with only small vugs visible. Charlton (4710 ft.)



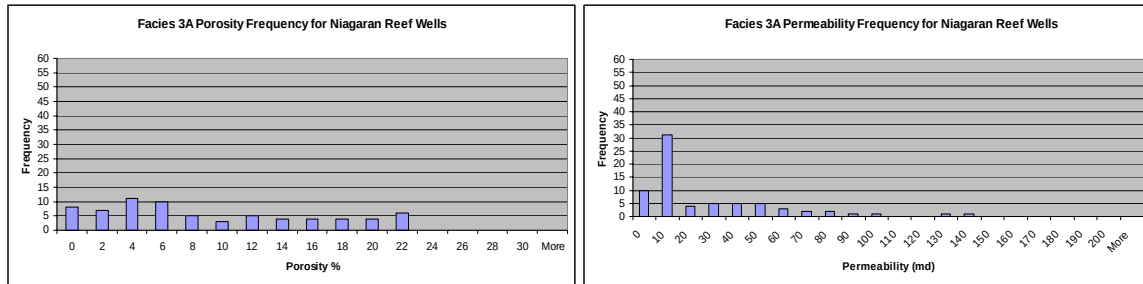


Figure 56a. Porosity and permeability frequency for all Niagaran cores examined to date for petrophysical facies P-4.

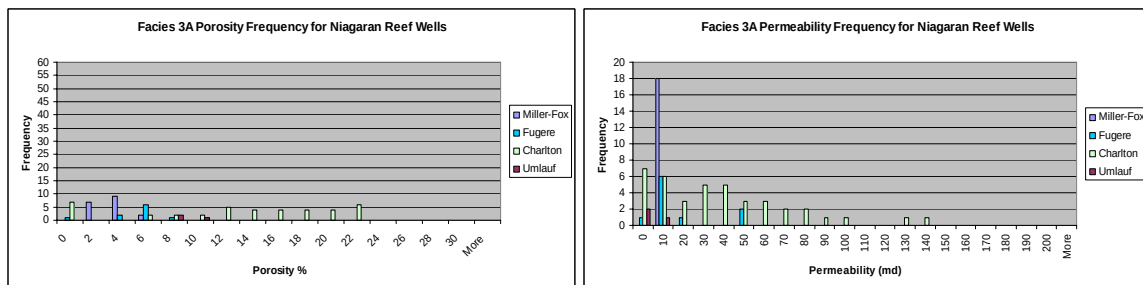
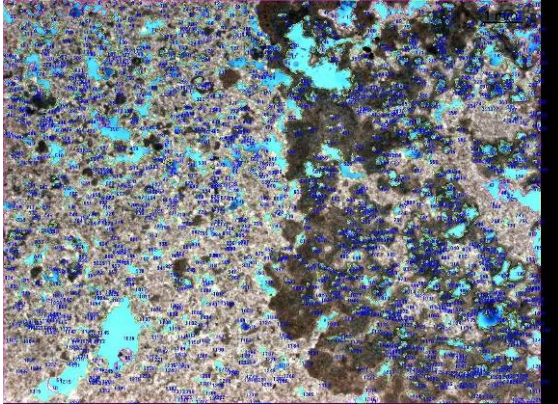
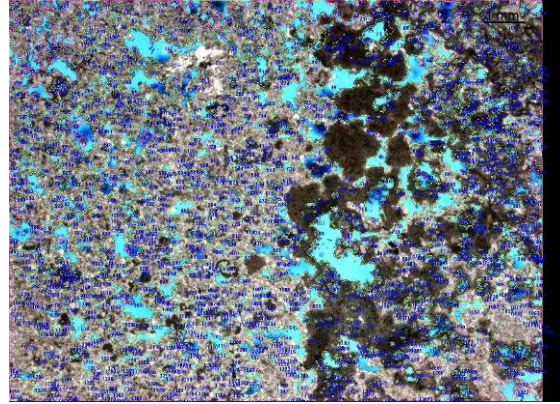


Figure 56b. Porosity and permeability frequency by well for all Niagaran cores examined to date for petrophysical facies P-4.



Charlton (4710 ft.) – top  
Porosity: 29%  
Gamma: 1.5



Charlton 4710 ft. – bottom  
Porosity: 21.5%  
Gamma: 1.4

Figure 57. Thin section photomicrographs (8x magnification) with porosity values from image analysis calculations for petrophysical facies P-4.

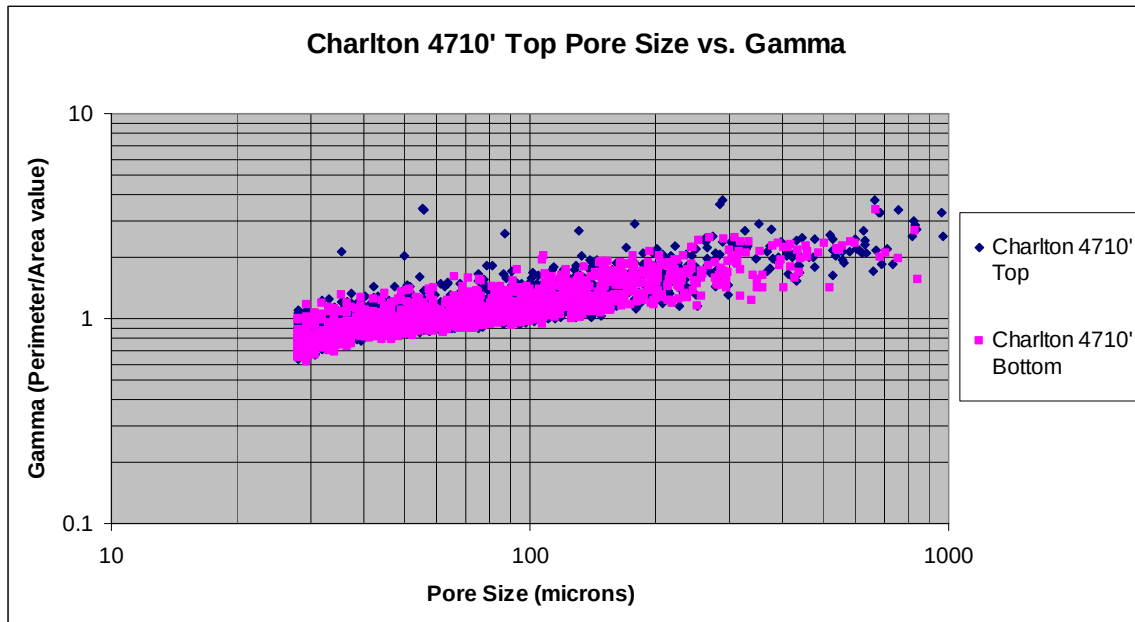


Figure 58. Graph of pore size versus “gamma” illustrating the more irregular shape of larger (>100 microns) pores.

## **SUMMARY OF CURRENTLY AVAILABLE GEOLOGIC DATA (THROUGH PHASE II)**

### ***Ordovician Trenton/Black River Production***

The Ordovician Trenton-Black River Formation is a fractured, dolomitized reservoir that has produced 140 MMBO and 260 BCFG in the State of Michigan. However, theories concerning the nature of fracturing, the controls exerted by the original depositional rock type and pattern, the extent of dolomitization, the types of fluids involved, and the various stages of diagenesis are still evolving. All previous studies deal only with data from specific field areas. There has never been a basin-wide synthesis and analysis of these data despite the fact that the Trenton-Black River Formation is one of the largest hydrocarbon producing reservoirs in the state. It is doubtful that the current Trenton-Black River exploration model, developed from independent field studies, adequately encompasses all the exploration and exploitation opportunities that exist for this reservoir in the Michigan Basin. Increasing the current total recovery for this unit by only 1% would add 1,380,000 BO and 2.6 BCF to the already recovered reserves. It is reasonable to expect that a comprehensive, basin-wide examination of the Trenton-Black River Formation, resulting in the development of additional exploration models and methods could ultimately produce a 5% increase in recoverable reserves (6.90 MMBO and 13 BCF).

### **Trenton-Black River Discovery and Development**

Drilling began in 1884 along the Findlay-Kankakee Arch in Indiana and Ohio (Davies, 1996, 2000) resulting in the first Trenton-Black River discoveries. This led to the drilling of over 100,000 wells and the production of 500 MBO along the Bowling Green Fault Zone.

The first commercial Trenton-Black River discovery in the State of Michigan occurred in 1936 in Monroe County. This resulted in the Deerfield Field located along the Lucas-Monroe monocline, an extension of Bowling Green Fault zone in Ohio. Reservoir quality dolomite lenses in the upper 125' of the Trenton Group produced more than 608 MBO by 1959 from 40 wells drilled on 360 acres.

The Albion-Scipio Field, a giant (>120 MMBO) Trenton-Black River field located in Calhoun & Hillsdale Counties, Michigan was discovered in 1955 – 1958 (Davies, 1996, 2000). The Scipio Field discovery well was the Houseknecht No. 1 (Sec 10, T5S-R3W – Hillsdale Co.) which was originally drilled for Devonian gas but proved dry. It was then deepened based upon the advice of a psychic family friend, encountered oil at 3900', and was completed at 140 BOPD with "considerable" gas. The Albion Field was discovered by the Rosenau No. 1 (Sec 23, T3S-R4W, Calhoun Co.) and completed for 200 BOPD. Subsequent drilling discovered the Pulaski, Barry, Sponseller, Van Wert, and Cal-Lee Fields; all to become part of the Albion-Scipio Trend. Over 961 wells were drilled by 1986, of which 573 are still producing.

Stoney Point Field (5 miles east and sub-parallel to Albion-Scipio) was not discovered until 27 years later in 1982 when the JEM Casler No. 1-30 (Sec 30, T4S-R2W, Jackson Co.) encountered dolomite reservoir 115' into the Trenton at 3910'. This well hit lost circulation at 4248'. Casing was set and the well was tested at 2000 BOPD from perforations at 4161' - 4179'. The bottom hole pressure drop never exceeded 3 psi and the well was put on production at 220 BOPD. Two hundred and ten wells were drilled around the Stoney Point Trend between 1983 and 1987. Seventy five wells were oil and gas producers.

Estimated oil-in-place figures are difficult to accurately calculate due to difficulties in establishing a reliable porosity number; however, Scipio Field is estimated to have 170 MMB OOIP, Albion Field is estimated to have 120 MMB OOIP. No figures are available for Stoney Point Field. There are 18 Trenton-Black River fields that have produced in Michigan.

### Stratigraphy and Structure

The Trenton-Black River Formation was originally deposited during the Ordovician in open marine conditions. Wackestone - mudstones were deposited on a basin-wide scale. Trenton-Black River carbonates in the Stoney Point Field area (south-central Michigan) are open marine, subtidal carbonates, typically crinoidal packstones/wackestones and mudstones with pervasive burrowing. Trenton rocks in the

Deerfield Field area (SE Michigan) prograde from open marine to intertidal carbonates while Black River rocks remain subtidal (Davies, 1996, 2000). The Trenton is overlain by the Utica Shale that forms a regional seal. This is in turn overlain by reef and inter-reef carbonates of the Niagara Formation and Salina Formation evaporates.

Repeated reactivation of a Precambrian left-lateral wrench fault system (en echelon faults with a total of 2.5 miles of offset) occurred throughout the early to mid Paleozoic. These faults (dominant set oriented N30W, conjugate set oriented east-west) are thought to have provided conduits through which dense Salina residual evaporite brines were able to flow downward into the Trenton-Black River formation. Dissolution and dolomitization of the Trenton-Black River occurred immediately adjacent to faults resulting in long, linear, porous dolomite reservoirs associated with downward collapse of overlying units. The collapsed interval extends into the Devonian section where it dies out. Fractures in the Utica Shale must have healed at the cessation of faulting to provide a seal for the Trenton-Black River reservoir. Tight un-dolomitized limestones act as lateral stratigraphic seals (Allen and Wiggins, 1993). DeHaas and Jones (1984, 1989) proposed cave development related to karsting responsible for lost-circulation zones; however, this theory has been largely discounted by recent workers.

Budros (APPG Annual Meeting, 2004) proposes that “sags” or “grabens” overlying dolomitized reservoirs (thereby defining Trenton-Black River fields) are in fact negative flower structures due to Reidel shear faulting with trans-tension and are not the result of previously considered collapse due to dissolution. He also proposes that some fields are characterized by positive flower structures produced by Reidel shear faulting with compression.

Faulting has compartmentalized the Albion-Scipio Trend. These compartments are probably due to a combination of Reidel shear negative and positive flower structures along the same fault trend; however, this hypothesis demands further investigation. These discontinuities do account for dry holes drilled apparently “directly on trend” (Davies, 1996, 2000).

Fields such as Deerfield Field exhibit a more circular pattern rather than a long, linear NW - SE pattern typically considered indicative in the current Trenton-Black River

exploration model. It is thought that secondary east-west oriented faults may have played a more significant role in the development of dolomitized reservoir facies in the Deerfield Field. Fractures and faults with minor displacement play an important roll controlling dolomitization and porosity development (Davies, 1996, 2000).

#### Trenton-Black River Reservoir Characteristics

Reservoir dolomites are composed of coarse crystalline dolomitized limestone host rocks that are vuggy and cavernous. Fractures and vugs are often solution enlarged and contain white saddle dolomite with minor anhydrite. Porosity normally ranges from 2-5%, but 8-12% porosity is present, though uncommon. Permeability is extremely variable (0.01 – 800 md) but is generally low (85% of samples < 10 md). Porosity and permeability plots do not show any uniform relationships. Isotopic, fluid inclusion and water chemistry analyses all indicate a hydrothermal genesis for reservoir dolomites with a dual source of fluids from the Salina and Trenton - Precambrian Formations (Allen and Wiggins, 1993).

#### Origin of Dolomite

Shortly after discovery of the Albion-Scipio Trend, Burgess (1960) determined that reservoir dolomite was a secondary mineral formed as Cambrian and Lower Ordovician waters moved up along fracture zones (analogs - Dover and Colchester Fields in Ontario).

Ells (1962) observed that Albion-Scipio Field dolomites were similar to Mississippi Valley-Type (MVT) lead-zinc mineral deposits. He proposed that magnesium-bearing waters ascending through fractures were responsible for dolomitization.

Beghini and Conroy (1966) stated that Trenton-Black River reservoirs were formed by pre-Black-River Group waters that moved through faults and fractures to produce secondary dolomite.

Buehner and Davis (1968) concluded that the Trenton-Black River reservoir facies was epigenetic dolomite related to a fault system.

Shaw (1975) described a mineral assemblage (including sphalerite) in Albion-Scipio cores similar to MVT mineral deposits. He noted 2-phase fluid inclusions in Albion-Scipio dolomites and pore filling saddle dolomites that he believed were precipitated from fluids at a minimum of 80 degree C. He also identified a liquid-hydrocarbon phase in some fluid inclusions indicating hydrocarbons were present at time of cementation. These observations allowed him to propose a model of replacement dolomitization and development of intercrystalline porosity during the Middle to Late Silurian by waters percolating through fractures. Magnesium was sourced from underlying Prairie du Chien dolomite or Trempealeau Formations. Then, a second phase of dolomitization occurred during Lower to Middle Devonian as hot fluids from the basin center created cavernous porosity, subsequent collapse, and precipitation of a MVT assemblage.

Ardrey (1978), DeHaas and Jones (1984, 1989) proposed that diagenesis of the Trenton-Black River in Albion-Scipio area was due to exposure as indicated by the top-of-Trenton unconformity. They also stated that dolomitization must have resulted from a mixing model based on the observation that Trenton Formation water is less saline than water in shallower horizons; therefore, it could not be of hydrothermal origin.

Taylor and Sibley (1986) identified 3 major types of dolomite (1) regional dolomite not associated with the field area, (2) cap dolomite that occurs in the top 40 feet (related to interaction of the Trenton with Fe-rich fluids formed during the de-watering of the overlying Utica Shale) (3) fracture-related dolomite (formed during deeper burial at approximately 80 degrees C based on geochemical results).

Budai and Wilson (1986) identified various MVT accessory minerals, including pyrite, calcite, anhydrite, barite, celestite, sphalerite, and fluorite in association with saddle dolomite cements. They proposed a hydrothermal model with Paleozoic and Precambrian basement rock as sources of iron, sulfur, and other trace metals.

Hurley and Cumella (1987) proposed a model based on (1) carbon, oxygen, and strontium isotopes, (2) fluid-inclusion geothermometry, (3) brine geochemistry, and (4) regional hydrologic constraints. Dolomitizing fluids were thought to be Silurian-Devonian hypersaline sea-waters that moved down fracture zones to meet with hot



limestone-dissolving fluids moving up from the basement. These fluids mixed in a pattern consistent with the known distribution of dolomite reservoirs and lost-circulation zones. This model is supported by Coniglio et al (1994) for Ordovician rocks in Ontario (Davies, 1996, 2000).

### Exploration

Originally, the Albion-Scipio Field was discovered by the advice of a psychic. “Trendology” quickly became the exploration method of choice as the linear field pattern began to emerge. Indications of a northwest-southeast linear fracture zone associated with a top-of-Trenton synclinal sag (up to 60’ recognized in early producing wells) has been the long held exploration model for the Trenton-Black River Formation.

Gravity was used through the 1960’s and early 70’s to define basement faults along the Albion-Scipio Trend. This met with limited drilling success because dolomite porosity mutes the density contrast between the regional limestones and dolomite reservoir rocks.

Magnetics was used in the 1970’s to detect basement discontinuities and faults; however, this also proved to have limited use. The giant Albion-Scipio does not appear as an individual feature on magnetic maps. Recently, micromagnetic surveys and resistivity profiles have been employed, but their significance is not yet proven.

Reflection-seismic is currently the primary exploration method; however, there are problems associated with this technique: (1) variable till overburden thicknesses produce noise and statics problems, (2) secondary porosity, the dominant reservoir characteristic, is not detected by P-waves, (3) reservoir dolomites (2-5% porosity) have an acoustic impedance similar to the regional limestones, and (4) reservoir geometries are difficult to image. To date, reflection-seismic Trenton-Black River discoveries have been based on: (1) disruptions (sags) at the Trenton event, (2) internal waveform changes, (3) disruption of lower events, and (4) recognition of faults from offsetting events and/or diffractions.

Soil gas geochemistry studies above Scipio field showed no correlation between soil gas and producing parts of the field; however, soil gas geochemistry reportedly played an important role in the Stoney Point Field discovery.

### Exploitation

Secondary Recovery has been minimal. Results were discouraging from a pilot waterflood of the Haskell Unit (near south end Scipio Field). Marathon Oil has drilled a number of Trenton-Black River horizontal wells that show considerable promise for future exploitation.

### Summary

This was intended to be (prior to funding being revoked) the first comprehensive, systematic study to determine the basin-wide relationships of: (1) original carbonate depositional patterns, (2) formation of early stage diagenetic dolomites vs. later stage burial and hydrothermal dolomites, (3) types and patterns of faulting, (4) types and patterns of dolomitization resulting from this faulting, (5) resulting reservoir rock quality, (6) oil accumulations (field delineation and orientation), and (7) hydrocarbon production. The current Trenton-Black River exploration model of looking for a seismic sag associated with basement faults in long linear patterns appears to be only partially correct. It is possible, in light of evolving geological concepts concerning the Michigan Basin, that other styles of Trenton-Black River fields exist. However, no exploration models covering these variations have yet been developed. This work will provide numerous opportunities to expand our understanding of Trenton-Black River hydrocarbon accumulations and significantly add to known reserves.

## ***Silurian Niagaran Production***

### General Observations

1. Production data for the Niagaran Trend is generally good. The play began in the early 1950's and hit its peak during the 1970's-1980's. Digital data bases

developed by the state beginning in 1981 include a large portion of the data for this play.

2. The log plot of the data displays a curve typical of that for a mature play. Nearly all field sizes are represented and no “gaps” in field size occur. The slope of the curve is shallow indicating full representation of each field size. Future potential is probably resource limited for this particular exploration model; however, new technology, combined with a new/expanded exploration model could potentially re-set the curve to a higher level.
3. There are 1,162 fields in this play. There are 1,063 fields producing oil. This volume of data makes it difficult to plot trends including individual field names. Rather, data can best be examined as categories based upon field size. “Cumulative Oil Production” can be broken down into 5 basic categories: 1) Fields 1-10 million barrels cumulative oil production, 2) Fields 100,000 – 1 million barrels cumulative oil production, 3) fields 10,000 – 100,000 barrels cumulative oil production, 4) fields 1,000 – 10,000 barrels oil cumulative production and 5) fields less than 1,000 barrels cumulative oil production.
4. Fields making less than 1,000 barrels oil cumulative production are probably not economic based upon oil production alone. The sharp drop-off in fields of this size is probably due to the fact that no one purposely looks for this sized field. However, a few disappointing fields of this size do occur and are produced to recover at least some of the cost of exploration and development. These fields, in most cases, are associated with gas production that makes the venture economic.
5. Gas is produced in 991 fields compared to oil being produced in 1,063 fields. Gas production volumes remain somewhat level in relationship to oil production volume (1 million BOE).

6. Brine is produced in 664 fields. Production of brine is roughly related to oil production. The larger oil fields all produce brine whereas the smaller the oil field, the less likely it is to produce brine. Only 8 fields produce only gas and brine. Brine volumes are roughly related to oil volumes. Only 28 fields produce more brine than oil. (refer to Cumulative Oil-Gas-Brine Production by field Graph)
7. The State of Michigan imposes a 200 barrel-per-day maximum allowable on production which often distorts the true capabilities/performance of the affected wells.
8. The graph of “Discovery Size (Cumulative Oil) by Year of Discovery” displays a wide variety of field performance for each year. Although originally kicked-off in 1950, Niagaran fields did not hit peak oil productivity until 1971 when drilling boomed with the discovery of 32 new fields that year. The 1970’s represent the “best times” for Niagaran discoveries, with a sharp decline after 1981. This data set does not include the onset of horizontal drilling during the 1990’s.
9. There are 1,162 fields in the Niagaran Trend. The oldest field in the trend was discovered in 1950. Only 9 fields in the Niagaran Trend have produced more than 35 years. Nearly one half of the fields have produced for 15 – 30 years (531 fields). Only 181 fields have produced for 5 years or less. Seventy-three fields were either produced for less than one year or not produced at all.
10. “Cumulative Oil Production” varies substantially when plotted against “Years of Production.” However, the best producers in each age bracket show impressive results. Nearly 10,000,000 barrels of cumulative oil have been produced by fields in the 30 to 50 year age bracket. Fields in production from 22 years to 30 years have top producers in the 1-5 million barrel range. Top producing fields in the 5 –

22 year bracket still hit the 1 million barrel mark other than for year 9. Even fields in production for only 1 year have obtained the 100,000 barrel mark.

### ***Devonian Dundee Trend Production***

#### General Observations

1. Production data for the Dundee Trend is generally good. Dundee production statistics go back to 1934 although commercial Dundee production began in 1928 and has remained a stalwart of the Michigan Basin ever since. Its production ranks second only to that of the Niagaran Trend; however, the Niagaran Trend contains 1,162 fields vs. only 178 fields in the Dundee Trend.
2. The log plot of the data displays a curve typical of that for a mature play. Nearly all fields sizes are represented and no “gaps” in field size occur. The slope of the curve is shallow indicating full representation of each field size. Future potential is probably resource limited for this particular exploration model; however, new technology, combined with a new/expanded exploration model could potentially re-set the curve to a higher level.
3. There are 178 fields in this play. There are 155 fields producing oil. This volume of data makes it difficult to plot trends including individual field names; therefore, data has been examined as categories based upon field size. “Cumulative Oil Production” can be broken down into 7 basic categories: 1.) 8 Fields making 10-50 million barrels cumulative oil production, 2.) 30 fields 1 – 10 million barrels cumulative oil production, 3.) 50 fields making 100,000 – 1 million barrels cumulative oil production, 4.) 39 fields making 10,000 – 100,000 barrels oil cumulative production and 5.) 20 fields making 1,000 – 10,000 barrels cumulative oil production, 6.) 8 fields making 0 – 1,000 barrels cumulative oil production, and 7.) 14 fields making 0 oil production.

4. Fields making less than 1,000 barrels oil cumulative production (9 fields) are probably not economic based upon oil production alone. The sharp drop-off in fields of this size is probably due to the fact that no one purposely looks for this sized field. However, a few disappointing fields of this size do occur and are produced to recover at least some of the cost of exploration and development.
5. Gas is produced in 41 fields compared to oil being produced in 155 fields (although many fields may have initially had gas, production was limited due to infrastructure and much of the gas production was flared).
6. Brine is produced in 141 fields. Only 13 oil fields do not produce brine. Only 4 gas fields do not produce brine.
7. The State of Michigan imposes a 200 barrel-per-day maximum allowable on production which often distorts the true capabilities/performance of the affected wells.

## REPORT REFERENCES

Adams, J.E., and M.L. Rhodes, 1960, Dolomitization by seepage refluxion: American Association of Petroleum Geologists Bulletin, v. 44, p. 1912-1921.

Allan, J.R., and Wiggins, W.D., 1993, Dolomite reservoirs. Geochemical Techniques for Evaluating Origin and Distribution. American Association of Petroleum Geologists, Continuing Education Course Notes, Series No. 36, 129 p.

Anselmetti, F.S., and G.P. Eberli, 1993, Controls on sonic velocity in carbonates: Pure and Applied Geophysics, v. 141/2-4, p. 287-323.

Anselmetti, F.S., and G.P. Eberli, 1997, Sonic velocity in carbonate sediments and rocks, in F.J. Marfurt and A. Palaz, eds. Carbonate Seismology: Society of Exploration Geophysicists, Geophysical Development Series no. 6, p. 53-74.

Anselmetti, F.S.; Luthi, S.M.; and Eberli, G.P, 1998, Quantitative characterization of carbonate pore systems by digital image analysis, AAPG Bulletin 82: 1815-1836.

Anselmetti, F.S. and Eberli, G.P., 1999, The velocity-deviation log; a tool to predict pore type and permeability trends in carbonate drill holes from sonic and porosity or density logs, AAPG Bulletin 83: 450-466.

Anselmetti, F.S. and Eberli, G.P., 2001, Sonic velocity in carbonates - a combined product of depositional lithology and diagenetic alterations, in R.N. Ginsburg, ed., Subsurface Geology of a Prograding Carbonate Platform Margin, Great Bahama Bank: Results of the Bahamas Drilling Project: SEPM Special Publication v. 70, p. 193-216.

Ardrey, R.H., 1978, Diagenesis of Middle Ordovician Trenton Formation in southern Michigan (M.S. thesis): Ann Arbor, Michigan, University of Michigan, 52 p.

Badiozamani, K., 1973, The dorag dolomitization model – application to the Middle Ordovician of Wisconsin: Journal of Sedimentary Petrology, v. 43, p. 965-984.

Barnes, DA, Girard, JP and Aronson, JL, 1992, K-Ar dating of illite diagenesis in the Middle Ordovician St. Peter Sandstone, central Michigan basin, USA: implications for thermal history: in Houseknecht, D and Pitmann, E, eds., Origin Diagenesis and Petrophysics of Clay Minerals in Sandstones, SEPM Sp. Pub. 47, pp. 35-48.

Bathurst, R. G. C., 1980, Stromatactis; origin related to submarine-cemented crusts in Paleozoic mud mounds, Geology 8: 131-134.

Bay, T.A. (1983) The Silurian of the northern Michigan Basin: in Harris, P.M., ed., Carbonate Buildups - a Core Workshop, Soc. Econ. Paleontologists and Mineralogists Core Workshop No. 4, p. 53-72.

Beghini, V.G., and Conroy, T.R., 1960, A history of the Trenton Albion-Scipio trend of Michigan: 5<sup>th</sup> Annual Ontario Petroleum Institute Conference Proceedings, London, Ontario, p. 1-21.

Blaske, Allan, 2000, Geochemistry and a mineralization of Michigan's Mississippi-Valley Type Deposit. Great Lakes Geological Conference 2000.

Bodner, R.J., 2003, Introduction to Fluid Inclusions, in: Samson, I., Anderson, A., and Marshall, d., eds., Fluid Inclusions: Analysis and Interpretation, Short Course Series vol. 32, Min. Assoc. Can., 2003, p. 1-8.

Budai, J.M., and Wilson, J.L., 1986, Depositional Patterns and diagenetic history of Trenton-Black River Formations in Michigan Basin (abs.): American Association of Petroleum Geologists Bulletin, v. 70, p. 1063.

Budai, J.M., and Wilson, J.L., 1991, Diagenetic History of the Trenton and Black River formations in the Michigan Basin, in: Catacosinos, P.A., and Daniels, P.A., Jr. Eds. Early Sedimentary Evolution of the Michigan Basin: Geol. Soc. Am. SP. Pap. 256, p. 73-88.

Budros, R. 2004, Structural Styles of Hydrothermal Dolomite Reservoirs in the Michigan Basin, abst., AAPG National Meeting, 2004 AAPG Bulletin Vol. 88, No. 13

Buehner, J.H., and Davis, Jr., S.H., 1968, Albion-Pulaski-Scipio Trend field: Michigan Basin Geological Society Oil and Gas Field Symposium, Lansing, Michigan, p. 37-48.

Burgess, R.J., 1960, Eastern Canada has a new exploratory target... oil in Trenton synclines: Oil and Gas Journal, v. 58, n. 33, p. 124-131.

Carballo, J.D., L.S. Land, and D.L. Miser, 1987, Holocene dolomitization of supratidal sediments by active tidal pumping, Sugarloaf Key, Florida: Journal of Sedimentary Petrology, v. 57, p. 153-165.

Catacosinos, P.A, and Daniels, P.A, Jr., 1991, Stratigraphy of Middle Proterozoic to Middle Ordovician formations of the Michigan basin, in P.A. Catacosinos and P.A. Daniels, Jr. (eds.), Early sedimentary evolution of the Michigan basin: GSA Special Paper 256, p. 53-71.

Catacosinos, P.A., Daniels, P.A., Harrison, W.B., III, 1991, Structure, Stratigraphy and Petroleum Geology of the Michigan Basin. Amer. Assoc. Petrol. Geol. Petroleum Basins Series: Interior Cratonic Basins, Chapter 30, p.561-601

Cercone, K.R. and K.C. Lohmann, 1985, Early diagenesis of Middle Silurian pinnacle reefs, northern Michigan, in K.R. Cercone and J.M. Budai, eds., Ordovician and Silurian



rocks of the Michigan basin and its margins, Michigan Basin Geological Society Special Paper, no. 4, p. 109-130.

Cercone, K.R., 1984, Thermal History of the Michigan Basin: American Association of Petroleum Geologists Bulletin, V.68, No.2, pp. 130-136.

Champion, B. L., 1968, Oil and gas producing zones in Michigan: Wollensack, M.W., Ed (2<sup>nd</sup> printing) Michigan Basin Geological Society, Oil and Gas Fields Symposium, v. 1, p. 17-36.

Chittick, S.J., 1995, Characterization of the Devonian Dundee Formation, Winterfield Field, Clare County, Michigan, M.S. Thesis, Michigan Technological Institute.

Chittick, Steven, 1996, Unpublished M.S. Thesis, MTU, Houghton, MI.

Chittick, S.J., 1995, Characterization of the Devonian Dundee Formation, Winterfield Field, Clare County, Michigan, M.S. Thesis, Michigan Technological Institute.

Choquette, P.W., eds., Carbonate Petroleum Reservoirs, Springer-Verlag, New York, p. 121-139.

Cohee, G.V. and Underwood, L.B., 1945, Lithology and thickness of the Dundee Formation and Rogers City limestone in the Michigan basin, U.S. Geological Survey Oil and Gas Investigations Preliminary Map38.

Coniglio, M., Sherlock, R., Williams-Jones, A.E., Middleton, K., and Frape, S.K., 1994, Burial and Hydrothermal Diagenesis of Ordovician Carbonates, from the Michigan Basin, Ontario, Canada, in B. Purser et al., eds., Dolomites – A Volume in Honour of Dolomieu: International Association of Sedimentologists Special Publication 21 p 231-254

Coniglio, M., Q. Zheng, and T.R. Carter, 2003, Dolomitization and recrystallization of middle Silurian reefs and platformal carbonates of the Guelph Formation, Michigan Basin, southwestern Ontario, Bulletin of Canadian Petroleum Geology 51, no. 2, p. 177-199.

Curran, B.C., and Hurley, N.F, 1992, Geology of the Devonian Dundee Reservoir, West Branch Field, Michigan. American Association of Petroleum Geologists Bulletin, V. 76, No. 9, pp. 1363-1383.

Davies, G.R., 2000, Hydrothermal Dolomite Reservoir Facies: Global and Western Canadian Perspectives, 2<sup>nd</sup> ed., Short Course Notes, Graham Davies Geol. Cons., 214p.

DeHaas, R.J. and Jones, M.W., 1984, Cave levels of Trenton-Black River in south-central Michigan (abs.): American Association of Petroleum Geologists Bulletin, v. 68, p. 1918.

DeHaas, R.J. and Jones, M.W., 1988, Cave levels of Trenton-Black River in central southern Michigan, in B.D. Keith, ed., the Trenton Group (Upper Ordovician Series) of eastern North American: American Association of Petroleum Geologists Studies in Geology, No. 29, p. 237-266.

Eberli, G.P., Baechele, G.T., Anselmetti, F.S., and M.I. Incze, 2003, Factors controlling elastic properties in carbonate sediments and rocks, Society of Economic Geophysicists, The Leading Edge, p. 654-660.

Ehrlich, R.; Kennedy, S.K.; Crabtree, S.J.; and Cannon, R.L., 1984, Petrographic image analysis; I, Analysis of reservoir pore complexes, Journal of Sedimentary Research 54: 1365-1378.

Ehrlich, R.; Crabtree, S.J.; Horkowitz, K.O.; and Horkowitz, J.P., 1991, Petrography and reservoir physics; I, Objective classification of reservoir porosity, AAPG Bulletin 75: 1547-1562.

Elderfield, H. (1986) Strontium isotope stratigraphy: in Shackleton, N.J., ed., Boundaries and Events in the Paleogene, Palaeogeography, Palaeoclimatology, Palaeoecology, Vol. 57, p. 71-90.

Ells, G.D., 1962, Structures associated with the Albion-Scipio oil field trend: Michigan Geological Survey, East Lansing, Michigan, 86 p.

Enos, P. and L.H. Sawatsky, 1981, Pore networks in Holocene carbonate sediments: Journal of Sedimentary Petrology, v. 51, p. 961-985.

Fara, D.R., and Keith, B.D., 1984, Depositional facies and diagenetic history of Trenton limestone in northern Indiana (Abst): Amer. Assoc. Petrol. Geologists, Bull. v. 68, p. 1919.

Fara, D. R., and B. D. Keith, 1988, Depositional facies and diagenetic history of the Trenton Limestone in northern Indiana, in B. D. Keith (ed.), The Trenton Group (Upper Ordovician Series) of eastern North America-deposition, diagenesis, and petroleum: American Association of Petroleum Geologists Studies in Geology 29, p. 277-298.

Fisher, J.H., Barratt, M.W., Droste, J.B., and Shaver, R.H., 1988, Michigan Basin, in L.L. Sloss, ed., Sedimentary Cover--North American Craton: U.S., The Geology of North America, v. D-2, Geol. Soc. America, p. 361-382.

Gardner, W.C., 1974, Middle Devonian Stratigraphy and Depositional Environments in the Michigan Basin. Mich. Basin Geol. Soc., Spec. Papers no.1, 138p.

Gill, D., 1973, Stratigraphy, facies, evolution and diagenesis of productive Niagaran Guelph reefs and Cayugan sabkha deposits, the Belle River Mills Gas Field, Michigan Basin, University of Michigan, Ann Arbor, MI, United States, Doctoral thesis

Gill, D., 1977, The Belle River Mills gas field; productive Niagaran reefs encased by sabkha deposits, Michigan Basin, Special Papers - Michigan Basin Geological Society, (2):187 pp.

Gill, D., 1977, Salina A-1 Sabkha cycles and the late Silurian Paleogeography of the Michigan Basin: *Journal of Sedimentary Petrology*, v. 47, p. 979-1017.

Gill, D., 1979, Differential entrapment of oil and gas in Niagaran Pinnacle-Reef belt of Northern Michigan: *AAPG Bulletin*, v. 63, p. 608-620.

Girard, J-P and Barnes, D.A., 1995, Illitization and Paleothermal Regimes in the Middle Ordovician St. Peter Sandstone, Central Michigan Basin, United States: K-Ar, Oxygen Isotope, and Fluid Inclusion Data. *Am. Assoc. Pet. Geology Bull.*, v. 79, p.49-69.

Goldstein, R.H., 2003, Petrographic Analysis of Fluid Inclusions, in: Samson, I., Anderson, A., and Marshall, d., eds., *Fluid Inclusions: Analysis and Interpretation*, Short Course Series vol. 32, Min. Assoc. Can., 2003, p. 9-54.

Grammer, G.M.; Harris, P.M.; and Eberli, G.P., 2004, Integration of outcrop and modern analogs in reservoir modelling, *AAPG Memoir*, 80 394 pp.

Grammer, G. M., Harris, P. M., and Eberli, G. P., 2004, Integration of modern and outcrop analogs for reservoir modeling – overview and examples from the Bahamas, in Grammer et. al. (eds.), *Integration of Outcrop and Modern Analogs in Reservoir Modeling*, AAPG Memoir 80, p. 1-22.

Gray, J., 1983, Prospects for deep drilling in Ohio: Ohio Oil and Gas Association, Winter Meeting, Columbus, Ohio, 27 p.

Hanshaw, B.B., W. Back, and R.G. Deike, 1971, A geochemical hypothesis for dolomitization by groundwater: *Economic Geology*, v. 66, p. 710-724.

Hardie, L.A. (1987) Dolomitization: a critical view of some current views: *Jour. Sed. Petrology*, Vol. 57, p. 166-183.

Hladil, Jindrich, 2005, The formation of stromatactis-type fenestral structures during the sedimentation of experimental slurries; a possible clue to a 120-year-old puzzle about stromatactis, *Bulletin of Geosciences (Praha)*, 80(3):193-211

Hogarth, C.G., and Sibley, D.F., 1985, Thermal history of the Michigan Basin: evidence from conodont coloration index: in K.R. Cercone and J.M. Budai (eds.) *Ordovician and*

Silurian Rocks of the Michigan Basin: Michigan Basin Geol. Soc. Symp., Spec. Paper 4, p. 45-58.

Humphrey, J.D. and T.M. Quinn, 1989, Coastal mixing zone dolomite, forward modeling, and massive dolomitization of platform-margin carbonates: *Journal of Sedimentary Petrology*, v. 59, p. 438-454.

Hurley, N.F. and Budros, R., 1990, Albion-Scipio and Stoney Point fields – U.S.A., Michigan Basin, in Beaumont, E.A., and N.H. Foster, eds., *Stratigraphic Traps I, Treatise of Petroleum Geology, Atlas of Oil and Gas Fields*: Tulsa, Oklahoma, American Association of Petroleum Geologists, p. 1-37.

Hurley, N.F., and Cumella, S.P., 1987, Dolomitization and reservoir development, Albion-Scipio field, Michigan (abs.): SEPM Annual Midyear Meeting, Program with Abstracts, v. 4, p. 37.

Jodry, R.L., 1955, Rapid method for determining magnesium/calcium ratios of well samples and its use in predicting structure and secondary porosity in calcareous formations: *AAPG Bulletin*, v. 39, p.493-511.

Jones G.D. and Xiao Y., 2005: Dolomitization, anhydrite cementation, and porosity evolution in a reflux system: Insights from reactive transport models. *American Association of Petroleum Geologists Bulletin* 89, no.5, p. 577-601.

Kaldi, J. and J. Gidman, 1982, Early diagenetic dolomite cements: Examples from the Permian Lower Magnesian Limestone of England and the Pleistocene carbonates of the Bahamas: *Journal of Sedimentary Petrology*, v. 52, p. 1073-1085.

Keith, B.D., 1985, Facies, diagenesis, and the upper contact of the Trenton Limestone of northern Indiana, in Cercone, K.R. and Budai, J.M., eds., *Ordovician and Silurian rocks of the Michigan Basin and its margins*: Michigan Basin Geological Society, Lansing Michigan, Special Paper 4, p. 15-32.

Kolata, D. R, J. K. Frost, and W. D. Huff, 1986, K-bentonites of the Ordovician Decorah Subgroup, upper Mississippi Valley: correlation by chemical fingerprinting: *Illinois State Geological Survey Circular* 537, 30 p.

Krause, F.F.; Scotese, C.R.; Nieto, C.; Sayegh, S.G.; Hopkins, J.C.; and Meyer, R.O., 2004, Paleozoic stromatolites and zebra carbonate mud-mounds: Global abundance and paleogeographic distribution, *Geology* 32: 181-184.

Lilienthal, R.T., 1978, Stratigraphic cross-sections of the Michigan Basin: *Michigan Geological Survey Division Report of Investigation* 19, 30 p.

Lucia, F.J., 1999, Carbonate Reservoir Characterization, Springer Verlag, New York, 226p.

Luczak, John A., 2001, Preliminary Results Of A Fluid-Inclusion Study On Fractured Carbonate Reservoirs Of The Dundee Formation, Central Michigan Basin, U.S.A: GSA Annual Meeting, November 5-8, 2001.

Lundy, C.L., 1968, Deep River Field, in: Wollensack, M.W., Ed (2<sup>nd</sup> printing) Michigan Basin Geological Society, Oil and Gas Fields Symposium, v. 1, p. 61-67.

Machel, H.G., and Lonnee, J., 2002, Hydrothermal Dolomite—a product of poor definition and imagination, *Sed. Geol.*, v. 152, p. 163-171.

Mavko, G., T. Mukerji, and J. Dvorkin, 1998, The rock physics handbook; tools for seismic analysis in porous media: Cambridge University Press, Cambridge, U.K., 329 p.

McCreesh, C.A.; Ehrlich, R.; and Crabtree S.J., 1991, Petrography and reservoir physics; II, Relating thin section porosity to capillary pressure, the association between pore types and throat size, *AAPG Bulletin* 75: 1563-1578.

McKenzie, J., 1981, Holocene dolomitization of calcium carbonate sediments from the coastal sabkhas of Abu Dhabi, U.A.E.: a stable isotope study: *Journal of Geology*, v. 89, p. 185-198.

Melim, L.A. and P.A. Scholle, 2002, Dolomitization of the Capitan Formation forereef facies (Permian, west Texas and New Mexico): seepage reflux revisited; *Sedimentology*, v. 49, p. 1207-1227.

Montgomery, Eric, 1986, Facies development and porosity relationships in the Dundee Limestone of Gladwin County, Michigan. Master's Thesis, Western Michigan University, 89 p.

Montgomery S.L.; Wood J.R.; Harrison W.B. III, 1998: Devonian Dundee Formation, Crystal Field, Michigan Basin: recovery of bypassed oil through horizontal drilling. *American Association of Petroleum Geologists Bulletin* 82, no.8, p. 1445-1462.

Nunn, J. A., N. H. Sleep, and W. G. Moore, 1984, Thermal subsidence and generation of hydrocarbons in Michigan basin: *American Association of Petroleum Geologists Bulletin*, v. 68, p.296-315.

Prouty, C.E., 1988, Trenton Exploration and Wrenching Tectonics – Michigan Basin and Environs, in B.D. Keith, ed. *The Trenton Group, (Upper Ordovician Series) of Eastern North America: AAPG Studies in Geology*, pp. 207-236.

Rafavich, F., C.G.St.C. Kendall, T.P. and Todd, 1984, The relationship between acoustic properties and the petrographic character of carbonate rocks: *Geophysics*, v. 49, p. 1622-1636.

Rooney, L.F., 1966, Evidence of unconformity at top of Trenton Limestone in Indiana and adjacent states: *American Association of Petroleum Geologists Bulletin*, v. 50, p. 533-546.

Ruppel, S.C. and H.S. Cander, 1988, Dolomitization of shallow-water carbonates by seawater and seawater-derived brines: San Andres Formation (Guadalupean), West Texas, in V. Shukla and P.A. Baker, eds., *Sedimentology and Geochemistry of Dolostones*: SEPM Special Publication 43, p. 245-262.

Sanford, B.V., Thompson, F. J., and McFall, G. H., 1985, Plate tectonics a possible controlling mechanism in the development of hydrocarbon traps in southwestern Ontario: *Bull. Can. Petrol. Geology*, v. 33, p. 52-71.

Sears, S.O., and F.J. Lucia, 1980, Dolomitization of northern Michigan Niagara reefs by brine refluxion and freshwater/seawater mixing, in D.H. Zenger et al., eds., *Concepts and Models of Dolomitization*: SEPM Special Publication 28, p. 215-235.

Shaw, B. 1975, *Geology of the Albion-Scipio trend, southern Michigan* (M.S. thesis): Ann Arbor, Michigan, University of Michigan, 69 p.

Simms, M., 1984, Dolomitization by groundwater flow systems in carbonate platforms: *Gulf Coast Association of Geological Societies, Transactions*, v. 24, p. 411-420.

Stout, J.L., 1964, Pore geometry as related to carbonate stratigraphic traps, *AAPG Bulletin* 48: 329-337.

Strecker, U., Carr, M., Knapp, S., Smith, M., Uden, R., and Taylor, G., 2005: Matching to Mode and Cut Risk, *AAPG Explorer*, V. 26, no.7, p. 26.

Swart, P.K. and L.A. Melim, 2000, The origin of dolomites in Tertiary sediments from the margin of Great Bahama Bank: *Journal of Sedimentary Research*, v. 70, p. 738-748.

Taylor, T.R. and Sibley, D.F., 1986, Petrographic and geochemical characteristics of dolomite types and the origin of ferron dolomite in the Trenton Formation, Ordovician, Michigan Basin, U.S.A.: *Sedimentology*, v. 33, p. 61-86.

Tedesco, S.A., 1994, Integrated exploration locates Cincinnati arch dolomite breccias. *Oil and Gas Journal*, November 28, p. 86-90.

- Tinkelpaugh, B.M., 1957, A chemically statistical and structural analysis of secondary dolomitization in the Rogers City-Dundee formation of the Central Michigan Basin: Michigan State University, unpublished Ph.D. thesis.
- Upp, J.E., Jr., 1968, Reed City Field, in: Wollensack, M.W., Ed (2<sup>nd</sup> printing) Michigan Basin Geological Society, Oil and Gas Fields Symposium, v. 1, p. 149-160.
- Wang, Z., 1997, Seismic properties of carbonate rocks, in I. Palaz and K.J. Marfurt, eds., Carbonate Seismology: Society of Exploration Geophysicists, Geophysical Development Series no.6, p. 29-52.
- Westjohn, D.B., and Weaver, T.L., 1996, Hydrogeologic framework of Mississippian rocks in the central Lower Peninsula of Michigan: U.S. Geological Survey Water-Resources Investigations Report 94-4246, 46 p.
- Whittaker, F.F., and Smart, P.L., 1990, Active circulation of saline ground waters in carbonate platforms: Evidence from the Great Bahama Bank: *Geology*, v. 18, p. 200-203.
- Whittaker, F.F., P.L. Smart, V.C. Vahrenkamp, H. Nicholson, and R.A. Wogelius, 1994, Dolomitization by near-normal seawater? Field evidence from the Bahamas, in B. Purser et al., eds., *Dolomites – A Volume in Honour of Dolomieu*: International Association of Sedimentologists Special Publication 21, p. 111-132.
- Wilson, J.L., and Sengupta, A., 1985, The Trenton formation in the Michigan Basin and environs: pertinent questions about its stratigraphy and diagenesis: in K.R. Cercone and J.M. Budai (eds.) *Ordovician and Silurian Rocks of the Michigan Basin*, Michigan Basin Geol. Soc. Symp. Spec. Paper 4, p. 1-13.
- Wood, J.R. and Harrison, W.B., 1999, Mapping and Visualization of Dolomite “Chimneys” in the Michigan Basin: DOE-PTTC Joint 1999 Oil and Gas Conference, Exploration Methods and Basin Analysis, (www version).
- Wood, J.R., 2003, Mapping Large-Scale Faults in the Michigan Basin using Tops Data: AAPG National Meeting, 2003 AAPG Bulletin Vol. 87, No. 13
- Zempolich, W.G., and L.A. Hardie, 1997, Geometry of dolomite bodies within deep-water resedimented oolite of the Middle Jurassic Vajont Limestone, Venetian Alps, Italy: analogs for hydrocarbon reservoirs created through fault-related burial dolomitization, in J.A. Kupecz et al., eds., *Reservoir Quality Prediction in Sandstones and Carbonates*: American Association of Petroleum Geologists Memoir 69, p. 127-162.

## BIBLIOGRAPHY (TASK 2.1)

- Abbott, P. L., 1974, Calcitization of Edwards Group dolomites in the Balcones Fault Zone aquifer, south-central Texas, v. 2, p. 359-362.
- Abdel-Gawad, A. M., and P. F. Kerr, 1963, Alteration of Chinle siltstone and uranium emplacement, Arizona and Utah: Geological Society of America Bulletin, v. 74, p. 23-46.
- Adams, J. E., and M. L. Rhodes, 1960, Dolomitization by seepage refluxion, v. 44, p. 1912-1920.
- Ahsan, N., 1998, Tithonian to Danian sedimentation in Hazara Basin, northern Pakistan: AAPG Foundation grants-in-aid recipients for 1998; abstracts AAPG Bulletin, v. 82, p. 2158.
- Aitken, J. D., 1967, Classification and environmental significance of cryptalgal limestones and dolomites, with illustrations from the Cambrian and Ordovician of SW Alberta, v. 37, p. 1163-1178, 22 Figs.
- Aitken, J. D., 1977, Classification and environmental significance of cryptalgal limestones and dolomites. With illustrations from the Cambrian and Ordovician of southwest Alberta, v. 14, p. 405-441.
- Al-Aasm, I. S., and J. J. Packard, 2000, Stabilization of early-formed dolomite: a tale of divergence from two Mississippian dolomites, v. 131, p. 97-108, 7 Figs., 1 Tab.
- Allan, J. R., and W. D. Wiggins, 1993, Dolomite reservoirs, geochemical techniques for evaluating origin and distribution, v. 36, p. 167pp.
- Alling, H. L., and L. I. Briggs, 1961, Stratigraphy of Upper Silurian Cayugan Evaporites: Bulletin of the American Association of Petroleum Geologists, v. 45, p. 515-547.
- Aminian, K., S. Ameri, and R. M. Bomar, 1987, Evaluation of Silurian-Niagaren Reef Belt in Northeastern Michigan: Society of Petroleum Engineers, p. 428-434.
- Al-Shaieb, Z., and J. W. Shelton, 1978, Secondary ferroan dolomite rhombs in oil reservoirs, Chadra sands, Gialo Field, Libya: AAPG Bulletin, v. 62, p. 463-468.
- Amiri-Garroussi, K., 1988, Eocene spheroidal dolomite from the western Sirte Basin, Libya, v. 35, p. 577-585, 4 Figs.
- Amthor, J. E., E. W. Mountjoy, and H. G. Machel, 1993, Subsurface dolomites in Upper Devonian Leduc Formation buildups central part of Rimbey-Meadowbrook reef trend, Alberta, Canada, v. 41, p. 164-185, 15 Figs., 5 Tabs.
- Amthor, J. E., and J. Okkerman, 1998, Influence of early diagenesis on reservoir quality of Rotliegende sandstones, northern Netherlands: AAPG Bulletin, v. 82, p. 2246-2265.
- Antonellini, M., and P. L. Mollema, 2000, A Natural Analog for a Fractures and Faulted Reservoir in Dolomite: Triassic Sella Group, Northern Italy: The American Association of Petroleum Geologists Bulletin, v. 84, p. 314-344.
- Antonellini, M., and P. N. Mollema, 2000, A natural analog for a fractured and faulted reservoir in dolomite; Triassic Sella Group, northern Italy: AAPG Bulletin, v. 84, p. 314-344.
- Aref, M. A. M., 1998, Biogenic carbonates; are they a criterion for underlying hydrocarbon accumulations? An example from the Gulf of Suez region, Egypt: AAPG Bulletin, v. 82, p. 336-352.
- Arvidson, R. S., and F. T. Mackenzie, 1997, Tentative kinetic model for dolomite



- precipitation rate and its application to dolomite distribution: *Aquatic Geochemistry*, v. 2, p. 273-298.
- Arvidson, R. S., and F. T. Mackenzie, 1999, The dolomite problem: control of precipitation eunetics by temperature and saturation state, v. 299.
- Arvidson, R. S., F. T. Mackenzie, and M. Guidry, 2002, Ocean/atmosphere history and carbonate precipitation rates: a solution to the 'dolomite problem'?, v. 66, p. 1-5, 4 Figs.
- Assereto, R., and R. L. Folk, 1980, Diagenetic fabrics of aragonite, calcite, and dolomite in an ancient peritidal-spelean environment; Triassic Calcare rosso, Lombardia, Italy: *Journal of Sedimentary Petrology*, v. 50, p. 371-394.
- Assereto, R., and R. L. Folk, 1980, Diagenetic fabrics of aragonite, calcite and dolomite in ancient peritidal-spelean environment: Triassic Calcare Rosso, Lombardia, Italy, v. 50/2, p. 371-394, 17 Figs.
- Assereto, R. L., and A. Rizzini, 1975, Reworked ferroan dolomite grains in the Triassic 'oolite a gasteropodi' of Camoniche Alps (Italy) as indicators of early diagenesis, v. 148/2, p. 215-232, 13 Figs.
- Atchley, S. C., M. G. Kozar, and L. A. Yose, 1999, A predictive model for reservoir distribution in the Permian (Leonardian) Clear Fork and Glorieta formations, Robertson Field area, West Texas: *AAPG Bulletin*, v. 83, p. 1031-1056.
- Ayyildiz, T., E. Tekin, and M. Satir, 2004, Water circulation near the mixed-water and microbiologic activity of the Mesozoic dolomite sequence, an example from the central Taurus, Turkey: *Carbonates and Evaporites*, v. 19, p. 107-117.
- Babic, L., 1969, Sphaerocodium or onkoids from the Upper Triassic Dolomite of Western Yugoslavia, v. 23, p. 11-19, 1 Fig., 1 Pl.
- Baker, P. A., and S. J. Burns, 1985, Occurrence and formation of dolomite in organic-rich continental margin sediments: *AAPG Bulletin*, v. 69, p. 1917-1930.
- Baker, P. A., and M. Kastner, 1981, Constraints on the formation of sedimentary dolomites, v. 213, p. 214-216.
- Balog, A., J. F. Read, and J. Haas, 1999, Climate-controlled early dolomite, Late Triassic cyclic platform carbonates, Hungary, v. A69, p. 267-282, 17 Figs., 3 Tabs.
- Balogh, R. J., 1981, A study of the Middle Silurian Belle River Mills, Peters, and Ray Pinnacle Reefs from the Michigan Basin: MS thesis, Bowling Green State University, 201 pp.
- Banner, J. L., G. N. Hanson, and W. J. Meyers, 1988, Rare earth element and Nd isotopic variations in regionally extensive dolomites from the Burlington-Keokuk Formation (Mississippian); implications for REE mobility during carbonate diagenesis: *Journal of Sedimentary Petrology*, v. 58, p. 415-432.
- Banner, J. L., G. N. Hansson, and W. J. Meyers, 1988, Rare earth elements and Nd isotope variations in regionally extensive dolomites from the Burlington-Keokuk Formation (Mississippian): implications for the REE Mobility during carbonate diagenesis, v. 58/3, p. 415-432, 15 Figs.
- Banner, J. L., G. N. Hansson, and W. J. Meyers, eds., 1988, Water-rock interaction history of regionally extensive dolomites of the Burlington-Keokuk Formation (Mississippian): Isotope evidence, v. 43: Tulsa, 97-111, 12 Figs. p.
- Barber, D. J., R. J. Reeder, and D. J. Smith, 1985, A TEM microstructural study of

- dolomite with curved facies (saddle dolomite), v. 91, p. 82-92.
- Barclay, S. A., R. H. Worden, J. Parnell, D. L. Hall, and S. M. Sterner, 2000, Assessment of fluid contacts and compartmentalization in sandstone reservoirs using fluid inclusions; an example from the Magnus oil field, North Sea: *AAPG Bulletin*, v. 84, p. 489-504.
- Barnaby, R. J., and J. F. Read, 1992, Dolomitization of a carbonate platform during late burial: Lower to Middle Cambrian Shady dolomite, Virginia Appalachians, v. 62/6, p. 1023-1043, 16 Figs., 1 Tab.
- Barrick, J. E., 1983, Wenlockian (Silurian) Conodont biostratigraphy, biofacies and carbonate lithofacies, Wayne formation, Central Tennessee: *Journal of Paleontology*, v. 57, p. 208-239.
- Bassias, Y., and P. Cros, 1992, Dolomite and chert diagenesis in Upper Cretaceous pelagic sediments. Southern Kerguelen Plateau Md48: Naska dredges, v. 184, p. 359-388, 4 Pls., 5 Figs., 4 Tabs.
- Baum, G. R., W. B. Harris, and P. E. Drez, 1985, Origin of dolomite in the Eocene Castle Hayne Limestone, North Carolina: *Journal of Sedimentary Petrology*, v. 55, p. 506-517.
- Baum, G. R., W. B. Harris, and P. E. Drez, 1985, Origin of dolomite in the Eocene Castle Hayne Limestone, North Carolina, v. 55/4, p. 506-517, 10 Figs.
- Bausch, W. M., and J. Hoefs, 1972, Die Isotopenzusammensetzung von Dolomiten und Kalken aus dem süddeutschen Malm, v. 37, p. 121-130, 5 Figs., 2 Tabs.
- Beales, F. W., and J. L. Hardie, 1980, Criteria for the recognition of diverse dolomite types with an emphasis on studies of host rocks for Mississippian Valles-type ore deposits, v. 28, p. 197-213, 4 Figs.
- Bein, A., and L. S. Land, 1983, Carbonate sedimentation and diagenesis associated with Mg-Ca-chloride brines; the Permian San Andres Formation in the Texas Panhandle: *Journal of Sedimentary Petrology*, v. 53, p. 243-260.
- Benedict G. L. I. and Walker K. R. (1978) Paleobathymetric analysis in Paleozoic sequences and its geodynamic significance. *American Journal of Science* 278, 579-607.
- Bernasconi, S. M., 1994, Geochemical and microbial controls on dolomite formation in anoxic environments: a case study from the Middle Triassic (Ticino, Switzerland), v. 19, p. 1-109, 7 Pls., 20 Figs., 6 Tabs.
- Bernoulli, D., L. Gasperini, E. Bonatti, and P. Stille, 2004, Dolomite formation in pelagic limestone and diatomite, Romanche fracture zone, Equatorial Atlantic: *Journal of Sedimentary Research*, v. 74, p. 924-932.
- Bertrand-Sarfati, J., and A. Moussine-Pouchkine, 1983, Platform-to-basin facies evolution; the carbonates of late Proterozoic (Vendian) Gourma (West Africa): *Journal of Sedimentary Petrology*, v. 53, p. 275-293.
- Biddle, K. T., 1983, Girvanella oncoids from Middle to Upper Triassic allochthonous boulders of the Dolomite Alps, Northern Italy: Berlin, Springer, p. 390-397, 6 Figs.
- Biddle, K. T., W. Schlager, K. W. Rudolph, and T. L. Bush, 1991, Seismic model of a progradational carbonate platform, Picco di Vallandro, the Dolomites, Northern Italy, v. 76/1, p. 14-50, 11 Figs.

- Biddle, K. T., W. Schlager, K. W. Rudolph, and T. L. Bush, 1992, Seismic model of a progradational carbonate platform, Picco di Vallandro, the dolomites, Italy, v. 76, p. 14-30.
- Biddle, K. T., W. Schlager, K. W. Rudolph, and T. L. Bush, 1992, Seismic model of a progradational carbonate platform, Picco di Vallandro, the Dolomites, Northern Italy: American Association of Petroleum Geologists Bulletin, v. 76, p. 14-30.
- Blake, D. F., D. R. Peacor, and B. H. Wilkinson, 1982, The sequence and mechanism of low-temperature dolomite formation: Calician dolomites in a Pennsylvanian echinoderm, v. 52/1, p. 59-70, 4 Figs.
- Blau, J., 1987, Neue Foraminiferen aus dem Lias der Lienzer Dolomiten Teil I: Die Foraminiferenfauna einer roten Spaltenfüllung in Oberrhätalkalken, v. 129, p. 495-523, 2 Figs., 7 Pls.
- Blau, J., 1987, Neue Foraminiferen aus dem Lias der Lienzer Dolomiten Teil II: Foraminiferen (Involutinen, Spirillinen) aus der Lavanter Breccie (Lienzer Dolomiten) und den Nördlichen Kalkalpen, v. 130, p. 5-23, 1 Fig., 5 Pls.
- Blau, J., and B. Grün, 1992, Calpionelen der tiefen Unterkreide im Apt/Alb der Lienzer Dolomiten: Ein Beispiel für umgelagerte Faunen, v. 48, p. 9-28, 2 Pls., 3 Figs.
- Blau, J., B. Grün, and M. Senff, 1993, Crustaceen-Koprolithen aus der Trias der westlichen Tethys (Lienzer Dolomiten, Österreich; Pragser Dolomiten, Italien) und vom Gondwana-Westrand (oberes Magdalenatal, Kolumbien, Südamerika), v. 67, p. 193-214, 12 Figs.
- Blendinger, W., 1985, Radiolarian limestones interfingering with Loferrites (Triassic, Dolomites, Italy), v. 1985, p. 193-202, 7 Figs.
- Blendinger, W., 1986, Isolated stationary carbonate platforms: the Middle Triassic (Ladinian) of the Marmolada area, Dolomites, Italy, v. 33, p. 159-183, 21 Figs.
- Blendinger, W., 1994, The carbonate factory of Middle Triassic buildups in the Dolomites, Italy: a quantitative analysis: Sedimentology, v. 41, p. 1147-1159.
- Blendinger, W., 1997, Dolomitization of the Dolomites (Triassic, Italy): pilot study, v. 204, p. 83-110.
- Blendinger, W., 2001, Triassic carbonate buildup flanks in the dolomites, northern Italy: breccias, boulder fabric and the importance of early diagenesis, v. 48, p. 919-933, 11 Figs.
- Blendinger, W., and E. Blendinger, 1989, Windward-leeward effect on Triassic carbonate bank margin facies of the Dolomites, northern Italy, v. 64, p. 143-166, 18 Figs.
- Blendinger, W., 1994, The carbonate factory of Middle Triassic buildups in the Dolomites, Italy: a quantitative analysis: Sedimentology, p. 1147-1159.
- Bliefnick, D. M., and W. C. Belfield, 1991, The Ordovician Arbuckle Group of Oklahoma - a karsted dolomite reservoir: Ortisei, p. 17-18.
- Boles, J. R., C. A. Landis, and P. Dale, 1985, The Moeraki Boulders; anatomy of some septarian concretions: Journal of Sedimentary Petrology, v. 55, p. 398-406.
- Bone, Y., N. P. James, and T. K. Kyser, 1992, Synsedimentary detrital dolomite in Quaternary cool-water carbonate sediments, Lacopede shelf, South Australia, v. 20, p. 109-112, 4 Figs., 1 Tab.
- Bone, Y., N. P. James, and T. K. Kyser, 1992, Syndsedimentary detrital dolomite in Quaternary cool-water carbonate sediments, Lacepee shelf, South Australia:

- Geology, v. 20, p. 109-112.
- Boni, M., G. Parente, T. Bechstadt, B. De Vivo, and A. Iannace, 2000, Hydrothermal dolomites in SW Sardinia (Italy): evidence for a widespread late-Variscan fluid flow event: *Sedimentary Geology*, v. 131, p. 181-200.
- Boni, M., G. Parente, T. Bechstadt, B. De Vivo, and A. Iannace, 2000, Hydrothermal dolomites in SW Sardinia (Italy): evidence for a widespread late-Variscan fluid flow event, v. 131, p. 181-200, 12 Figs., 2 Tabs.
- Boone, P. A., and D. B. Moore, 1975, Churchill Field; giant in the making?: *AAPG Bulletin*, v. 59, p. 1723-1724.
- Bornemann, E., and J. H. Doveton, 1983, Lithofacies mapping of Viola Limestone in south-central Kansas, based on wireline logs: *AAPG Bulletin*, v. 67, p. 609-623.
- Bosellini, A., 1966, Protointraclasts: texture of some Werfenian (Lower Triassic) limestones of the Dolomites (Northeastern Italy), v. 6, p. 333-337, 2 Figs.
- Bosellini, A., 1984, Progradation geometries of carbonate platforms: examples from the Triassic of the Dolomites, northern Italy: *Sedimentology*, v. 31, p. 1-24.
- Bosellini, A., and D. Rossi, 1974, Triassic carbonate buildups of the dolomites, northern Italy: *Referin Time and Space*, p. 209-233.
- Bourque, P., M. Malo, and D. Kirkwood, 2000, Paleogeography and tectono-sedimentary history at the margin of Laurentia during Silurian to earliest Devonian time: The Gaspe Belt, Quebec: *GSA Bulletin*, v. 112, p. 4-20.
- Bourque, P.-A., 1989, Silurian Reefs, in H. H. J. Geldsetzer, N. P. James, and G. E. Tebbutt, eds., *Reefs, Canada and Adjacent Areas*, v. Memoir 13, Canadian Society of Petroleum Geologists, p. 245-250.
- Brachert, T. C., and W. C. Dullo, 1994, Micrite crusts on Ladinian foreslopes of the dolomites seen in the light of a modern scenario from the Red Sea: *Abh. Geol. B.-A.*, v. 50, p. 57-68.
- Brachert, T. C., and W. C. Dullo, 1994, Micrite crusts on Ladinian foreslopes of the Dolomites seen in the light of a modern scenario from the Red Sea, v. 50, p. 57-68, 3 Pls., 3 Figs.
- Brady, P. V., Krumhansl, J.L., and Papenguth, H.W., 1996, Surface complexation clues to dolomite growth: *Geochimica et Cosmochimica acta*, v. 60, p. 727-731.
- Braithwaite, C. J. R., 1986, Mechanically induced stylolites and loss of porosity in dolomites, v. 9, p. 343-348.
- Brandner, R., E. Flügel, and B. Senowbari-Daryan, 1991, Microfacies of carbonate slope boulders: indicator of the source area (Middle Triassic: Mählknecht Cliff, Western Dolomites), v. 25, p. 279-296, Pl. 69-74, 3 Figs., 1 Tab.
- Bruckschen, P., S. Nöth, and D. K. Richter, 1990, Tempered microdolomites in crinoids: a new criterion for high diagenesis, v. 5, p. 197-207.
- Bruckschen, P., S. Nöth, and D. K. Richter, 1990, Tempered microdolomites in crinoids: a new criterion for high-grade diagenesis, v. 5, p. 197-207, 9 Figs., 1 Tab.
- Brunton, F. R., L. Smith, O. A. Dixon, P. Copper, H. Nestor, and S. Kershaw, 1998, Silurian reef episodes, changing seascapes, and paleobiogeography: *Bulletin - New York State Museum*, v. 491.
- Budai, J. M., K. C. Lohmann, and R. M. Owen, 1984, Burial dedolomite in the Mississippian Madison Limestone, Wyoming and Utah Thrust Belt: *Journal of*

- Sedimentary Petrology, v. 54, p. 276-288.
- Budd, D. A., 1997, Cenozoic dolomites of carbonate islands: their attributes and origin, v. 42, p. 1-47.
- Budros, R., 1974, The stratigraphy and petrogenesis of the Ruff formation, Salina Group in Southeast Michigan: Masters of Science thesis, University of Michigan, Ann Arbor, 178 p.
- Budros, R., and L. I. Briggs, 1975, Depositional environment of Ruff Formation in Southeast Michigan: AAPG Bulletin, v. 59, p. 1734-1735.
- Buelter, D. P., and R. N. Guillemette, eds., 1988, Geochemistry of epigenetic dolomite associated with lead-zinc mineralization of the Viburnum Trend, Southeast Missouri: A reconnaissance study, v. 43: Tulsa, 85-93, 8 Figs. p.
- Bullen, S. B., and D. F. Sibley, 1984, Dolomite selectivity and mimic replacement, v. 12, p. 655-658.
- Burger, D., ed., 1989, Dolomite weathering and micromorphology of palaeosoils in the Franconian Jura, v. 15: Cremlingen, 261-267, 13 Figs. p.
- Burns, S. J., and P. A. Baker, 1987, A geochemical study of dolomite in the Monterey Formation, California, v. 57/1, p. 128-139, 9 Figs.
- Burns, S. J., P. A. Baker, and W. J. Showers, eds., 1988, The factors controlling the formation and chemistry of dolomite in organic-rich sediments.: Miocene Drakes Bay Formation, California, v. 43: Tulsa, 41-52, 10 Figs. p.
- Burns, S. J., J. A. McKenzie, and G. Vasconcelos, 2000, Dolomite formation and biogeochemical cycles in the Phanerozoic, v. 47, p. 49-61, 4 Figs.
- Butler, P. E., 1961, Morphologic classification of sponge spicules, with descriptions of siliceous spicules from the Lower Ordovician Bellefonte dolomite in Central Pennsylvania, v. 35, p. 191-200, Pl. 39, 7 Figs.
- Calver, C. R., and P. W. Baillie, 1990, Early diagenetic concretions associated with intrastratal shrinkage cracks in an upper Proterozoic dolomite, Tasmania, Australia: Journal of Sedimentary Petrology, v. 60, p. 293-305.
- Calver, C. R., and P. W. Baillie, 1990, Early diagenetic concretions associated with interstratal shrinkage cracks in an Upper Proterozoic dolomite, Tasmania, Australia, v. 60/2, p. 293-305, 7 Figs.
- Canaveras, J. C., S. Sanchez-Moral, J. P. Calvo, M. Hojos, and S. Ordonez, 1996, Dedolomites associated with karstification, an example of early dedolomitization in lacustrine sequences from the Tertiary Madrid Basin, Central Spain, v. 11, p. 85-103, 13 Figs.
- Cander, H. S., 1994, An example of mixing-zone dolomite, Middle Eocene Avon Park Formation, Floridan aquifer system, v. A64, p. 615-629, 13 Figs.
- Capo, R. C., C. E. Whipkey, J. R. Blachère, and O. A. Chadwick, 2000, Pedogenic origin of dolomite in a basaltic weathering profile, Kohala peninsula, Hawaii, v. 28, p. 271-274, 3 Figs., 2 Tab.
- Carpenter, A. B., 1980, The chemistry of dolomite formation I: the stability of dolomite, v. 28, p. 111-121, 7 Figs., 5 Tabs.
- Catacosinos P. A., Harrison W. B. I., Reynolds R. F., Westjohn D. B., and Wollensak M. S. (2001) *Stratigraphic Lexicon for Michigan*. Geological Survey Division of the DEQ and the Michigan Basin Geological Society 56 pp.

- Catalov, A. G., 1999, Calcitization of dolomite in Spathian and Anisian carbonate rocks from the Western Balkanides, Bulgaria, v. 1999, p. 614-640, 8 Figs.
- Cayeux, L., 1970, Les roches sédimentaires de France. Roches carbonatées (calcium et dolomies) - Sedimentary rocks of France. Carbonate rocks (limestones and dolomites): Darien, Hafner, 506 pp., 26 Figs.
- Cercone, K. R., and K. C. Lohman, 1987, Late Burial Diagenesis of the Niagaran (Middle Silurian) Pinnacle Reefs in Michigan Basin: AAPG Bulletin, v. 71, p. 156-166.
- Cercone, K. R., and K. C. Lohmann, 1986, Diagenetic History of the Union 8 Pinnacle Reef (Middle Silurian), Northern Michigan, USA, in J. H. Schroeder, and B. H. Purser, eds., Reef Diagenesis: Springer- Verlag Berlin Heidelberg, p. 382-388.
- Cercone, K. R., and K. C. Lohmann, 1987, Late Burial Diagenesis of Niagaran (middle Silurian) Pinnacle Reefs in Michigan Basin: The American Association of Petroleum Geologists Bulletin, v. 71, p. 156-166.
- Chafetz, H. S., and P. F. Rush, 1994, Diagenetically altered sabkha-type Pleistocene dolomite from the Arabian Gulf, v. 41, p. 409-421, 6 Figs., 3 Tabs.
- Chafetz, H. S., and J. Zhang, 1998, Authigene euhedral megaquartz crystals in Quaternary dolomite, v. A68, p. 994-1000, 5 Figs.
- Chahi, A., P. Düringer, M. Ais, M. Bouabdelli, F. Gauthier-Lafaye, and B. Fritz, 1999, Diagenetic transformation of dolomite into stevensite in lacustrine sediments from Jbel Rhassoul, Morocco, v. A69, p. 1123-1135, 14 Figs., 4 Tabs.
- Charbonneau, S. L., 1990, Subaerial Exposure of Middle Silurian Guelph Formation Pinnacle Reefs of the Michigan Basin, Southwestern Ontario: Ontario Petroleum Institute, v. 29, p. 1-22.
- Chave, K. E., 1952, A solid solution between calcite and dolomite: Journal of Geology, v. 60, p. 190-192.
- Choquette, P. W., and R. P. Steinen, 1980, Mississippian non-supratidal dolomite: Ste. Genevieve Limestone, Illinois Basin: evidence for mixed-water dolomitization, v. 28, p. 163-196.
- Choquette, P. W., and R. P. Steinen, 1985, Mississippian oolite and non-supratidal dolomite reservoirs in the Ste. Genevieve Formation, North Bridgeport Field, Illinois Basin: New York, Springer, p. 207-225, 14 Figs.
- Chow, N., and F. J. Longstaffe, 1995, Dolomites of the Middle Devonian Elm Point Formation, southern Manitoba; intrinsic controls on early dolomitization, v. 43, p. 214-255.
- Cioppa, M. T., I. S. Al-Aasm, D. T. A. Symons, and K. P. Gillen, 2003, Dating penecontemporaneous dolomitization in carbonate reservoirs; paleomagnetic, petrographic, and geochemical constraints: AAPG Bulletin, v. 87, p. 71-88.
- Clari, P., S. Cavagna, L. Martire, and J. Hunziker, 2004, A Miocene mud volcano and its plumbing system; a chaotic complex revisited (Monferrato, NW Italy): Journal of Sedimentary Research, v. 74, p. 662-676.
- Clasen, S., R. Jantschik, and D. Meischner, 1991, Authigenic dolomite in the North Atlantic deep sea: Ortisei, p. p. 53.
- Cocks L. R. M. (2001) Ordovician and Silurian global geography. *Journal of the Geological Society of London* 158, 197-210.
- Compton, J. S., ed., 1988, Sediment composition and precipitation of dolomite and pyrite

- in the Neogene Monterey and Sisquoc Formations, Santa Maria Basin area, California, v. 43: Tulsa, 53-64, 7 Figs. p.
- Compton, J. S., 1988, Degree of supersaturation and precipitation of organogenic dolomite, v. 16, p. 318-321.
- Compton, J. S., D. L. Hall, D. J. Mallinson, and D. A. Hodell, 1994, Origin of dolomite in the phosphatic Miocene Hawthorn Group of Florida, v. A64, p. 638-649, 9 Figs., 5 Tabs.
- Cooper, M., 1999, Exploring for hydrocarbons in the Cambro-Ordovician of Newfoundland and Quebec: 1999-2000 AAPG distinguished lecturers AAPG Bulletin, v. 83, p. 1879.
- Cooper, M., J. Weissenberger, I. Knight, D. Hostad, D. Gillespie, H. Williams, E. Burden, J. Porter-Chaudhry, D. Rae, and E. Clark, 2001, Basin evolution in western Newfoundland; new insights from hydrocarbon exploration: AAPG Bulletin, v. 85, p. 393-418.
- Craig, D. H., 1988, Caves and other features of Permian karst in San Andres Dolomite, Yates Field Reservoir, West Texas: Berlin, Springer, p. 342-363, 18 Figs., 1 Tab.
- Cros, P., 1977, Données nouvelles sur la dolomitisation des carbonates triasiques des Dolomites Italiennes, v. 21/4, p. 307-355, 4 Pls., 10 Figs.
- Curtis, C. D., and M. L. Coleman, 1986, Controls on the precipitation of early diagenetic calcite, dolomite and siderite concretions in complex depositional sequences, v. 38, p. 23-33, 7 Figs.
- Curtis, R., G. Evans, D. J. J. Kinsmann, and D. J. Shearman, 1963, Association of dolomite and anhydrite in the Recent sediments of the Persian-Gulf, v. 197, p. 697-680.
- Czurda, K., and L. Nicklas, 1970, Zur Mikrofazies und Mikrostratigraphie des Hauptdolomites und Plattenkalk-Niveaus der Klostertaler Alpen und des Rhätikon (Nördliche Kalkalpen, Vorarlberg), p. 165-253.
- Danin, A., R. Gerson, K. Marton, and J. Garty, 1982, Patterns of limestone and dolomite weathering by lichens and blue-green algae and their palaeoclimatic significance, v. 37, p. 221-233, 10 Figs.
- Dapples, E. C., 1962, Stages of diagenesis in the development of sandstones: Geological Society of America Bulletin, v. 73, p. 913-933.
- Daughtry, A. C., D. Perry, and M. Williams, 1962, Magnesium isotopic distribution in dolomite, v. 26, p. 857-866, 3 Figs.
- Davidson, P. M., 1994, Ternary iron, magnesium, calcium carbonates - a thermodynamic model for dolomite as an ordered derivative of calcite-structure solutions, v. 79, p. 332-229.
- Davies, G. R., 1979, Dolomite reservoir rocks: processes, controls, porosity development, v. 11, p. C1-C17.
- Davies, G. R., 2000, Hydrothermal Dolomite Reservoir Facies: Global and Western Canadian Perspectives: Calgary.
- Davis, R. A., Jr., 1966, Willow River Dolomite: Ordovician analogue of modern algal stromatolite environments: Journal of Geology, v. 74, p. 908-923.
- Dawans, J. M., and P. K. Swart, 1988, Textural and geochemical alternations in Late Cenozoic Bahamian dolomites, v. 35, p. 385-403, 15 Figs.

- Dawans, J. M., and P. K. Swart, 1988, Textural and geochemical alterations in Late Cenozoic Bahamian dolomites: *Sedimentology*, v. 35, p. 385-403.
- De Deckker, P., and W. M. Last, 1989, Modern, non-marine dolomite in evaporitic playas of western Victoria, Australia, v. 64/4, p. 223-238, 6 Figs.
- De Leeuw, N. H., 2002, Surface structures, stabilities, and growth of magnesian calcites—a computational investigation from the perspective of dolomite formation, v. 87, p. 679-689.
- de Souza, R. S., L. F. de Ros, and S. Morad, 1995, Dolomite diagenesis and porosity preservation in lithic reservoirs; Carmopolis Member, Sergipe-Alagoas Basin, northeastern Brazil: *AAPG Bulletin*, v. 79, p. 725-748.
- DeCelles, P. G., and R. C. Gutschick, 1983, Mississippian wood-grained chert and its significance in the Western Interior United States: *Journal of Sedimentary Petrology*, v. 53, p. 1175-1191.
- Deckker, P., and W. M. Last, 1988, Modern dolomite deposition in continental, saline lakes, western Victoria, Australia, v. 16, p. 29-32.
- Deelman, J. C., L. S. Land, and R. L. Folk, 1975, Mg/Ca ratio and salinity; two controls over crystallization of dolomite: *AAPG Bulletin*, v. 59, p. 2056-2057.
- Degens, E. T., and S. A. Epstein, 1964, Oxygen and carbon isotope ratios in coexisting calcites and dolomites from recent and ancient sediments, v. 28, p. 23-44.
- Dehler, C. M., M. Elrick, J. D. Bloch, L. J. Crossey, K. E. Karlstrom, and D. J. Des Marais, 2005, High-resolution delta (super 13) C stratigraphy of the Chuar Group (ca. 770-742 Ma), Grand Canyon; implications for mid-Neoproterozoic climate change: *Geological Society of America Bulletin*, v. 117, p. 32-45.
- Deike, R. G., 1990, Dolomite dissolution rates and possible Holocene dedolomitization of water-bearing units in the Edwards Aquifer, south-central Texas, v. 112, p. 335-373.
- Demicco, R. V., 1983, Wavy and lenticular-bedded carbonate ribbon rocks of the Upper Cambrian Conococheague Limestone, central Appalachians: *Journal of Sedimentary Petrology*, v. 53, p. 1121-1132.
- DeMis, W. D., and D. Petty, 1990, Depositional facies, textural characteristics, and reservoir properties of dolomites in Frobisher-Alida interval in Southwest North Dakota; discussion and reply: *AAPG Bulletin*, v. 74, p. 564-566.
- Depowski, S., and T. M. Peryt, 1985, Carbonate Petroleum Reservoirs in the Permian Dolomites of the Zechstein, Fore-Sudetic Area, Western Poland: New York, Springer, p. 251-264, 11 Figs.
- Derby, J. R., and J. T. Kilpatrick, 1985, Ordovician Red River Dolomite Reservoirs, Killdeer Field, North Dakota: New York, Springer, p. 59-69, 9 Figs.
- Devaney, K. A., B. H. Wilkinson, and R. van der Voo, 1986, Deposition and compaction of carbonate clinothems: The Silurian Pipe Creek Junior Complex of east-central Indiana: *GSA Bulletin*, v. 97, p. 1367-1381.
- Dickson, J. A. D., 2004, Echinoderm skeletal preservation; calcite-aragonite seas and the Mg/Ca ratio of Phanerozoic oceans: *Journal of Sedimentary Research*, v. 74, p. 355-365.
- Dockal, J. A., 1988, Thermodynamic and kinetic description of dolomitization of calcite and calcitization of dolomite (dedolomitization), v. 3/2, p. 125-141, 8 Figs.



- Doglioni, C., A. Bosellini, and P. R. Vail, 1990, Stratal patterns: a proposal of classification and examples from the Dolomites, v. 2, p. 83-95, 18 Figs.
- Doherty, P. D., G. S. Soreghan, and J. P. Castagna, 2002, Outcrop-based reservoir characterization; a composite phylloid-algal mound, western Orogrande Basin (New Mexico): AAPG Bulletin, v. 86, p. 779-795.
- Donaldson, A. C., M. T. Heald, J. J. Renton, and S. M. Warshauer, 1975, Depositional environment of Rome Trough rocks, Mingo County Well, West Virginia: AAPG Bulletin, v. 59, p. 1735.
- Dorobek, S. L., and R. H. Filby, 1988, Origin of dolomites in a downslope biostrome, Jefferson Formation (Devonian), Central Idaho: Evidence from reef patterns, stable isotopes, and petrography, v. 36, p. 202-215, 9 Figs.
- Dorobek, S. L., T. M. Smith, and P. M. Whitsitt, 1990, Microfabrics and geochemical trends associated with meteoric alteration of early, near-surface dolomite, p. p. 33.
- Dorobek, S. L., T. M. Smith, and P. M. Whitsitt, eds., 1993, Microfabrics and geochemistry of meteorically altered dolomite in Devonian and Mississippian carbonates, Montana and Idaho: New York, Springer, 205-225, 13 Figs. p.
- dos Anjos, S. M. C., L. F. De Ros, R. Schiffer de Souza, C. M. de Assis Silva, and C. L. Sombra, 2000, Depositional and diagenetic controls on the reservoir quality of Lower Cretaceous Pendencia sandstones, Potiguar rift basin, Brazil: AAPG Bulletin, v. 84, p. 1719-1742.
- Dozet, S., 1990, The Lofer cyclothem in the main dolomite (Hauptdolomit) of the Kocevje area, v. 37, p. 507-528.
- Dozet, S., 1990, The Lofer cyclothem in the Main Dolomite (Hauptdolomit) of the Kocevje area, v. 37, p. 507-528, 4 Pls., 3 Figs.
- Dozet, S., 1991, Norian oncoids in the Main Dolomite of the Kocevje area, v. 38, p. 79-95, 2 Pls., 1 Fig.
- Dravis, J. J., and I. D. Muir, 1991, Controls on widespread dissolution of burial dolomites, Middle Devonian Upper Elk Point Group, western Canada: Ortisei, p. p. 64.
- Droste, J. B., and R. H. Shaver, 1976, Synchronization of Deposition: Silurian Reef-Bearing Rocks on Wabash Platform with Cyclic Evaporites of Michigan Basin: AAPG Bulletin, p. 93-109.
- Droste, J. B., and R. H. Shaver, 1982, The Salina Group (Middle and Upper Silurian) of Indiana: Department of Natural Resources Geological Survey Special Report, v. 24, p. 41 pp.
- Droste, J. B., and R. H. Shaver, 1985, Comparative Stratigraphic Framework for Silurian Reefs--Michigan Basin to Surrounding Platforms: Ordovician and Silurian Rocks of the Michigan Basin and its Margins, p. 73-93.
- Durocher, S., and I. S. Al-Aasm, 1997, Dolomitization and neomorphism of Mississippian (Visean) upper Debolt Formation, Blueberry Field, northeastern British Columbia; geologic, petrologic, and chemical evidence: AAPG Bulletin, v. 81, p. 954-977.
- Dworkin, S. I., and L. S. Land, 1991, Depositional and pore fluid controls on the formation of dolomite cements, Smackover Sandstones, Gulf of Mexico: Ortisei, p. 66.

- Ehlers E. G. and Kesling R. V. (1957) *Silurian Rocks of the Northern Peninsula of Michigan*. Michigan Basin Geological Society, pp 63.
- Ehlers G. M. (1921) Niagaran Rocks of the Northern Peninsula of Michigan. *GSA Bulletin* 32, 129-130.
- Ehlers G. M. (1930) Stratigraphy of the Niagaran Series of the Northern Peninsula of Michigan. Ph.D., University of Michigan, pp 339.
- Ehlers G. M. (1973) *Stratigraphy of the Niagaran Series of the Northern Peninsula of Michigan*. University of Michigan, pp 200.
- Ehlers G. M. and Kesling R. V. (1962) *Silurian Rocks of Michigan and their Correlation*. University of Michigan, 20 pp.
- Ehrenberg, S. N., and T. A. Svana, 2001, Use of spectral gamma-ray signature to interpret stratigraphic surfaces in carbonate strata; an example from the Finnmark carbonate platform (Carboniferous-Permian), Barents Sea: *AAPG Bulletin*, v. 85, p. 295-308.
- Eichenseer, H. T., F. R. Walgenwitz, and P. J. Biondi, 1999, Stratigraphic control on facies and diagenesis of dolomitized oolitic siliciclastic ramp sequences (Pinda Group, Albian, offshore Angola): *AAPG Bulletin*, v. 83, p. 1729-1758.
- Embry A. F. and Klovan J. E. (1971) A late Devonian Reef tract on Northeastern Banks Island, Northwest Territories. *Bulletin of Canadian Petroleum Geology* 19, 730-781.
- El-Sayed, M. I., 2001, The nature and possible origin of dolomite in ArRub'Al Khali, The UAE, v. 16, p. 210-223, 9 Figs., 1 Tab.
- Epstein, S. A., D. L. Graf, and E. T. Degens, 1963, Oxygen isotope studies on the origin of dolomites: Amsterdam, North Holland Publ., p. 169-180.
- Ernst, W. G., and E. D. Paylor, II, 1996, Study of the Reed Dolomite aided by remotely sensed imagery, central White-Inyo Range, easternmost California: *AAPG Bulletin*, v. 80, p. 1008-1026.
- Eschard, R., P. Lemouzy, C. Bacchiana, G. Desaubliaux, J. Parpant, and B. Smart, 1998, Combining sequence stratigraphy, geostatistical simulations, and production data for modeling a fluvial reservoir in the Chaunoy Field (Triassic, France): *AAPG Bulletin*, v. 82, p. 545-568.
- Everham, W. D., 1998, Modeling the thermal history of the Michigan Basin: Implications for a complex Burial History: Masters of Science in Geophysics thesis, Michigan Technological University, Houghton, 118 p.
- Fairchild, I. J., 1983, Chemical controls of cathodoluminescence of natural dolomites and calcites: new data and review: *Sedimentology*, v. 30, p. 579-583.
- Farinacci, A., 1965, Breccias and laminated dolomites of the Gavignano exposure, v. 4, p. 129-144, 12 Figs.
- Farr, M. R., 1989, Compositional zoning characteristics of late dolomite cement in the Cambrian Bonnetterre Formation, Missouri: Implications for parent fluid migration pathways, v. 4/2, p. 177-194, 15 Figs.
- Farr, M. R., 1992, Geochemical variation of dolomite cement within the Cambrian Bonnetterre Formation, Missouri: evidence for fluid mixing, v. 62/4, p. 636-651, 13 Figs., 3 Tabs.
- Fei, Q., and X.-P. Wang, 1984, Significant role of structural fractures in Renqiu buried-

- hill oil field in eastern China: AAPG Bulletin, v. 68, p. 971-982.
- Fischer, H. J., ed., 1988, Dolomite diagenesis in the Metaline Formation, northeastern Washington State, v. 43: Tulsa, 209-219, 10 Figs. p.
- Flood, P. G., J. A. Fagerstrom, and F. Rougerie, 1996, Interpretation of the origin of massive replacive dolomite within atolls and submerged carbonate platforms: strontium isotopic signature ODP Hole 866a, Resolution Guyot, Mid-Pacific Mountains, v. 101, p. 9-13, 2 Figs.
- Flügel, E., and S. Kraus, 1988, The Lower Permian Sexten breccia (Sexten Dolomites) and the Tarvis breccia (Carnic Alps): microfacies, depositional environment and paleotectonic implications, v. 34, p. 67-90.
- Foellmer, K. E. H., and F. A. Stoakes, 1987, Fault-controlled dolomite reservoirs in the Wabamun Group of the Peace River Arch, West Central Alberta, p. 1p.
- Folk, R. L., and R. Assereto, 1974, Giant aragonite rays and baroque white dolomite in tepee-filling, Triassic of Lombardy, Italy (abs.), v. 164, p. 34-35.
- Folk, R. L., and L. S. Land, 1975, Mg/Ca Ratio and Salinity; Two Controls over Crystallization of Dolomite: AAPG Bulletin, v. 59, p. 60-68.
- Folkman, Y., 1969, Diagenetic dedolomitization in the Albian-Cenomanian Yagur Dolomite on Mount Carmel (Northern Israel), v. 37, p. 1204-1215.
- Freeman, T., D. Rothbard, and A. Obrador, 1983, Terrigenous dolomite in the Miocene of Menorca (Spain): Provenance and diagenesis, v. 53/2, p. 543-548, 5 Figs.
- Friedman, G. M., 1966, Occurrence and origin of Quaternary dolomite of Salt flat, West Texas, v. 36, p. 263-267, 2 Figs.
- Friedman, G. M., 1972, Petrographic data and comments on the depositional environment of the Miocene sulfates and dolomites at sites 124, 132 and 134 Western Mediterranean Sea, v. 13, p. 695-707, 20 Figs.
- Friedman, G. M., 1980, Dolomite is an evaporite mineral: evidence from the rock record and from sea-marginal ponds of the Red Sea, v. 28, p. 69-80, 9 Figs.
- Friedman, G. M., 1989, Characteristics of deep-marine dolomite - discussion, v. 59/5, p. 879-880, 1 Fig.
- Friedman, G. M., and D. C. Kopaska-Merkel, 1991, Late Silurian Pinnacle Reefs of the Michigan Basin, in P. A. Catocinos, and P. A. J. Daniels, eds., Early Sedimentary Evolution of the Michigan Basin, v. Special Paper 256, Geological Society of America, p. 89-100.
- Friedman, G. M., 1995, Diverse origin of modern dolomite in the Levant, v. 10, p. 65-78, 9 Figs., 5 Tabs.
- Friedman, G. M., 1996, Strontium-isotopic signatures reflect an origin of dolomite by fresh-water effluent: The Pine Plains Formation (Wappinger Group, Cambrian) of southeastern New York, v. 11, p. 134-140, 4 Figs., 1 Tab.
- Fritz, P., 1971, Geochemical characterizations of dolomite and the  $^{18}\text{O}$  content of Devonian oceans, v. 11, p. 277-282.
- Fritz, P., and D. G. W. Smith, 1970, The isotopic concentration of secondary dolomites, v. 34, p. 1161-1163.
- Füchtbauer, H., and H. Goldschmidt, 1965, Beziehungen zwischen Calciumgehalt und Bildungsbedingungen der Dolomite, v. 55, p. 29-40, 8 Figs., 2 Tabs.
- Galli, G., 1989, Depositional mechanisms of storm sedimentation in the Triassic

- Dürrenstein Formation, Dolomites, Italy, v. 61, p. 81-93, 7 Figs.
- Gao, G., 1991, Early Ordovician Cool Creek Dolomite, Middle Arbuckle group, Slick Hills, SW Oklahoma, U.S.A.; origin and modification, v. 61/2, p. 161-173, 8 Figs., 3 Tabs.
- Gao, G., S. D. Hovorka, and H. H. Posey, 1990, Limpid dolomite in Permian San Andres Halite Rocks, Palo Duro Basin, Texas Panhandle: Characteristics, possible origin, and implications for brine evolution: *Journal of Sedimentary Petrology*, v. 60, p. 118-124.
- Gao, G., L. S. Land, and R. L. Folk, 1992, Meteoric modification of early dolomite and late dolomitization by basinal fluids, upper Arbuckle Group, Slick Hills, southwestern Oklahoma: *AAPG Bulletin*, v. 76, p. 1649-1664.
- Garrison, R. E., M. Kastner, and D. H. Zenger, 1984, Dolomites of the Monterey Formation and other organic-rich units: Los Angeles, 215 pp. p.
- Gasiewicz, A., and T. M. Peryt, 1994, Biolaminites at the Zechstein (Upper Permian) Platy Dolomite (Ca3)-Main Anhydrite (A3) boundary: implications for evolution of an evaporite basin, v. 19, p. 91-101, 3 Pls., 1 Fig.
- Gensmer, R. P., and M. P. Weiss, 1980, Accuracy of calcite/dolomite ratios by X-ray diffraction and comparison with results from staining techniques, v. 50/2, p. 626-629, 2 Figs.
- Gerhard, L. C., 1974, Redescription and New Nomenclature of Manitou Formation, Colorado: *AAPG Bulletin*, v. 58, p. 1397-1402.
- Germann, K., 1969, Reworked dolomite crusts in the Wettersteinkalk (Ladinian, Alpine Triassic) as indicators of early supratidal dolomitization and lithification, v. 12, p. 257-277, 13 Figs.
- Gerthofferova, H., and M. Misik, 1971, Electron microscope study of some limestones and dolomites of the Carpathian Mountains, v. 21, p. 163-186, Pl. 26-40, 3 Figs.
- Gianolla, P., C. Siorpaes, and P. Vail, 1991, Carnian stratigraphic record in the Dolomites. An example of outcrop sequence stratigraphy: *Ortisei*, p. 82-83.
- Gilhaus, A., J. Meijer, D. K. Richter, and A. Stephan, 2000, Quantitative Kathodolumineszenz-Spektroskopie Mn<sup>2+</sup>-aktivierter diagenetischer und hydrothermaler Dolomite, v. 43, p. 49-50.
- Gill, D., 1977, MBGS Special Papers No. 2: The Belle River Mills Gas Field: Productive Niagaran Reefs Encased by Sabkha Deposits, Michigan Basin, Michigan Basin Geological Society, 187 pp.
- Gill, D., 1977, Salina A-1 Sabkha cycles and the late Silurian Paleogeography of the Michigan Basin: *Journal of Sedimentary Petrology*, v. 47, p. 979-1017.
- Gill, D., 1979, Differential entrapment of oil and gas in Niagaran Pinnacle-Reef belt of Northern Michigan: *AAPG Bulletin*, v. 63, p. 608-620.
- Gillen, K. P., R. Van der Voo, and J. H. Thiessen, 1999, Late Cretaceous-early Tertiary remagnetization of the Devonian Swan Hills Formation recorded in carbonate cores from the Caroline gas field, Alberta, Canada: *AAPG Bulletin*, v. 83, p.

- 1223-1235.
- Gillhaus, A., 2000, Petrographisch/geochemische Untersuchungen zur Genese und Diagenese der Dolomite von Hydra (Griechenland) unter besonderer Berücksichtigung der Kathodolumineszenz-Mikroskopie, v. 54, p. 1-123, 4 Pls., 31 Figs.
- Gillhaus, A., D. K. Richter, J. Meijer, R. D. Neuser, and A. Stephan, 2001, Quantitative high resolution cathodoluminescence spectroscopy of diagenetic and hydrothermal dolomites, v. 140, p. 191-199.
- Gillott, J. E., 1963, Petrology of dolomitic limestones, Kingston, Ontario, Canada: Geological Society of America Bulletin, v. 74, p. 759-778.
- Gindy, A. R., A. J. Al-Shakiry, and N. A. Sa'ad, 1985, Spheroidal weathering in marls and chalks of Gebel Gurnah near Luxor, southern Egypt: Journal of Sedimentary Petrology, v. 55, p. 762-768.
- Given, R. K., and B. H. Wilkinson, 1987, Dolomite abundance and stratigraphic age: constraints on rates and mechanisms of Phanerozoic dolostone formation, v. 57/6, p. 1068-10787, 4 Figs., 2 Tabs.
- Goldhammer, R. K., P. A. Dunn, and L. A. Hardie, 1991, Sequence stratigraphy and systems tract development of the Latemar platform, Middle Triassic of the Dolomites: outcrop calibration keyed by cycle stacking patterns: Ortisei, p. 90.
- Goldhammer, R. K., and M. T. Harris, eds., 1989, Eustatic controls on the stratigraphy and geometry of the Latemar buildup (Middle Triassic), the Dolomites of Northern Italy, v. 44: Tulsa, 323-338, 18 Figs. p.
- Goldhammer, R. K., M. T. Harris, P. A. Dunn, and L. A. Hardie, eds., 1993, Sequence stratigraphy and systems tract development of the Latemar platform, Middle Triassic of the Dolomites (Northern Italy): outcrop calibration keyed by cycle stacking patterns, v. 57: Tulsa, 353-387, 25 Figs. p.
- Goldsmith, J. R., and D. L. Graf, 1958, Structural and compositional variations in some natural dolomites: Journal of Geology, v. 66, p. 678-692.
- Goldsmith, J. R., D. L. Graf, J. Witters, and D. A. Northrop, 1962, Studies in the system  $\text{CaCO}_3$  -  $\text{MgCO}_3$  -  $\text{FeCO}_3$ : 1. Phase relations; 2. A method for major-element spectrochemical analysis; 3. Compositions of some ferroan dolomites, v. 70/6, p. 659-668, 11 Figs., 10 Tabs.
- Gotthardt, R., H. J. Hoppe, and E. Schiele, 1967, Das Sinterverhalten von Dolomiten unterschiedlicher Petrographie, v. 91, p. 121-125.
- Gournay, J., B. L. Kirkland, R. L. Folk, and F. L. Lynch, 1999, Evidence for nanobacterially precipitated dolomite in Pennsylvanian rocks, Utah, v. 126, p. 243-252.
- Gournay, J. P., 1998, Diagenesis and porosity/permeability prediction in Pennsylvanian phylloid algal bioherms of the Paradox Basin, southeastern Utah: AAPG Foundation grants-in-aid recipients for 1998; abstracts AAPG Bulletin, v. 82, p. 2162-2163.
- Gournay, J. P., B. L. Kirkland, R. L. Folk, and F. L. Lynch, 1999, Nanometer-scale features in dolomite from Pennsylvanian rocks, Paradox Basin, Utah, v. 126, p. 245-254.
- Gregg, J. M., 1983, On the formation and occurrence of saddle dolomite; discussion:

- Journal of Sedimentary Petrology, v. 53, p. 1025-1026.
- Gregg, J. M., 1985, Regional epigenetic dolomitization in the Bonnetterre Dolomite (Cambrian), southeastern Missouri, v. 13, p. 503-506.
- Gregg, J. M., ed., 1988, Origins of dolomite in the offshore facies of the Bonnetterre Formation (Cambrian), Southeast Missouri, v. 43: Tulsa, 67-83, 13 Figs., 1 Tab. p.
- Gregg, J. M., S. A. Howard, and S. J. Mazzullo, 1992, Early diagenetic recrystallization of Holocene (<3000 years old) peritidal dolomites, Ambergris Cay, Belize, v. 39, p. 143-160, 11 Figs., 2 Tabs.
- Gregg, J. M., P. R. Laudon, R. E. Woody, and K. L. Shelton, 1993, Porosity evolution of the Cambrian Bonnetterre Dolomite, south-eastern Missouri, USA, v. 40, p. 1153-1169, 9 Figs., 2 Tabs.
- Gregg, J. M., and K. L. Shelton, 1990, Dolomitization and dolomite neomorphism in the back reef facies of the Bonnetterre and Davis Formations (Cambrian), southeastern Missouri, v. 60/4, p. 549-562, 10 Figs.
- Gregg, J. M., and D. F. Sibley, 1984, Epigenetic dolomitization and the origin of xenotopic dolomite texture, v. 54/3, p. 908-931, 19 Figs.
- Grobe, M., and H. G. Machel, 1997, Petrographic and geochemical evidence for fault-controlled hydrothermal mineralization of the Brilon reef complex, Germany: AAPG Foundation grants-in-aid abstracts AAPG Bulletin, v. 81, p. 1775.
- Gümbel, C. W., 1873, Mikroskopische Untersuchungen alpiner Triaskalke und Dolomite, v. 7/8, p. 141-144.
- Gunatilaka, A., 1989, Spheroidal dolomites - arigin by hydrocarbon seepage?, v. 36, p. 701-710, 4 Figs.
- Gunatilaka, A., 1991, Dolomite formation in coastal Al-Khiran, Kuwait Arabian Gulf - a re-examination of the sabkha model, v. 72, p. 35-53, 3 Figs., 2 Tabs.
- Gunatilaka, A., A. Saleh, A. Al-Temeemi, and N. Nassar, 1984, Occurrence of Subtidal Dolomite in a Hypersaline Lagoon, Kuwait: Nature, v. 311, p. 450-452.
- Guo, B., J. E. Sanders, and G. M. Friedman, 1996, Timing and origin of dedolomite in the Lower Ordovician (Wappinger Group) strata, southeastern New York, v. 11, p. 113-133, 14 Figs., 2 Tabs.
- Guoqiu, G., L. S. Land, and R. L. Folk, 1992, Meteoric modification of early dolomite and late dolomitization by basinal fluids, Upper Arbuckle Group, slick Hill, Southwestern Oklahoma, v. 76, p. 1649-1664, 10 Figs., 3 Tabs.
- Guthrie, J. M., and L. M. Pratt, 1995, Geochemical character and origin of oils in Ordovician reservoir rock, Illinois and Indiana, USA: AAPG Bulletin, v. 79, p. 1631-1649.
- Habermann, D., R. D. Neuser, and D. K. Richter, 1996, REE-activated cathodoluminescence of calcite and dolomite: high-resolution spectrometric analysis of CL emission (HRS-CL), v. 101, p. 1-7, 7 Figs.
- Hanor, J. S., 2004, A model for the origin of large carbonate- and evaporite-hosted celestine (SrSO (sub 4) ) deposits: Journal of Sedimentary Research, v. 74, p. 168-175.
- Hardie, L. A., E. N. Wilson, and R. K. Goldhammer, 1991, Cyclostratigraphy and dolomitization of the Middle Triassic Latemar buildup, te Dolomites, northern

- Italy, p. 56 pp.
- Harris, M. T., 1994, The Foreslope and toe-of-facies of the middle triassic latemar buildup (Dolomites, Northern Italy): *Sedimentary Research*, v. 64, p. 132-145.
- Harrison W. B. I. (1985) Lithofacies and depositional environments of the Burnt Bluff Group in the Michigan Basin. In *Michigan Basin Geological Society Special Paper No. 4: Ordovician and Silurian Rocks of the Michigan Basin and its Margins* (ed. K. R. Cercone and J. M. Budai), pp. 95-108. Michigan Basin Geological Society.
- Haynes, F. M., and S. E. Kesler, 1989, Pre-Alleghenian (Pennsylvanian-Permian) hydrocarbon emplacement along Ordovician Knox unconformity, eastern Tennessee: *AAPG Bulletin*, v. 73, p. 289-297.
- Hendry, J. P., M. Wilkinson, A. E. Fallick, and N. H. Trewins, 2000, Dissepimented 'jigsaw piece' dolomite in Upper Jurassic shelf sandstones, Central North Sea: an example of cement growth during bioturbation?, v. 47, p. 631-644, 7 Figs., 1 Tab.
- Hennessy, J., and L. P. Knauth, 1985, Isotopic variations in dolomite concretions from the Monterey Formation, California, v. 55/1, p. 120-130, 10 Figs.
- Hennessy, J., and L. P. Knauth, 1985, Isotopic variations in dolomite concretions from the Monterey Formation, California: *Journal of Sedimentary Petrology*, v. 55, p. 120-130.
- Hennings, P. H., 2002, Present and future of building, sharing, and exploiting 3-D models for characterization of strongly deformed reservoirs: 2001-2002 AAPG distinguished lecturers; North America distinguished lecture abstracts AAPG Bulletin, v. 86, p. 197-198.
- Henrich, R., and J. Mirsal, 1982, A comparative study of the Supratidal and Basin Dolomites in the Anisian and Ladinian Carbonates of the Hohenstaufen Massiv (Northern limestone Alps), v. 28, p. 95-108, 2 Pls., 3 Tabs.
- Henton, J., 1991, Geochemical constraints on uplift-related calcitization of Triassic dolomites in the Catalan Basin, Northeast Spain: *Ortisei*, p. p. 109.
- Heydari, E., 2003, Meteoric versus burial control on porosity evolution of the Smackover Formation: *AAPG Bulletin*, v. 87, p. 1779-1797.
- Hoholick, J. D., T. Metarko, and P. E. Potter, 1984, Regional variations of porosity and cement; St. Peter and Mount Simon sandstones in Illinois Basin: *AAPG Bulletin*, v. 68, p. 753-764.
- Holail, H., 1994, Carbon and oxygen ratios of Middle Eocene dolomite, Gebel Ataqu, Egypt, v. 191, p. 111-124, 4 Figs., 1 Tab.
- Holser, W. T., and M. Magaritz, 1985, The Late Permian carbon isotope anomaly in the Bellerophon Basin, Carnic and Dolomite Alps, v. 128, p. 75-82, 3 Figs.
- Hood, S. D., C. S. Nelson, and P. J. J. Kamp, 2003, Modification of fracture porosity by multiphase vein mineralization in an Oligocene nontropical carbonate reservoir, Taranaki Basin, New Zealand: *AAPG Bulletin*, v. 87, p. 1575-1597.
- Howell, P. D., and B. A. van der Pluijm, 1990, Early history of the Michigan Basin: Subsidence and Appalachian tectonics: *Geology*, v. 18, p. 1195-1198.
- Howell, P. D., and B. A. van der Pluijm, 1999, Structural Sequences and Styles of Subsidence in the Michigan Basin: *GSA Bulletin*, v. 111, p. 974-991.

- Hsü, J., 1966, Origin of dolomite in sedimentary sequences: a critical analysis, v. 2, p. 133-138, 2 Figs.
- Hsü, K. J., 1967, Chemistry of dolomite formation: Amsterdam, p. 169-191.
- Hsü, K. J., and C. Siegenthaler, 1969, Preliminary experiments and hydrodynamic movement induced by evaporation and their bearing on the dolomite problem, v. 12, p. 11-25.
- Hubert, J. F., and A. A. Reed, 1978, Red-bed diagenesis in the East Berlin Formation, Newark Group, Connecticut Valley: *Journal of Sedimentary Petrology*, v. 48, p. 175-184.
- Huh, J. M., and L. I. Briggs, Stratigraphy and diagenesis of Niagaran pinnacle reefs (Silurian) in northern Michigan Basin: *The American Association of Petroleum Geologists Bulletin*, v. 57, p. 785.
- Huh, J. M., L. I. Briggs, and D. Gill, 1976, Depositional Environments of Pinnacle Reefs, Niagara and Salina Groups, Northern Shelf, Michigan Basin, p. 1-21.
- Hulen, J. B., S. R. Bereskin, and L. C. Bortz, 1990, High-temperature hydrothermal origin for fractured carbonate reservoirs in the Blackburn oil field, Nevada: *AAPG Bulletin*, v. 74, p. 1262-1272.
- Humphrey, J. D., and T. M. Quinn, 1989, Coastal Mixing Zone Dolomite, Forward Modeling, and Massive Dolomitization of Platform-Margin Carbonates: *Journal of Sedimentary Petrology*, v. 59, p. 438-545.
- Huntoon, J. E., P. L. Hansley, and N. D. Naeser, 1999, The search for a source rock for the giant Tar Sand Triangle accumulation, southeastern Utah: *AAPG Bulletin*, v. 83, p. 467-495.
- Hurley, N.F. and Budros, R., 1990, Albion-Scipio and Stoney Point Fields – U.S.A., Michigan Basin, *AAPG Treatise of Pet. Geol., Atlas of Oil and Gas Fields, Stratigraphic traps*, p. 1-37.
- Hurley, N.F., and Swagger, D. (1991) A classic fracture-controlled dolomite reservoir, Albion-Scipio Trend, Michigan. *AAPG Bulletin* 75(11), 1806.
- Hurst, R. W., 1986, Chemical and Sr isotopic variations during diagenesis of Miocene siliceous sediments of the Monterey Formation, California; discussion of the Sr isotopic data and its relevance to the timing of Monterey Formation fracturing: *Journal of Sedimentary Petrology*, v. 56, p. 569-573.
- Hyde, M. K., 1979, A Study of the Dolomite/Calcite Ratios Relative to the Structures and Producing Zones of the Kawkawlin Oil Field, Bay County, Michigan: MS thesis, Michigan State University, Lansing, 92 p.
- Ifechukwu, O. P., 1997, Sequence stratigraphy and reservoir geology of the Glauconitic Sandstone Member and adjacent strata, Mannville Group, central Alberta: *AAPG Foundation grants-in-aid abstracts AAPG Bulletin*, v. 81, p. 1780.
- Ilich, M., 1974, Hydrothermal-Sedimentary Dolomite: the Missing Link?: *AAPG Bulletin*, v. 58, p. 1331-1347.
- Illing, L. V., A. J. Wells, and J. C. Taylor, eds., 1965, Penecontemporary dolomite in the Persian Gulf, v. 13: Tulsa, 89-111, 10 Figs., 1 Tab. p.
- Ingels, J. J. C., 1963, Geometry, Paleontology, and Petrography of Thornton Reef Complex, Silurian of Northeastern Illinois: *AAPG Bulletin*, v. 47, p. 405-440.
- Jacka, A. D., 1976, Factors controlling porosity relations in Pennsylvanian and Permian



- carbonate reservoirs of Permian Basin: AAPG Bulletin, v. 60, p. 325-326.
- Jahn, B., J. Bertrand-Sarfati, N. Morin, and J. Mace, 1990, Direct dating of stromatolitic carbonates from the Schmidtsdrif Formation (Travsvaal Dolomite), South Africa, with implications on the age of the Ventersdorp Supergroup: *Geology*, v. 18, p. 1211-1214.
- Jarosewich, E., and I. G. MacIntyre, 1983, Carbonate reference samples for electron microprobe and scanning electron microscope analyses: *Journal of Sedimentary Petrology*, v. 53, p. 677-678.
- Jingquan, Z., 1998, Characteristics and origin of polycrystalline dolomite needles in the Triassic Jialingjiang Formation, Upper Yangtze Platform, southwest China, v. 118, p. 119-126, 4 Figs.
- Jingquan, Z., 1998, Characteristics and origin of polycrystalline dolomite needles in the Triassic Jialingjiang Formation, Upper Yangtze Platform, southwest China, v. 118, p. 119-126, 4 Figs.
- Jodry, R. L., 1969, Growth and dolomitization of Silurian Reefs, St. Clair County, Michigan: AAPG Bulletin, v. 53, p. 957-981.
- Joergensen, N. O., 1983, Dolomitization in chalk from the North Sea central graben: *Journal of Sedimentary Petrology*, v. 53, p. 557-564.
- Johnson, A., and Sorenson, H. (1978) Drill core investigation of the Fiborn Limestone Member in Schoolcraft County, Mackinac and Chippewa Counties, Michigan. Geological Survey Division Report of Investigation 18, 51 pp.
- Johnson, C. L., and S. A. Graham, 2004, Cycles in perilacustrine facies of late Mesozoic rift basins, southeastern Mongolia: *Journal of Sedimentary Research*, v. 74, p. 786-804.
- Johnson, J. G., 1974, Great Basin Silurian to Lower Lower Devonian; a Biostratigraphic Case History: AAPG Bulletin, v. 58, p. 139-141.
- Johnson, M. E., 1980, Paleoeological structure in early Silurian platform seas of the North American midcontinent: *Palaeogeography, Palaeoclimatology, Palaeoecology*, p. 191-216.
- Johnson, M. E., and G. T. Campbell, 1980, Recurrent carbonate environments in the lower Silurian of Northern Michigan and their inter-regional correlation: *Journal of Paleontology*, v. 54, p. 1041-1057.
- Johnson M. E. (1981) Correlation of Lower Silurian strata from the Michigan Upper Peninsula to Manitoulin Island. *Canadian Journal of Earth Sciences* 18, 869-883.
- Johnson M. E. (1989) Tempestites recorded as variable *Pentamerus* layers in the Lower Silurian of Southern Norway. *Journal of Paleontology* 63(2), 195-205.
- Johnson, M. E., and B. G. Baarli, 1987, Encrusting corals on a latest Ordovician to earliest Silurian rocky shore, southwest Hudson Bay, Manitoba, Canada: *Geology*, v. 15, p. 15-17.
- Jones, B., 1989, Syntaxial overgrowth on dolomite crystals in the Bluff Formation, Grand Cayman, British West Indies, v. 59/5, p. 839-847, 6 Figs.
- Jones, B., 2004, Petrography and significance of zoned dolomite cements from the Cayman formation (Miocene) of Cayman Brac, British West Indies, v. 74, p. 95-109, 12 Figs.

- Jones, B., 2005, Dolomite Crystal Architecture: Genetic Implications for the Origin of the Tertiary Dolostones of the Cayman Islands: *Journal of Sedimentary Research*, v. 75, p. 177-189.
- Jones, B., and R. W. Luth, 2003, Petrography of finely crystalline Cenozoic dolostones as revealed by backscatter electron imaging; case study of the Cayman Formation (Miocene), Grand Cayman, British West Indies: *Journal of Sedimentary Research*, v. 73, p. 1022-1035.
- Jones, B., S. M. Pleydell, N. Kwok-Choi, and F. J. Longstaffe, 1989, Formation of poikilotopic calcite-dolomite fabrics in the Oligocene-Miocene Bluff Formation of Great Cayman, British West Indies, v. 37/3, p. 255-265, 5 Figs.
- Jones, G. D., and Y. Xiao, 2005, Dolomitization, anhydrite cementation, and porosity evolution in a reflux system: Insights from reactive transport models: *The American Association of Petroleum Geologists Bulletin*, v. 89, p. 577-601.
- Jorgenson, N. O., 1988, Dolomite and dedolomitization in Danian bryozoan limestone from Fakse, Denmark, v. 37, p. 63-74, 15 Figs.
- Jorgenson, N. O., 1991, Oxygen isotope fraction between dolomite and calcite - evidence from a natural system in a recent marine environment: *Ortisei*, p. 128-129, 1 Fig.
- Kahle, C. F., and C. J. Livchack, 1996, Peritidal carbonates and evaporative drawdown: A case study from the Silurian Tymochtee Dolomite, Ohio, *in* B. A. Van der Pluijm, and P. A. Catacosinos, eds., *Basement and Basins of Eastern North America*, v. Special Paper 308: Boulder, Colorado, Geological Society of America, p. 157-168.
- Kahle, C. F., 1994, Facies and Evolution of a Silurian Coral-microbialite Reef Complex, Maumee, Ohio, USA: *Journal of Sedimentary Research*, v. A64, p. 711-725.
- Kahle, C. F., 2001, Biosedimentology of a Silurian Thrombolite Reef with Meter-Scale Growth Framework Cavities: *Journal of Sedimentary Research*, v. 71, p. 410-422.
- Kaldi, J., and J. Gidman, 1982, Early diagenetic dolomite cements: examples from the Permian Lower Magnesian Limestone of England and the Pleistocene carbonates of the Bahamas, v. 52/4, p. 1073-1085, 10 Figs.,.
- Kantor, J., and M. Misik, 1992, Isotopic composition of oxygen and carbon in selected Mesozoic and Tertiary limestones and dolomites in Slovakia, v. 15, p. 7-27.
- Kargel, J. S., J. F. Schreiber, and C. P. Sonett, 1996, Mud cracks and dedolomitization in the Wittenoom Dolomite, Hamersley Group, Western Australia, v. 14, p. 73-96, 5 Figs.
- Kastner, M., 1983, Origin of dolomite and its spatial and chronological distribution; a new insight: *AAPG Bulletin*, v. 67, p. 2156.
- Kastner, M., 1983, Origin of dolomite and its spatial and chronological distribution - a new insight, v. 67, p. 21-56.
- Kastner, M., 1984, Control of dolomite formation, v. 311, p. 410-411.
- Katz, A., 1968, Calcian dolomites and dedolomitization, v. 217, p. 439-440.
- Katz, A., 1971, Zoned dolomite crystals, v. 79, p. 38-51, 3 Pls., 4 Figs.
- Keim, L., and W. Schlager, 1999, Automicrite facies on steep slopes (Triassic, Dolomites, Italy), v. 41, p. 15-26, Pl. 5-7, 4 Figs., 1 Tab.
- Kendall, A. C., M. W. Longman, T. G. Fertil, and J. S. Glennie, 1984, Origin and

- geometry of Red River Dolomite reservoirs, western Williston Basin; discussion and reply: AAPG Bulletin, v. 68, p. 776-784.
- Kendall, G. W., J. G. Johnson, J. O. Brown, and G. Klapper, 1983, Stratigraphy and facies across Lower Devonian-Middle Devonian boundary, central Nevada: AAPG Bulletin, v. 67, p. 2199-2207.
- Kenig, F., R. Baltzer, J. C. Fontes, and B. H. Purser, 1991, Possible relationship between organic matter and dolomite in the sabkha of Abu Dhabi (U.A.E.): *Ortisei*, p. 132-133, 3 Figs.
- Kenny, R., 1992, Origin of disconformity dedolomite in the Martin Formation (Late Devonian, northern Arizona), v. 78, p. 137-146, 7 Figs., 1 Tab.
- Kessels, L. A., D. F. Sibley, and S. H. Nordeng, 2000, Nanotopography of synthetic and natural dolomite crystals, v. 47, p. 173-186, 11 Figs.
- Klupsch, N., A. T. S. Ramsay, and P. Rothe, 1988, Intertidal- und Supratidal-Phasen im Kalktertiär-Profil (Oberoligozän-Untermiozän) Mainz-Weisenau - Caliche und frühdiagenetische Dolomite, v. 110, p. 165-172, 3 Figs.
- Klusman, R. W., 2003, A geochemical perspective and assessment of leakage potential for a mature carbon dioxide-enhanced oil recovery project and as a prototype for carbon dioxide sequestration; Rangely Field, Colorado: AAPG Bulletin, v. 87, p. 1485-1507.
- Kolkas, M. M., and G. M. Friedman, 1998, Diagenetic history and geochemistry of the Beekmantown-Group dolomites (Sauk Sequence) of New York, USA, v. 13, p. 69-85, 17 Figs.
- Kretz, R., 1992, Caroused model for the crystallization of saddle dolomite, v. 62/2, p. 190-195, 9 Figs., 1 Tab.
- Kupecz, J. A., 1990, Recrystallization of dolomite with time, p. p. 37.
- Kupecz, J. A., and L. S. Land, 1991, Status of 'burial dolomite' and an alternative interpretation for post-lithification dolomite: *Ortisei*, p. p. 141.
- Kupecz, J. A., I. P. Montanez, and G. Gao, eds., 1993, Recrystallization of dolomite with time: New York, Springer, 187-194 p.
- Kuslansky, G. H., and G. M. Friedman, 1981, Chertification of crinoids may yield a product resembling "dedolomite": *Journal of Sedimentary Petrology*, v. 51, p. 795-798.
- Kuznetsov, V. G., 1999, Petrography and origin of dolomite in carbonate deposits in various paleoclimates, v. 14, p. 125-137, 8 Figs.
- Laghi, G. F., G. Martinelli, and F. Russo, 1984, Localization of minor elements by Eds microanalysis in aragonic sponges from the St. Cassian Beds, Italian Dolomites, p. 133-138, 3 Tabs.
- Land, L. S., 1980, The isotopic and trace element geochemistry of dolomite: the state of the art, v. 28, p. 87-110.
- Land, L. S., 1985, The Origin of Massive Dolomite: *Journal of Geological Education*, v. 33, p. 112-125.
- Land, L. S., 1986, Environments of limestone and dolomite diagenesis: some geochemical considerations, v. 81, p. 26-41.
- Land, L. S., M. R. I. Salem, and D. W. Morrow, 1975, Paleohydrology of ancient dolomites; geochemical evidence: AAPG Bulletin, v. 59, p. 1602-1625.

- Lane, A. C., C. S. Prosser, W. H. Sherzer, and A. W. Grabau, 1909, Nomenclature and subdivision of the Upper Siluric strata of Michigan, Ohio, and Western New York: GSA Bulletin, v. 19, p. 553-556.
- Langbein, R., and S. Röhling, 1991, Appearance and distribution of ferroan calcite and low-concentration dolomite in Lower Palaeozoic deep-water carbonates of the Thuringikum, v. 51, p. 241-249, 10 Figs.
- Lasemi, Z., M. R. Boardman, and P. A. Sandberg, 1989, Cement origin of supratidal dolomite, Andros Island, Bahamas, v. 59/2, p. 249-257, 5 Figs.
- Laskaridis, K., 1987, Beurteilung griechischer weißer Kalke und Dolomite für den industriellen Einsatz (z.B. in der Papierindustrie), p. 241 pp., 121 Figs., 30 Tabs., 1 Pl.
- Last, W. M., 1990, Lacustrine dolomite - an overview of Modern, Holocene, and Pleistocene occurrences, v. 27, p. 221-263.
- Laubach, S., R. Marrett, and J. Olson, 2000, New directions in fracture characterization: The Leading Edge, p. 704-711.
- Laughrey, C. D., and F. J. Baldassare, 1998, Geochemistry and origin of some natural gases in the Plateau Province, central Appalachian Basin, Pennsylvania and Ohio: AAPG Bulletin, v. 82, p. 317-335.
- Lawrence, M. J. F., 1994, Conceptual model for early diagenetic chert and dolomite, Amuri Limestone Group, north-eastern South Island, New Zealand, v. 41, p. 479-498, 9 Figs., 4 Tabs.
- Leach, D. L., G. S. Plumlee, A. H. Hofstra, G. P. Landis, E. L. Rowan, and J. G. Viets, 1991, Origin of late dolomite cement by CO<sub>2</sub>-saturated deep basin brines: Evidence from the Ozark region, Central United States: Geology, v. 19, p. 348-351.
- Lee, M.-K., and C. M. Bethke, 1994, Groundwater flow, late cementation, and petroleum accumulation in the Permian Lyons Sandstone, Denver Basin: AAPG Bulletin, v. 78, p. 217-237.
- Leibold, A. W., 1992, Sedimentological and Geochemical Constraints on Niagara/Salina deposition, Michigan Basin: Ph.D. dissertation, University of Michigan, Ann Arbor, 280p.
- Leutloff, A. H., and W. J. Meyers, 1984, Regional distribution of microdolomite inclusions in Mississippian echinoderms from southwestern New Mexico, v. 54/2, p. 432-446, 9 Figs.
- Lilling, L. V., A. J. Wells, and J. C. Taylor, eds., 1965, Penecontemporaneous dolomite in the Persian Gulf, v. 13: Tulsa, 89-111 p.
- Lock, B. E., L. J. Williams, and D. P. Cheney, 1991, Dolomite cements in modern supratidal sands, western Sonora, Mexico: Ortisei, p. p. 150.
- Lohmann, K. C., and W. J. Meyers, 1977, Microdolomite inclusions in cloudy prismatic calcites: a proposed criterion for former high-magnesium calcites, v. 47/3, p. 1078-1088, 6 Figs.
- Longacre, S. A., 1980, Dolomite reservoirs from Permian biomicrites, v. 1, p. 105-117.
- Longman, M. W., T. G. Fertal, and J. S. Glennie, 1983, Origin and geometry of Red River dolomite reservoirs, western Williston Basin: AAPG Bulletin, v. 67, p. 744-771.

- Lopez-Gomez, J., and B. Mamet, 1990, Sedimentology and Petrology of the Canete Dolomite and Limestone Formation (Muschelkalk Facies, Middle to Upper Triassic) Southern Iberian Ranges, Eastern Spain, v. 23, p. 1-16, 9 Figs., Pls. 1-2.
- Loucks, R. G., and J. H. Anderson, 1980, Depositional facies and porosity development in Lower Ordovician Ellenburger Dolomite, Puckett Field, Pecos County, Texas, v. 1, p. 1-31, 17 Figs., 2 Tabs.
- Loucks, R. G., and J. H. Anderson, 1985, Depositional Facies, Diagenetic Terranes, and Porosity Development in Lower Ordovician Ellenburger Dolomite, Puckett Field, West Texas: New York, Springer, p. 19-37, 14 Figs.
- Loveland, M. W., 1986, Geophysics of the Michigan Basin: An overview of the Seismology and Geology of the Northern Michigan Reef Trend and Center Basin Gas Play: The Interstate Oil Compact Commission Committee Bulletin, v. 28, p. 82-95.
- Lowenstam, H. A., 1950, Niagaran reefs of the Great Lake area, GSA Bull. v. 58, p. 430-487.
- Lucia, F. J., 2000, Origin and petrophysics of carbonate rock fabrics: 2000-2001 AAPG distinguished lecturers; abstracts AAPG Bulletin, v. 84, p. 1879.
- Lucia, F. J., 2000, Dolomitization; a porosity-destructive process: 2000-2001 AAPG distinguished lecturers; abstracts AAPG Bulletin, v. 84, p. 1879.
- Luebbing, G. A., M. W. Longman, and W. J. Carlisle, 2001, Unconformity-related chert/dolomite production in the Pennsylvanian Amsden Formation, Wolf Springs fields, Bull Mountains Basin of central Montana: Chert reservoirs of North America AAPG Bulletin, v. 85, p. 131-148.
- Lumsden, D. N., 1979, Discrepancy between thin-section and x-ray estimates of dolomite in limestone, v. 49/2, p. 429-436, 5 Figs.
- Lumsden, D. N., 1985, Secular variations in dolomite abundance in deep marine sediments: Geology, v. 13, p. 766-769.
- Lumsden, D. N., 1988, Characteristics of deep-marine dolomite, v. 58/6, p. 1023-1031, 6 Figs.
- Lumsden, D. N., and J. S. Chimahuskey, eds., 1980, Relationship between dolomite nonstoichiometry and carbonate facies parameters, v. 28, 123-127 p.
- Lumsden, D. N., and R. V. Lloyd, eds., 1988, An update of ESR spectroscopy studies of dolomite origin., v. 43: Tulsa, 3-10, 4 Figs. p.
- Lyday, J. R., 1985, Atokan (Pennsylvanian) Berlin Field; genesis of recycled detrital dolomite reservoir, deep Anadarko Basin, Oklahoma: AAPG Bulletin, v. 69, p. 1931-1949.
- Macaulay, C. I., A. J. Boyce, A. E. Fallick, and R. S. Haszeldine, 1997, Quartz veins record vertical flow at a graben edge; Fulmar oil field, central North Sea: AAPG Bulletin, v. 81, p. 2024-2033.
- Machel, H. G., 1985, Cathodoluminescence in calcite and dolomite and its chemical interpretation, v. 12, p. 139-142, 8 Figs.
- Machel, H. G., 1987, Saddle dolomite as a by-product of chemical compaction and thermochemical sulfate reduction, v. 15, p. 936-940, 7 Figs.
- Machel, H. G., ed., 1988, Fluid flow direction during dolomite formation as deduced from trace-element trends, v. 43: Tulsa, 115-125, 5 Figs. p.

- Machel, H. G., 1997, Recrystallization versus neomorphism, the concept of "significant recrystallization" in dolomite research: *Sedimentary Geology*, v. 113, p. 161-168.
- Machel, H. G., 2000, Dolomite formation in Caribbean islands - driven by plate tectonics?, v. A70, p. 977-984, 7 Figs.
- Machel, H. G., and E. A. Burton, eds., 1991, Factors governing cathodoluminescence in calcite and dolomite, and their implications for studies of carbonate diagenesis, v. 25: Tulsa, 37-57, 16 Figs. p.
- Machel, H. G., and E. A. Burton, 1991, Barbados dolomite: origin from seawater with variable temperature and/or modified by evaporation, bacterial metabolism, or oxidized methane: *Ortisei*, p. 137-138.
- Machel, H. G., and E. A. Burton, 1994, Golden Grove dolomite, Barbados: origin from modified seawater, v. A64, p. 741-751, 13 Figs., 1 Tab.
- Machel, H. G., R. A. Mason, A. N. Mariano, and A. Mucci, 1991, Causes and Emission of Luminescence in Calcite and Dolomite, in C. E. Barker, and O. C. Kopp, eds., *Luminescence Microscopy: Quantitative and Qualitative Aspects*: Tulsa, SEPM, p. 9-25.
- Machent, P. G., 2000, Spatial distribution and style of carbonate cements in distal, sandstone sequences; Upper Cretaceous Panther Tongue Member and Kenilworth Member, Book Cliffs, east-central Utah, USA: AAPG Foundation grants-in-aid recipients for 2000 AAPG Bulletin, v. 84, p. 1867.
- MacNeil, A. J., 1999, Diagenesis and dolomitization of the Pliocene Pedro Castle Formation, Cayman Brac, British West Indies: AAPG Foundation grants-in-aid abstracts AAPG Bulletin, v. 83, p. 1890.
- Madsen, B. M., 1984, Micromarker beds in the Upper Permian Castile Formation, Delaware Basin, West Texas and southeastern New Mexico: *Journal of Sedimentary Petrology*, v. 54, p. 1169-1174.
- Major, R. P., M. R. Lloyd, and F. J. Lucia, 1992, Oxygen isotope composition of Holocene dolomite formed in a humid hypersaline setting: *Geology*, v. 20, p. 586-588.
- Maliva, R. G., G. P. Kennedy, W. K. Martin, T. M. Missimer, E. S. Owosina, and J. A. D. Dickson, 2002, Dolomitization-induced aquifer heterogeneity; evidence from the upper Floridan Aquifer, Southwest Florida: *Geological Society of America Bulletin*, v. 114, p. 419-427.
- Maliva, R. G., and R. Siever, 1990, Influences of dolomite precipitation on quartz surface textures, v. 60/6, p. 820-826, 2 Figs.
- Malone, M. J., P. A. Baker, and S. J. Burns, 1994, Recrystallization of dolomite: evidence from the Monterey Formation (Miocene), California, v. 41, p. 1223-1239, 12 Figs., 1 Tab.
- Malpas, J. A., 2000, Integrated sedimentology and palaeontological analysis of marine flooding surfaces; a case study of the Miocene, Nukhul Formation, Gulf of Suez: AAPG Foundation grants-in-aid recipients for 2000 AAPG Bulletin, v. 84, p. 1867-1868.
- Mancini, E. A., T. A. Blasingame, R. Archer, B. J. Panetta, J. C. Llinas, C. D. Haynes, and D. J. Benson, 2004, Improving recovery from mature oil fields producing from carbonate reservoirs; Upper Jurassic Smackover Formation, Womack Hill

- Field (eastern Gulf Coast, U.S.A.): AAPG Bulletin, v. 88, p. 1629-1651.
- Mantek, W., 1973, Niagaran Pinnacle Reefs in Michigan, Jackson, MI, Consumers Power Company, p. 32.
- Marcantel, J., 1975, Late Pennsylvanian and early Permian sedimentation in northeast Nevada: AAPG Bulletin, v. 59, p. 2079-2098.
- Maresch, O., 1970, Elektronenmikroskopische Untersuchungen von Kalken und Dolomiten, v. 1970/4, p. 648-672, 8 Pls., 2 Figs., 1 Tab.
- Marss, T., 1999, A new Late Silurian or Early Devonian thelodont from the Boothia Peninsula, Arctic Canada: Palaeontology, v. 42, p. 1079-1099.
- Martin, A. J., S. T. Solomon, and D. J. Hartmann, 1997, Characterization of petrophysical flow units in carbonate reservoirs: AAPG Bulletin, v. 81, p. 734-759.
- Martin, J. B., and R. A. Rymerson, 2002, A coupled fluid-inclusion and stable isotope record of paleofluids in the Monterey Formation, California: Geological Society of America Bulletin, v. 114, p. 269-280.
- Masetti, D., C. Neri, and A. Bosellini, 1991, Deep-Water asymmetric cycles and progradation of carbonate platforms governed by high frequency eustatic oscillations (Triassic of the Dolomites, Italy): Geology, v. 19, p. 336-339.
- Mastandrea, A., and F. Russo, 1995, Microstructure and diagenesis of calcified demosponges from the Upper Triassic of the northeastern Dolomites (Italy), v. 69, p. 416-431, 10 Figs., 4 Tabs.
- Mattavelli, L., 1966, Osservazioni petrografiche sull sostituzione della dolomite con la calcite (dedolomitizzazione) in alcune facies carbonate italiane, v. 105/3, p. 294-316, 16 Figs.
- Maurer, F., 2000, Growth mode of Middle Triassic carbonate platforms in the Western Dolomites (Southern Alps, Italy), v. 134, p. 275-286.
- Maurer, F., J. J. G. Reijmer, and W. Schlager, 2003, Quantification of input and compositional variations of calcitubidites in a Middle Triassic basinal succession (Seceda, Dolomites, southern Alps), v. 92, p. 593-609, 14 Figs., 3 Tabs.
- Mazzullo, S. J., 1986, Mississippi valley-type sulfides in Lower Permian dolomites, Delaware Basin, Texas; implications for basin evolution: AAPG Bulletin, v. 70, p. 943-952.
- Mazzullo, S. J., 1992, Geochemical and neomorphic alteration of dolomite: a review, v. 7, p. 21-37, 10 Figs.
- Mazzullo, S. J., and A. M. Reid, 1988, Sedimentary textures of recent Belizean peritidal dolomite, v. 58/3, p. 479-488, 6 Figs.
- McCunn, H. J., 1976, Origin of dolomite; model based on cyclic interaction of continental soda-rich waters with concentrated sea water: AAPG Bulletin, v. 60, p. 696.
- McHargue, T. R., and R. C. Price, 1982, Dolomite from clay in argillaceous or shale-associated marine carbonates, v. 52/3, p. 873-886, 9 Figs.
- McKenzie, J. A., 2001, Deep-sea dolomite formation and the microbial factor.
- McKenzie, J. A., K. J. Hsü, and J. F. Schneider, 1980, Movement of subsurface waters under the sabkha, Abu Dhabi, Uae and its relation to evaporative dolomite genesis, v. 28, p. 11-30.

- McNeill, D. F., and M. Aissaoui, 1991, Magnetostratigraphy in shallow-water limestone and dolomite: the legacy of magnetization through early recrystallization: *Ortisei*, p. p. 166.
- Meischner, D., and R. Vollbrecht, 1991, Dolomite-free carbonate environment: the Bermuda carbonate platform: *Ortisei*, p. p. 167.
- Melim, L. A., P. K. Swart, and G. P. Eberli, 2004, Mixing-zone diagenesis in the subsurface of Florida and the Bahamas: *Journal of Sedimentary Research*, v. 74, p. 904-913.
- Mercurio, R. N., and L. E. Monley, 1976, Block 16 Field, Ward County, Texas: *AAPG Bulletin*, v. 60, p. 327.
- Merino, E., 1975, Diagenesis in Tertiary sandstones from Kettleman North Dome, California; I, Diagenetic mineralogy: *Journal of Sedimentary Petrology*, v. 45, p. 320-336.
- Mesolella, K. J., 1972, Geologic aspects of Silurian reefs and associated strata, Northern Michigan Basin: *Annual Conference - Ontario Petroleum Institute*, p. 34.
- Mesolella, K. J., J. D. Robinson, L. M. McCormick, and A. R. Ormiston, 1974, Cyclic deposition of Silurian Carbonates and Evaporites in Michigan Basin: *AAPG Bulletin*, v. 58, p. 34-62.
- Metwalli, M. H., and Y. E. Abd El-Hady, 1975, Petrographic characteristics of oil-bearing rocks in Alamein Oil Field; significance in source-reservoir relations in northern Western Desert, Egypt: *AAPG Bulletin*, v. 59, p. 510-523.
- Meyers, W. J., and K. C. Lohman, 1978, Microdolomite-rich syntaxial cements: Proposed meteoric-marine mixing zone phreatic cements from Mississippian Limestones, New Mexico: *Journal of Sedimentary Petrology*, v. 48, p. 475-488.
- Meyers, W. J., and K. C. Lohmann, 1978, Micro-dolomite rich syntaxial cements: proposed meteoric-marine mixing zone phreatic cements from Mississippian limestones, New Mexico, v. 48, p. 475-488.
- Meyers, W. J., and K. C. Lohmann, 1978, Microdolomite-rich syntaxial cements: Proposed meteoric-marine mixing zone phreatic cements from Mississippian Limestones, New Mexico: *Journal of Sedimentary Petrology*, v. 48, p. 475-488.
- Middelburg, J. J., G. J. de Lange, and R. Kreulen, 1990, Dolomite fromation in anoxic sediments of Kau Bay, Indonesia: *Geology*, v. 18, p. 399-402.
- Middleburg, J. J., G. J. d. Lange, and R. Kreulen, 1990, Dolomite formation in anoxic sediments of Kau Bay, Indonesia, v. 18, p. 399-402, 2 Figs.
- Mitchell, J. T., L. S. Land, and D. E. Miser, 1987, Modern marine dolomite cement in a north Jamaica fringing reef, v. 15, p. 557-560.
- Molnar, B., 1980, Hypersaline lacustrine dolomite formation in the Danube - Tisza interfluve, v. 110, p. 45-64, 2 Pls., 9 Figs., 2 Tabs.
- Molnar, B., M. I. Murvai, and J. Hegyi-Pako, 1976, Recent lacustrine dolomite formation in the Great Hungarian Plain, v. 20, p. 179-198, 9 Figs., 2 Tabs.
- Molnar, B., M. Szonoky, and S. Kovacs, 1980, Diagenetic and lithification processes of recent hypersaline dolomites on the Danube-Tisza interfluve, v. 24, p. 315-337, 5 Pls., 6 Figs.
- Molnar, B., M. Szonoky, and S. Kovacs, 1981, Modern hypersaline dolomites in the Danube - Tisza interfluve: diagenetic and lithification processes, v. 111, p. 119-



- 144, 5 Pls., 6 Figs.
- Montanaze, I. P., and J. F. Read, 1992, Fluid-rock interaction history during stabilization of early dolomites, Upper Knox Group (Lower Ordovician), U.S. Appalachians, v. 62/5, p. 753-778, 17 Figs., 2 Tabs.
- Montanez, I. P., 1994, Late diagenetic dolomitization of Lower Ordovician, upper Knox carbonates; a record of the hydrodynamic evolution of the southern Appalachian Basin: AAPG Bulletin, v. 78, p. 1210-1239.
- Montgomery, S. L., S. Goolsby, and D. Pierini, 1998, Permian (Wolfcampian) Admire "C"; new exploratory potential in the northern Denver Basin: AAPG Bulletin, v. 82, p. 2173-2191.
- Moore, R. E., and J. M. Gregg, 1991, Geochemistry and sedimentology of dolomite used in refractories in metallurgical furnace construction: *Ortisei*, p. 172-173, 1 Tab.
- Moraes, M. A. S., 1991, Diagenesis and microscopic heterogeneity of lacustrine deltaic and turbiditic sandstone reservoirs (Lower Cretaceous), Potiguar Basin, Brazil: AAPG Bulletin, v. 75, p. 1758-1771.
- Moraes, M. A. S., and R. C. Surdam, 1993, Diagenetic heterogeneity and reservoir quality; fluvial, deltaic, and turbiditic sandstone reservoirs, Potiguar and Reconcavo rift basins, Brazil: AAPG Bulletin, v. 77, p. 1142-1158.
- Morrow, D., 1982, Diagenesis 2. Dolomite-Part 2 Dolomitization Models and Ancient Dolostones: *Geoscience Canada*, v. 9, p. 95-107.
- Morrow, D. W., Diagenesis 1. Dolomite-part 1: The Chemistry of Dolomitization and Dolomite Precipitation: *Geoscience Canada*, v. 9, p. 5-13.
- Morrow, D. W., 1978, Dolomitization of lower Paleozoic burrow-fillings: *Journal of Sedimentary Petrology*, v. 48, p. 295-305.
- Morrow, D. W., 1982, Diagenesis 1; Part 1: The Chemistry of Dolomitization and Dolomite Precipitation: *Geoscience Canada*, v. 9, p. 5-13.
- Morrow, D. W., 1982, Dolomite - part 2: dolomitization models and ancient dolostones, v. 9, p. 95-107.
- Morrow, D. W., ed., 1990, Dolomite - part 1: the chemistry of dolomitization and dolomite precipitation, v. 4: *St. John's, Geol. Assoc. Canada*, 113-123, 8 Figs., 1 Tab. p.
- Morrow, D. W., ed., 1990, Dolomite - part 2: dolomitization models and ancient dolostones, v. 4: *St. John's, Geol. Assoc. Canada*, 125-139, 9 Figs. p.
- Morrow, D. W., 2001, Distribution of porosity and permeability in platform dolomites: insight from the Permian of west Texas: discussion, v. 85, p. 525-529, 2 Figs.
- Morrow, D. W., G. L. Cumming, and R. B. Koepnick, 1986, Manetoe facies; a gas-bearing, megacrystalline, Devonian dolomite, Yukon and Northwest Territories, Canada: AAPG Bulletin, v. 70, p. 702-720.
- Morrow, D. W., and B. D. Ricketts, 1986, Chemical controls on the precipitation of mineral analogues of dolomite: The sulfate enigma, v. 14, p. 408-410, 2 Figs.
- Morrow, D. W., and B. D. Ricketts, eds., 1988, Experimental investigation of sulfate inhibition of dolomite and its mineral analogues, v. 43: *Tulsa*, 25-38, 7 Figs. p.
- Morrow, D. W., A. H. Saller, and N. Henderson, 2001, Distribution of porosity and permeability in platform dolomites; insight from the Permian of West Texas; discussion and reply: AAPG Bulletin, v. 85, p. 525-532.

- Morrow, D. W., M. Zhao, and L. D. Stasiuk, 2002, The gas-bearing Devonian Presqu'île Dolomite of the Cordova embayment region of British Columbia; Canada: dolomitization and the stratigraphic template, v. 86, p. 1609-1638, 13 Figs.
- Mountjoy, E. W., H. G. Machel, D. Green, J. Duggan, and A. E. Williams-Jones, 1999, Devonian matrix dolomites and deep burial carbonate cements: a comparison between the Rimbey-Meadowbrook reef trend and the deep basin of west-central Alberta, v. 47, p. 487-509.
- M'Rabet, A., 1981, Differentiation of environments of dolomite formation, Lower Cretaceous of central Tunisia: *Sedimentology*, v. 28, p. 331-352.
- Muir, M., D. Lock, and C. Von der Borch, 1980, The Coorong model for penecontemporaneous dolomite formation in the Middle Proterozoic McArthur Group, Northern Territories, Australia, v. 28, p. 51-67, 10 Figs.
- Mukhopadhyay, J., S. K. Chanda, M. Fukuoka, and A. K. Chaudhuri, 1996, Deep-water dolomites from the Proterozoic Penganga Group in the Pranhita-Godavari Valley, Andhra Pradesh, India, v. A66, p. 223-230, 15 Figs., 1 Tab.
- Müller, G., 1970, High-magnesian calcite and protodolomite in Lake Balaton (Hungary) sediments, v. 226, p. 749-750.
- Muller, G., and M. Illic, 1975, Hydrothermal-sedimentary dolomite; the missing link?: *AAPG Bulletin*, v. 59, p. 1690-1692.
- Müller-Wille, S., and J. Reitner, 1993, Palaeobiological reconstructions of selected sphinctozoan sponges from the Cassian Beds (Lower Carnian) of the Dolomites (Northern Italy), v. E9, p. 253-281, 4 Pls., 8 Figs.
- Mullins, H. T., G. R. Dix, A. F. Garduliski, and L. S. Land, eds., 1988, Neogene deep-water dolomite from the Florida-Bahamas platform, v. 43: Tulsa, 235-243, 7 Figs. p.
- Murray, R. C., 1964, Preservation of primary structures and fabrics in dolomite: New York, Wiley, p. 388-403.
- Murray, R. C., and F. J. Lucia, 1967, Cause and control of dolomite distribution by rock selectivity, v. 78, p. 21-36, 5 Pls., 7 Figs.
- Myszkowska, J., 1992, Lithofacies and sedimentation of *Diplopora* dolomite (Middle Muschelkalk) in the east part of the Cracovian-Silesian Region, v. 62, p. 19-62, 9 Figs.
- Nahsen, M., 1913, Über die Gesteine des norddeutschen Korallenooliths, insbesondere die Bildungsweise der oolithe und Dolomite, v. 35, p. 277-.
- Naiman, E. R., A. Bein, and R. L. Folk, 1983, Complex polyhedral crystals of limpid dolomite associated with halite, Permian upper Clear Fork and Glorieta formations, Texas: *Journal of Sedimentary Petrology*, v. 53, p. 549-555.
- Naiman, E. R., A. Bein, and R. L. Folk, 1983, Complex polyhedral crystals of limpid dolomite associated with halite, Permian Upper Clear Fork and Glorieta Formations, Texas, v. 53/2, p. 549-555, 6 Figs., 3 Tabs.
- Narkiewicz, M., 1979, Telo- and mesogenetic dolomites in subsurface Upper Devonian to Lower Carboniferous sequences of southern Poland, v. 158, p. 180-208, 19 Figs., 1 Tab.
- Narkiewicz, M., 1983, Dolomite from clay in argillaceous or shale-associated marine carbonates - discussion, v. 52/4, p. 1353-1359.

- Narkiewicz, M., R. C. Price, and T. R. McHargue, 1983, Dolomite from clay in argillaceous or shale-associated marine carbonates; discussion and reply: *Journal of Sedimentary Petrology*, v. 53, p. 1353-1355.
- Nash, A. J., and E. D. Pittman, 1975, Ferro-magnesian calcite cement in sandstones: *Journal of Sedimentary Petrology*, v. 45, p. 258-265.
- Neri, C., 1991, Sequence stratigraphy of the early Triassic Werfen Formation (Dolomites, Northern Italy): *Ortisei*, p. 194-195.
- Neumann, E. R., 1978, Experimental recrystallization of dolomite and comparison of preferred orientations of calcite and dolomite in deformed rocks, v. 77, p. 426-438.
- Neuweiler, F., and J. Reitner, 1995, Epifluorescence microscopy of selected automicrites from lower Carnian Cipit-boulders of the San Cassian Formation (Seeland Alpe, Dolomites), v. 32, p. 26-28, Pl. 6.
- Newman, J., and G. Mitra, 1994, Fluid-induced deformation and recrystallization of dolomite at low temperatures along a natural fault zone, Mountain City Window, Tennessee, v. 106, p. 1642.
- Nielsen, P., and R. Swennen, 1991, Influence of recrystallization phenomena on the isotopic signature within massive ancient dolomite units: an example from the Lower Visean of E-Belgium: *Ortisei*, p. 198.
- Nielsen, P., R. Swennen, and E. Keppens, 1994, Multiple-step recrystallization within massive ancient dolomite units: an example from the Dinantian of Belgium, v. 41, p. 567-584, 7 Figs., 4 Tabs.
- Nordeng, S. H., and D. F. Sibley, 1996, A crystal growth rate equation for ancient dolomites: evidence for millimeter-scale flux-limited growth, v. A66, p. 477-481, 3 Figs., 1 Tab.
- Nöth, S., P. Bruckschen, and D. K. Richter, 1991, Conodont color alteration and microdolomite composition - implications to the Muschelkalk limestones (Upper Triassic) overlying the Upper Cretaceous intrusive body of the Vlotho Massif (Weserbergland, Northwest Germany), v. 70, p. 265-273, 8 Figs.
- Nunn J. A., Sleep N. H., and Moore W. E. (1984) Thermal Subsidence and Generation of Hydrocarbons in Michigan Basin. *AAPG Bulletin* 68(3), 296-315.
- Oglesby, T. W., W. J. Meyers, and K. C. Lohmann, 1979, Microdolomite-rich syntaxial cements; proposed meteoric-marine mixing zone phreatic cements from Mississippian limestones, New Mexico: *Journal of Sedimentary Petrology*, v. 49, p. 670-676.
- Orpin, A. R., 1997, Dolomite chimneys as possible evidence of coastal fluid expulsion, uppermost Otago continental slope, southern New Zealand, v. 138, p. 51-67.
- Packard, J. J., I. Al-Aasm, I. Samson, Z. Berger, and J. Davies, 2001, A Devonian hydrothermal chert reservoir; the 225 bcf Parkland Field, British Columbia, Canada: Chert reservoirs of North America *AAPG Bulletin*, v. 85, p. 51-84.
- Patterson, R. J., and D. J. J. Kinsman, 1982, Formation of diagenetic dolomite in coastal sabkhas along the Arabian (Persian) Gulf, v. 66, p. 28-43.
- Patterson, R. J., and J. J. Kinsman, 1982, Formation of diagenetic dolomite in coastal sabkha along Arabian (Persian) Gulf: *AAPG Bulletin*, v. 66, p. 28-43.

- Pearce, L. A., C. M. Hewitt, and L. M. Corder, 2003, Horizontal Drilling in the Northern Reef Trend of the Michigan Basin, in T. R. Carr, E. P. Mason, and C. T. Feazel, eds., *Horizontal Wells: Focus on the Reservoir*, v. AAPG Methods in Exploration No. 14, p. 193-203.
- Pedone, V. A., and J. A. D. Dickson, 2000, Replacement of aragonite by quasi-rhombohedral dolomite in a Late Pleistocene tufa mound, Great Salt Lake, Utah, U.S.A., v. A70, p. 1152-1159, 4 Figs., 3 Tabs.
- Peryt, T., 1991, Dolomitization model of evaporite-associated dolomites: lesson from the Zechstein (Upper Permian) of Poland: *Ortisei*, p. p. 208.
- Peryt, T. M., 1985, Permian beach in the Zechstein dolomites of western Poland: influence on reservoirs, v. 8, p. 463-474, 4 Figs.
- Peryt, T. M., 1986, The Zechstein (Upper Permian) Main Dolomite deposits of the Leba Elevation, Northern Poland: Facies and depositional history, v. 14, p. 151-200, Pls. 24-37, 10 Figs.
- Peryt, T. M., 1992, Debris-flow deposits in the Zechstein (Upper Permian) Main dolomite of Poland: significance for the evolution of the basin, v. 185, p. 1-19, 8 Figs.
- Petty, D. M., 1988, Depositional facies, textural characteristics, and reservoir properties of dolomites in Frobisher-Alida interval in Southwest North Dakota: *AAPG Bulletin*, v. 72, p. 1229-1253.
- Pfeil, R. W., and J. F. Read, 1980, Cambrian Carbonate Platform Margin Facies, Shady Dolomite, Southwestern Virginia, U.S.A.: *Journal of Sedimentary Petrology*, v. 50, No.1, p. 91-116.
- Pichler, T., and J. D. Humphrey, 2001, Formation of dolomite in recent island-arc sediments due to gas-seawater-sediment interaction, v. A71, p. 394-399, 5 Figs.
- Pierre, C., L. Ortlieb, and A. Person, 1984, Supratidal evaporitic dolomite at Ojo de Liebre Lagoon: mineralogical and isotopic arguments for primary crystallization, v. 54/4, p. 1049-1061, 8 Figs.
- Pierson, B. J., 1981, The control of cathodoluminescence in dolomite by iron and manganese, v. 28, p. 601-610.
- Pitman, J. K., T. D. Fouch, and M. B. Goldhaber, 1982, Depositional setting and diagenetic evolution of some Tertiary unconventional reservoir rocks, Uinta Basin, Utah: *AAPG Bulletin*, v. 66, p. 1581-1596.
- Pokrovsky, O. S., J. Schott, and F. Thomas, 1999, Dolomite surface speciation and reactivity in aquatic systems, v. 63, p. 3133-3143.
- Pomar, L., and W. C. Ward, 1999, Reservoir-scale heterogeneity in depositional packages and diagenetic patterns on a reef-rimmed platform, upper Miocene, Mallorca, Spain: *AAPG Bulletin*, v. 83, p. 1759-1773.
- Pope, M. C., and J. F. Read, 1997, High-resolution surface and subsurface sequence stratigraphy of late Middle to Late Ordovician (late Mohawkian-Cincinnatian) foreland basin rocks, Kentucky and Virginia: *AAPG Bulletin*, v. 81, p. 1866-1893.
- Porcher, E. N., 1985, Lithofacies and geochemistry of interreef carbonates, Middle Silurian, Michigan Basin: MS thesis, Western Michigan University, Kalamazoo, 118p.

- Pranter, M. J., 1998, Use of petrophysical-based reservoir zonation and time-lapse, multicomponent (4D, 3C) seismic attributes for improved geologic modeling: AAPG Foundation grants-in-aid recipients for 1998; abstracts AAPG Bulletin, v. 82, p. 2167.
- Purser, B. H., 1985, Dedolomite porosity and reservoir properties of Middle Jurassic carbonates in the Paris Basin, France: Berlin, p. 343-355, 12 Figs.
- Purser, B. H., 1991, Origins and distribution of porosity in the dolomites of Mururoa Atoll French Polynesia: *Ortisei*, p. p. 219.
- Purser, B. H., M. E. Tucker, and D. H. e. Zanger, 1994, Dolomites, v. 21, p. 464 pp., 279 Figs.
- Purser, B. H., M. E. Tucker, and D. H. e. Zenger, 1994, Dolomites. A volume in honor of Dolomieu, v. 21, p. 464 pp., 279 Figs.
- Purser, N. H., A. Brown, and D. M. Aissaoui, 1994, Nature, origins and evolution of porosity in dolomites: *Spec. Pub. Inter, Assoc. of Sedimentologists*, v. 21, p. 283-308, 15 Figs.
- Purser, N. H., A. Brown, and D. M. Aissaoui, eds., 1994, Nature, origins and evolution of porosity in dolomites, v. 21: Oxford, 283-308, 15 Figs. p.
- Qing, H., 1998, Petrography and geochemistry of early-stage, fine- and medium-crystalline dolomites in the Middle Devonian Presqu'ile Barrier at Pine Point, Canada, v. 45, p. p. 433-.
- Qing, H., and E. W. Mountjoy, 1994, Formation of coarsely crystalline, hydrothermal dolomite reservoirs in the Presqu'ile barrier, Western Canada sedimentary basin: AAPG Bulletin, v. 78, p. 55-77.
- Qing, H., and E. W. Mountjoy, 1994, Rare earth element geochemistry of dolomites in the Middle Devonian Presqu'ile barrier, Western Canada Sedimentary Basin: implications for fluid-rock ratios during dolomitization, v. 41, p. 787-804, 14 Figs., 3 Tabs.
- Quing, H., and E. Mountjoy, 1991, Presqu'ile Dolomite at Pine Point and adjacent subsurface: evidence for hydrothermal dissolution and a Late Cretaceous maximum burial origin for saddle dolomites and mineralization: *Ortisei*, p. 220-221.
- Radke, B. M., and R. L. Mathis, 1980, On the formation and occurrence of saddle dolomite, v. 50/4, p. 1149-1168, 12 Figs.
- Rao, C. G., 1969, Dolomitization, dedolomitization and the dolomite question in carbonate rocks, v. 1, p. 209-216.
- Read, J. F., and R. W. Pfeil, 1983, Fabrics of allochthonous reefal blocks, Shady dolomite (Lower to Middle Cambrian), Virginia Appalachians, v. 52/3, p. 761-778, 9 Figs.
- Reeder, R. J., and J. L. Prosky, 1986, Compositional sector zoning in dolomite, v. 56/2, p. 237-247, 10 Figs.
- Reid, S. A., and J. L. McIntyre, 2001, Monterey Formation porcelanite reservoirs of the Elk Hills Field, Kern County, California: Chert reservoirs of North America AAPG Bulletin, v. 85, p. 169-189.
- Reijmer, J. J. G., 1998, Compositional variations during phases of progradation and retrogradation of a Triassic carbonate platform (Picco di Vallandro/Dürrenstein

- Dolomites, Italy), v. 87, p. 436-448, 5 Figs., 4 Tab.
- Reinhold, C., 1998, Multiple episodes of dolomitization and dolomite recrystallization during shallow burial in Upper Jurassic shelf carbonates: eastern Swabian Alb, southern Germany, v. 121, p. 71-95, 14 Figs.
- Richter, D. K., 1972, Eine subrezente spätdiagenetische Dolomitisierung mit prätertiären Dolomiten als Keime (Bucht von Volos, Griechenland), v. 1972/8, p. 490-506, 10 Figs., 1 Tab.
- Richter, D. K., 1974, Entstehung und Diagenese der devonischen und permotriassischen Dolomite in der Eifel, v. 2, p. 1-101.
- Richter, D. K., 1985, Mikrodolomite om Crionoiden des Trochitenkalks (mo1) und die Wärmeanomalie von Vlotho, v. 1985, p. 681-690.
- Ricketts, B. D., 1982, Comment on Precambrian dolomites: petrographic and isotopic evidence that they differ from Phanerozoic dolomites, v. 10, p. p. 663.
- Riley, R. A., J. Wicks, and J. Thomas, 2002, Cambrian-Ordovician Knox production in Ohio; three case studies of structural-stratigraphic traps: AAPG Bulletin, v. 86, p. 539-555.
- Rock, L., 1998, Differences between limestone and dolomite reservoir properties of Swan Hills Ante Creek pools and Leduc Simonette Pool, west central Alberta: AAPG Foundation grants-in-aid recipients for 1998; abstracts AAPG Bulletin, v. 82, p. 2167.
- Rosen, M. R., and L. Coshell, 1992, A new location of Holocene dolomite formation , Lake Hayward, Western Australia, v. 39, p. 161-166, 2 Figs.
- Rosen, M. R., and G. R. Holdren, 1986, Origin of Dolomite Cement in Chesapeake Group (Miocene) Siliciclastic Sediments: An Alternative Model To Burial Dolomitization: Journal of Sedimentary Petrology, v. 56, p. 788-798.
- Rosen, M. R., and G. R. Holdren, Jr., 1986, Origin of dolomite cement in Chesapeake Group (Miocene) siliciclastic sediments: an alternative model to burial dolomitization, v. 56/6, p. 788-798, 8 Figs.
- Rosen, M. R., D. E. Miser, M. A. Starcher, and W. J.K., 1989, Formation of dolomite in the Coorong region, South Australia, v. 53, p. 661-669, 6 Figs.
- Ross, R. J., Jr., 1975, Ordovician sedimentation in western United States: Rocky Mountain sections, AAPG and SEPM annual meeting; Rocky Mountain energy resources, discovery and development AAPG Bulletin, v. 59, p. 921.
- Rudolph, K. W., W. Schlager, and K. T. Biddle, 1989, Seismic models of a carbonate foreslope-to-basin transition, Picco di Vallandro, Dolomite Alps, northern Italy: Geology, v. 17, p. 453-456.
- Rudolph, K. W., W. Schlager, and K. T. Biddle, 1989, Seismic models of a carbonate foreslope-to-basin transition, Picco di Vallandro, Dolomite Alps, northern Italy, v. 17, p. 453-456.
- Russo, F., A. Mastandrea, M. Stefani, and C. Neri, 2000, Carbonate facies dominated by syndepositional cements: a key component of Middle Triassic platforms. The Marmolada case history (Dolomites, Italy), v. 42, p. 211-226, Pl. 38-43, 4 Figs.
- Russo, F., C. Neri, A. Mastandrea, and A. Baracca, 1997, The mud mound nature of the Cassian platform margins of the Dolomites. A case history: the Cipit boulders from Punta Grohmann (Sasso Piatto Massif, Northern Italy), v. 36, p. 25-36, Pl. 8-

- 10, 4 Figs., 1 Tab.
- Ruzyla, K., and G. M. Friedman, 1985, Factors controlling porosity in dolomite reservoirs of the Ordovician Red River Formation, Cabin Creek Field, Montana: Berlin, Springer, p. 41-58, 12 Figs.
- Sabins, F. F. J., 1962, Grains of detrital, secondary, and primary dolomite from Cretaceous strata of the Western Interior, v. 73, p. 1183-1196, 5 Figs.
- Saller, A., B. Ball, S. Robertson, B. McPherson, C. Wene, R. Nims, and J. Gogas, 2001, Reservoir characteristics of Devonian cherts and their control on oil recovery; Dollarhide Field, West Texas: Chert reservoirs of North America AAPG Bulletin, v. 85, p. 35-50.
- Saller, A. H., 1984, Petrologic and geochemical constraints on the origin of subsurface dolomite, Enewetak Atoll: an example of dolomitization by normal seawater, v. 12, p. 217-220.
- Saller, A. H., and N. Henderson, 1998, Distribution of porosity and permeability in platform dolomites; insight from the Permian of West Texas: AAPG Bulletin, v. 82, p. 1528-1550.
- Saller, A. H., and N. Henderson, 2001, Distribution of porosity and permeability in platform dolomites: insight from the Permian of west Texas: reply, v. 85, p. 530-532, 2 Figs.
- Sander, B., 1936, Beiträge zur Kenntnis der Anlagerungsgefüge (Rhythmische Kalke und Dolomite aus der Trias), v. 48, p. 27-139, 36 Figs., 7 Pls.
- Sano, H., 1983/1984, Displaced dolomites in radiolarian cherts of the Chichibu belt on Shikoku Island, southwest Japan, v. 37, p. 203-223, 9 Figs.
- Sarg, J. F., 1982, Off-reef Salina deposition (Silurian), southern Michigan Basin -- implications for reef genesis: Depositional and diagenetic spectra of evaporites: a core workshop, p. 354-384.
- Sargent, K. A., 1976, Chemical and isotopic investigation of stratigraphic and tectonic dolomites in Arbuckle Group, Arbuckle Mountains, South-central Oklahoma: AAPG Bulletin, v. 60, p. 719.
- Sarin, D. D., 1962, Cyclic sedimentation of primary dolomite and limestone, v. 32/3, p. 451-471, 16 Figs., 1 Tab.
- Sass, E., 1965, Dolomite-calcite relationships in seawater: theoretical considerations and preliminary experimental results, v. 35, p. 339-347, 4 Figs.
- Sass, E., and A. Bein, eds., 1988, Dolomites and salinity: a comparative geochemical study, v. 43: Tulsa, 223-233, 7 Figs. p.
- Sass, E., and A. Katz, 1982, The origin of platform dolomites: new evidence, v. 282, p. 1184-1213.
- Schaefer, K. W., and E. Usdowski, 1992, Application of stable carbon and sulfur isotope models to the development of ground water in a limestone-dolomite-anhydrite-gypsum area: Berlin, Springer, p. 157-163, 3 Figs., 3 Tabs.
- Schauer, M., and T. Aigner, 1997, Cycle stacking pattern, diagenesis and reservoir geology of peritidal dolostones, Trigonodus-Dolomite, Upper Muschelkalk (Middle Triassic, SW-Germany, v. 37, p. 99-114, Pl. 23-25, 8 Figs., 2 Tabs.
- Schindler, J. L., 1999, Quantification of vuggy porosity using electrical borehole images, nuclear magnetic resonance images, and core in the Upper Pennsylvanian of the

- Indian Basin Field, New Mexico: AAPG Foundation grants-in-aid abstracts  
AAPG Bulletin, v. 83, p. 1896.
- Schlanger, S. O., 1957, Dolomite growth in coralline algae, v. 57, p. 181-186.
- Schmoker, J. W., K. B. Krystinik, and R. B. Halley, 1985, Selected characteristics of limestone and dolomite reservoirs in the United States: AAPG Bulletin, v. 69, p. 733-741.
- Scudeler Baccelle, L., and L. Secco, 1991, Relation between crystal chemistry and genetic processes in sedimentary dolomites: Ortisei, p. p. 242.
- Searl, A., 1991, Discontinuous solid solution in calcium-rich dolomites: Ortisei, p. 243-244, 3 Figs.
- Searl, A., 1992, Dolomite-carbonate replacement textures in veins cutting Carboniferous rocks in East Fife, v. 77, p. 1-14, 9 Figs.
- Sears, S. O., and F. J. Lucia, 1979, Reef-growth model for Silurian pinnacle reefs, Northern Michigan reef trend: Geology, v. 7, p. 299-302.
- Sears, S. O., and F. J. Lucia, 1980, Dolomitization of northern Michigan Niagara Reefs by brine refluxion and freshwater/seawater mixing, SEPM Special Publication No. 28, SEPM, p. 215-235.
- Senowbari-Daryan, B., R. Zühlke, T. Bechstädt, and E. Flügel, 1993, Anisian (Middle Triassic) buildups of the Northern Dolomites (Italy): the recovery of reef communities after the Permian/Triassic crisis, v. 28, p. 181-256, Pl. 40-65, 17 Figs.
- Sharma, G. D., 1966, Geology of Peters reef, St. Clair County, Michigan: AAPG Bulletin, v. 50, p. 327-350.
- Shaver, R. H., 1974, Silurian Reefs of Northern Indiana: Reef and Interreef Macrofaunas: AAPG Bulletin, v. 58, p. 934-956.
- Shaver, R. H., 1976, Indiana Portion of a Guidebook for a field trip on Silurian Reefs, Interreef facies, and Faunal zones of Northern Indiana and Northeastern Illinois: North-Central Section of the GSA and WMU.
- Shaver, R. H., 1976, Silurian Reefs, Interreef Facies, and Faunal zones of Northern Indiana and Northeastern Illinois: North-Central section of the Geological Society of America and Western Michigan University, p. 1-37.
- Shaver, R. H., 1991, A history of study of Silurian reefs in the Michigan Basin environs: Geological Society of America, p. 101-137.
- Shaver R. H. (1996) Silurian sequence stratigraphy in the North American craton, Great Lakes area. In *Silurian Sequence stratigraphy in the North American craton, Great Lakes area*, Vol. 306 (ed. B. J. Witzke, G. A. Ludvigson, and J. Day), pp. 193-202. Geological Society of America.
- Shaver, R. H., 1997, Silurian Reef Geometry-New Dimensions to explore.: Journal of Sedimentary Petrology, v. 47, p. 1409-1424.
- Shaver, R. H., and J. A. Sunderman, 1982, Silurian Reefs at Delphi and Pipe Creek Jr. Quarry, Indiana, with Emphasis on the Question of Deep vs. Shallow Water: Geological Society of America, p. 1-39.
- Shaver, R. H., and J. A. Sunderman, 1989, Silurian seascapes: Water depth, clinothems, reef geometry, and other motifs-A critical review of the Silurian reef model: Geological Society of America Bulletin, v. 101, p. 939-951.



- Shelden F. D. (1963) Transgressive marginal lithotopes in Niagaran (Silurian) of Northern Michigan Basin. *AAPG Bulletin* 47(1), 129-149.
- Shinn E. A. (1983) Tidal Flat. In *Carbonate Depositional Environments*, Vol. 33 (ed. P. A. Scholle, D. G. Bebout, and C. H. Moore), pp. 171-210. AAPG.
- Shearman, D. J., J. Khouri, and S. Taha, 1961, On replacement of dolomite by calcite in some Mesozoic limestones from the French Jura, v. 72/1, p. 1-12, Pl. 1.
- Sheehan, P. M., 1980, The Late Ordovician and Silurian of the Eastern Great Basin, Part 3: Brachiopods of the Tony Grove Lake Member of the Laketown Dolomite: Contributions in Biology and Geology of the Milwaukee Public Museum, v. 30, p. 1-23.
- Shimmield, G. B., and N. B. Price, eds., 1984, Recent dolomite formation in hemipelagic sediments of Baja California, Mexico: Los Angeles, 5-18 p.
- Shinn, E. A., and R. N. Ginsburg, 1964, Formation of recent dolomite in Florida and the Bahamas (abs.), v. 48, p. p. 547-.
- Shinn, E. A., R. N. Ginsburg, and R. M. Lloyd, 1965, Recent supratidal dolomite from Andros Island, Bahamas: Society of Economic Paleontologists and Mineralogists Special Publication, p. 112-123.
- Shinn, E. A., R. N. Ginsburg, and R. M. Lloyd, eds., 1965, Recent supratidal dolomite from Andros Island, Bahamas, v. 13: Tulsa, 112-123, 8 Figs. p.
- Shiyun, T., and J. M. Gregg, 1991, Application of multivariate statistical analysis to geochemical differentiation of dolomite, v. 6, p. 75-81, 3 Figs., 2 Tabs.
- Shrock R. R. (1939) Wisconsin Silurian Bioherms (Organic Reefs). *GSA Bulletin* 50, 529-562.
- Shukla, V., 1986, Epigenetic dolomitization and the origin of xenotopic dolomite texture - discussion, v. 56/5, p. 733-734, 1 Fig.
- Shukla, V., ed., 1988, Sedimentology and geochemistry of regional dolostones: Correlation of trace elements with dolomite fabrics, v. 43: Tulsa, 145-157, 14 Figs. p.
- Sibley, D. F., 1982, The origin of common dolomite fabrics: clues from the Pliocene, v. 52/4, p. 1087-1100, 8 Figs., 1 Tab.
- Sibley, D. F., 1991, Secular changes in the amount and texture of dolomite: *Geology*, v. 19, p. 151-154.
- Sibley, D. F., 1991, Dolomite mineralogy and texture in time and space: *Ortisei*, p. p. 255.
- Sibley, D. F., and J. M. Gregg, 1987, Classification of dolomite rock textures, v. 57/5, p. 967-975, 11 Figs.
- Sibley, D. F., J. M. Gregg, R. G. Brown, and P. R. Laudon, 1990, Dolomite crystal size distribution in the burial environment, p. p. 36.
- Sibley, D. F., J. M. Gregg, R. G. Brown, and P. R. Laudon, 1993, Dolomite crystal size distribution, p. 195-204, 12 Figs.
- Siegmund, H., and B.-D. Erdtmann, 1994, Facies and diagenesis of some Upper Proterozoic dolomites of South China, v. 31, p. 255-264, Pl. 29-30, 2 Figs., 1 Tab.
- Simonson, B. M., and D. G. Jarvis, eds., 1993, Microfabrics of oolites and pisolites in the

- Early Precambrian Carawine dolomite of Western Australia: New York, Springer, 227-237, 13 Figs. p.
- Skilliter, C. C., 1998, Stratigraphic and geochemical investigation of Middle to Upper Devonian "aquifers" in west-central Alberta, Canada: AAPG Foundation grants-in-aid recipients for 1998; abstracts AAPG Bulletin, v. 82, p. 2168.
- Smith, A. L., and J. A. Legault, 1985, Preferred Orientations of Middle Silurian Guelph-Amabel Reefs of Southern Ontario: Bulletin of Canadian Petroleum Geology, v. 33, No.4, p. 421-426.
- Smith, T. M., and S. L. Dorobek, 1993, Alteration of early-formed dolomite during shallow to deep burial: Mississippian Mission Canyon Formation, central to southwestern Montana: GSA Bulletin, v. 105, p. 1389-1399.
- Soderman J. W. and Carozzi A. V. (1963) Petrography of algal bioherms in Burnt Bluff Group (Silurian), Wisconsin. *AAPG Bulletin* 47(9), 1682-1708.
- Sonnenfeld, P., 1963, Dolomites and dolomitization: a review, v. 12, p. 101-132.
- Sonnenfeld, P., and I. Al-Aasm, 1991, The Salina Evaporites in the Michigan Basin, in P. A. Catascinos, and P. A. J. Daniels, eds., Early Sedimentary Evolution of the Michigan Basin: Geological Society of America Special Paper 256, p. 139-153.
- Soreghan, G. S., M. H. Engel, R. A. Furley, and K. A. Giles, 2000, Glacioeustatic Transgressive Reflux: Stratiform Dolomite in Pennsylvanian Bioherms of the Western Orogrande Basin, New Mexico: Journal of Sedimentary Research, v. 70, p. 1315-1332.
- Spence, B. R., 1997, Sedimentology and diagenesis of the Lower Cretaceous Basal Quartz Formation, Crossfield/Delacour Field, Calgary area: AAPG Foundation grants-in-aid abstracts AAPG Bulletin, v. 81, p. 1782.
- Spencer-Cervato, C., and J. Mullis, 1991, Fluid inclusions in dolomite: determination of the composition of the dolomitizing paleo-fluid: Ortisei, p. p. 261.
- Sperber, C. M., B. H. Wilkinson, and D. R. Peacor, 1984, Rock composition, dolomite stoichiometry, and rock/water reactions in dolomitic carbonate rocks: Journal of Geology, v. 92, p. 609-622.
- Stauffer, C. R., 1937, A diminutive fauna from the Shakopee Dolomite (Ordovician) at Cannon Falls, Minnesota: Journal of Paleontology, v. 11, p. 55-60.
- Stauffer, C. R., 1937, Mollusca from the Shakopee Dolomite (Ordovician) at Stillwater, Minnesota: Journal of Paleontology, v. 11, p. 61-68.
- Sternbach, C. A., and G. M. Friedman, 1986, Dolomites formed under conditions of deep burial: Hunton Group carbonate rocks (upper Ordovician to Lower Devonian) in the deep Anadarko Basin of Oklahoma and Texas., v. 1/1, p. 69-73, 19 Figs.
- Sternbach, C. A., and G. M. Friedman, 1986, Dolomites formed under conditions of deep burial: Hunton Group carbonate rocks (Upper Ordovician to Lower Devonian) in the deep Anadarko Basin of Oklahoma and Texas, v. 1, p. 69-73, 19 Figs.
- Stock, H. W., 1994, Spurenfossilien als Faziesindikatoren im Campan der NE' Dolomiten (Italien), v. 51, p. 277-289.
- Stock, H. W., 1994, Stratigraphie, Sedimentologie und Paläogeographie der Oberkreide in den nordöstlichen Dolomiten (Italien)x, v. 137, p. 393-406, 3 Pls., 11 Figs.
- Stoessell, R. K., and C. H. Moore, 1983, Chemical constraints and origins of four groups of Gulf Coast reservoir fluids: AAPG Bulletin, v. 67, p. 896-906.

- Strahan, R. K., 1975, Geology of Chatom Field, Washington County, Alabama: AAPG Bulletin, v. 59, p. 1731.
- Suhm, R. W., 1974, Stratigraphy of Everton Formation (Early Medial Ordovician), Northern Arkansas: AAPG Bulletin, v. 58, p. 685-707.
- Sun, S. Q., 1994, A reappraisal of dolomite abundance and occurrence in the Phanerozoic, v. A64, p. 396-404, 4 Figs., 3 Tabs.
- Sun, S. Q., 1995, Dolomite reservoirs; porosity evolution and reservoir characteristics: AAPG Bulletin, v. 79, p. 186-204.
- Swart, P. K., D. L. Cantrell, H. Westphal, C. R. Handford, and C. G. Kendall, 2005, Origin of dolomite in the Arab-D reservoir from the Ghawar Field, Saudi Arabia: Evidence from petrographic and geochemical constraints: Journal of Sedimentary Research, v. 75, p. 476-491.
- Swart, P. K., and L. A. Melim, 2000, The Origin of dolomites in Tertiary sediments from the margin of Great Bahama Bank: Journal of Sedimentary Petrology Research, v. 70, p. 738-748.
- Swart, P. K., E. A. Shinn, J. A. McKenzie, C. G. S. C. Kendall, and S. E. Hajari, 1987, Spontaneous precipitation of dolomite in brines from Umm Sid sabkha (qatar (abstr.)), v. 39, p. 1202-1228.
- Tagai, H., 1957, On the texture of salking-proof dolomite clinker observed by electronmicroscope, v. 65, p. 175-179, 11 Figs.
- Tan, F. C., and J. D. Hudson, 1971, Carbon and oxygen isotopic relationships of dolomite and co-existing calcites, Great Estuarine Series (Jurassic), Scotland, v. 35, p. 755-767.
- Tanguay, L. H., and G. M. Friedman, 2001, Petrophysical characteristics and facies of carbonate reservoirs; the Red River Formation (Ordovician), Williston Basin: AAPG Bulletin, v. 85, p. 491-523.
- Tatarskyi, V. B., 1949, Distribution of rocks in which dolomite is replaced by calcite, v. 69, p. 849-851.
- Taylor, T. R., and D. F. Sibley, 1986, Petrographic and geochemical characteristics of dolomite tps and the origin of ferroan dolomite in the Trenton Formation, Ordovician, Michigan Basin, U.S.A., v. 33, p. 61-86, 17 Figs.
- Taylor, T. R., and C. H. Soule, 1993, Reservoir characterization and diagenesis of the Oligocene 64-Zone sandstone, North Belridge Field, Kern County, California: AAPG Bulletin, v. 77, p. 1549-1566.
- Textoris, D. A., and A. V. Carozzi, 1964, Petrography and evolution of Niagaran (Silurian) Reefs, Indiana: AAPG Bulletin, v. 48, p. 397-425
- Tlig, S., and A. M'Rabet, 1985, A comparative study of the Rare Earth Element (Ree) distributions within the Lower Cretaceous dolomites and limestones of Central Tunisia, v. 32, p. 897-907, 8 Figs.
- Torok, A., 2000, Formation of dolomite mottling in Middle Triassic ramp carbonates (Southern Hungary): Sedimentary Geology, v. 131, p. 131-145.
- Török, A., 2000, Formation of dolomite mottling in the Middle Triassic ramp carbonates (Southern Hungary), v. 131, p. 131-145, 16 Figs., 1 Tab.
- Tucker, K. E., P. M. Harris, and R. C. Nolen-Hoeksema, 1998, Geologic investigation of cross-well seismic response in a carbonate reservoir, McElroy Field, West Texas:

- AAPG Bulletin, v. 82, p. 1463-1503.
- Tucker, M. E., 1982, Precambrian dolomites: petrographic and isotopic evidence that they differ from Phanerozoic dolomites, v. 10, p. 7-12.
- Tucker, M. E., 1983, Diagenesis, geochemistry, and origin of a Precambrian dolomite: The Beck Spring Dolomite of eastern California, v. 53/4, p. 1097-1119, 15 Figs.
- Underwood, C. A., M. L. Cooke, J. A. Simo, and M. A. Muldoon, 2003, Stratigraphical controls on vertical fracture patterns in Silurian dolomite, northeastern Wisconsin, v. 87, p. 121-142, 15 Figs.
- Usdowski, E., 1994, Synthesis of dolomite and geochemical implications, v. 21, p. 345-360, 8 Figs., 5 Tabs.
- Usdowski, H. E., 1989, Synthesis of dolomite and magnesite at 60°C in the system  $\text{Ca}^{2+}$ - $\text{Mg}^{2+}$ - $\text{Cl}^{2-}$ - $\text{H}_2\text{O}$ , v. 76, p. 374-375, 1 Tab.
- Usdowski, H. E., 1991, Synthesis of dolomite and magnesite at 60° C and geochemical implications: Ortisei, p. p. 277.
- Üsenmez, S., G. M. Friedman, and D. C. Kopaska-Merkel, 1988, Fabric and composition of dolostones and dedolomites from near Karapinar (Adana, southern Turkey), v. 2/2, p. 101-108, 16 Figs., 2 Tabs.
- Vahrenkamp, V. C., and P. K. Swart, 1990, New distribution coefficient for the incorporation of strontium into dolomite and its implications for the formation of ancient dolomites: Geology, v. 18, p. 387-391.
- Vahrenkamp, V. C., and P. K. Swart, 1990, New distribution coefficient for the incorporation of strontium into dolomite and its implications for the formation of ancient dolomites, v. 18, p. 387-391, 5 Figs.
- Vahrenkamp, V. C., and P. K. Swart, 1990, New distribution coefficient for the incorporation of strontium into dolomite and its implications for the formation of ancient dolomites: Geology, v. 18, p. 387-391.
- Vahrenkamp, V. C., and P. K. Swart, 1991, Late Cenozoic sea water generated dolomites of the Bahamas: metastable analogues for the genesis of ancient platform dolomites: Ortisei, p. 279-280, 5 Figs.
- Vasconcelos, C., and J. A. McKenzie, 1997, Microbial mediation of modern dolomite precipitation and diagenesis under anoxic conditions (Lagoa Vernelha, rio de janeiro, Brazil, v. 67, p. 378-390.
- Vegh-Neubrandt, E., 1963, Die durch Gipsauflösung entstandene Porosität in den ungarischen Trias-Dolomiten, v. 6, p. 203-211, 4 Pls., 3 Figs.
- Versical, R. T., 1991, Basement control of the development of selected Michigan Basin oil and gas fields as constrained by fabric elements in Paleozoic limestones: MS thesis, Western Michigan University, Kalamazoo, 200 p.
- Von der Borch, C. C., and D. Lock, 1979, Geological significance of Coorong dolomites, v. 23, p. 587-591.
- Voss, R. L., R. D. Hagni, and J. M. Gregg, 1989, Sequential deposition of zoned dolomite and its relationship to sulfide mineral paragenetic sequence in the Viburnum Trend, southeast Missouri, v. 4/2, p. 195-209, 11 Figs.
- Wacey, D., and D. T. Wright, 2001, Microbial mediation of dolomite precipitation in the Coorong region, South Australia.

- Wan, M., 1998, Dolomitization of an Eocene lacustrine carbonate oil reservoir, Eagle Springs Field, east-central Nevada: AAPG Foundation grants-in-aid recipients for 1998; abstracts AAPG Bulletin, v. 82, p. 2169-2170.
- Wanas, H. A., 2002, Petrography, geochemistry and primary origin of spheroidal dolomite from the Upper Cretaceous/Lower Tertiary Maghra El-Bahari Formation at Gabal Ataqa, Northwest Gulf of Suez, Egypt, v. 151, p. 211-224.
- Wardlaw, N. C., 1976, Pore geometry of carbonate rocks as revealed by pore casts and capillary pressure: AAPG Bulletin, v. 60, p. 245-257.
- Warren, J., 2000, Dolomite: occurrence, evolution and economically important associations, v. 52, p. 1-81.
- Warren, J. K., 1988, Sedimentology of Coorong dolomite in the Salt Creek region, South Australia, v. 3/2, p. 175-199, 13 Figs.
- Warren, J. K., 1990, Sedimentology and mineralogy of dolomite Coorong Lakes, South Australia, v. 60/6, p. 843-858, 10 Figs.
- Warthmann, R., Y. van Lith, C. Vasconcelos, J. A. MacKenzie, and A. M. Karpoff, 2000, Bacterially induced dolomite precipitation in anoxic culture experiments: Geology, v. 28, no.12, p. 1091-1094.
- Watkins R. (1996) Skeletal composition of Silurian Benthic Marine Faunas. *Palaios* 11(6), 550-558.
- Watney, W. L., W. J. Guy, and A. P. Byrnes, 2001, Characterization of the Mississippian chert in south-central Kansas: Chert reservoirs of North America AAPG Bulletin, v. 85, p. 85-113.
- Welch, C. L., 2000, Petrography and geochemistry of dolomites in the Lower Cretaceous Edwards Formation in Taylor County, Texas: AAPG Foundation grants-in-aid recipients for 2000 AAPG Bulletin, v. 84, p. 1875.
- Wheeler, C. W., P. Aharon, and R. E. Ferrell, 1999, Successions of Late Cenozoic platform dolomites distinguished by texture, geochemistry, and crystal chemistry: Niue, south Pacific, v. A69, p. 239-255, 8 Figs., 2 Tabs.
- Willems, H., and M. Wuttke, 1987, Lithogenese lakustriner Dolomite und mikrobiell induzierte "Weichteil-Erhaltung" bei Tetrapoden des Unter-Rotliegenden (Perm, Saar-Nahe-Becken, SW-Deutschland). v. 174, p. 213-238, 5 Figs.
- Wilson, E. N., L. A. Hardie, and O. M. Phillips, 1990, Dolomitization front geometry, fluid flow patterns, and the origin of massive dolomite: the Triassic Latemar buildup, Northern Italy, v. 290, p. 741-796, 23 Figs., 3 Tabs.
- Winston, G. O., 1978, Rebecca Shoal reef complex (Upper Cretaceous and Paleocene) in South Florida: AAPG Bulletin, v. 62, p. 121-127.
- Winter, B. L., J. W. Valley, J. A. Simo, G. C. Nadon, and C. M. Johnson, 1995, Hydraulic seals and their origin; evidence from the stable isotope geochemistry of dolomites in the Middle Ordovician St. Peter Sandstone, Michigan Basin: AAPG Bulletin, v. 79, p. 30-48.
- Wright, D. T., 1999, The role of sulphate-reducing bacteria and cyanobacteria in dolomite formation in distal ephemeral lakes of the Coorong region, South Australia, v. 126, p. 147-157.
- Wright, D. T., 2002, Benthic microbial communities and dolomite formation in marine and lacustrine environments - a new dolomite model, v. 66, p. 7-20, 10 Figs.

- Wright, P., S. Vanstone, and J. Marshall, 1991, Contrasting drowning histories of Mississippian platforms: 'marine' alteration of paleosols and dolomite formation: Ortisei, p. 292-293, 1 Fig.
- Yoo, C. M., and Y. I. Lee, 1998, Origin and modification of early dolomites in cyclic shallow platform carbonates, Yeongheung Formation (middle Ordovician), Korea, v. 118, p. 141-157, 10 Figs., 1 Tab.
- Yoo, C. M., and Y. I. Lee, 1998, Origin and modification of early dolomites in cyclic shallow water platform carbonates, Yeongheung Formation (middle Ordovician), Korea, v. 118, p. 141-158, 10 Figs.
- Zankl, H., and M. U. E. Merz, 1994, The possible contribution of fresh water cyanobacteria to Northern Alpine Hauptdolomite sedimentation, v. 19, p. 261-264.
- Zeeh, S., T. Bechstadt, M. Fröhler, C. Klebahn, and U. Walter, 1991, Dedolomitization of Cambrian dolomites of southwestern Sardinia: Ortisei, p. 295-296.
- Zempolich, W. G., 2002, Dolomite reservoirs created through fault-related burial dolomitization; analogs from the Italian Alps: 2001-2002 AAPG distinguished lecturers; North America distinguished lecture abstracts AAPG Bulletin, v. 86, p. 200.
- Zempolich, W. G., and L. A. Hardie, 1997, Geometry of Dolomite Bodies Within Deep-Water Resedimented Oolite of the Middle Jurassic Vajont Limestone, Venetian Alps, Italy: Analogs for Hydrocarbon Reservoirs Created Through Fault-Related Burial Dolomitization: AAPG Memoir, p. 127-162.
- Zempolich, W. G., B. H. Wilkinson, and K. C. Lohmann, 1988, Diagenesis of late Proterozoic carbonates: the Beck Spring Dolomite of eastern California, v. 58, p. 656-672, 18 Figs.
- Zenger, D. H., 1973, Syntaxial calcite borders on dolomite crystals, Little Falls Formation (Upper Cambrian), New York, v. 43, p. 118-124.
- Zenger, D. H., 1981, On the formation and occurrence of saddle dolomite - discussion, v. 51/4, p. 1350-1352.
- Zenger, D. H., 1982, Comment on Precambrian dolomites: petrographic and isotopic evidence that they differ from Phanerozoic dolomites, v. 10, p. 662.
- Zenger, D. H., 1992, Burrowing and dolomitization patterns in the Steamboat Point Member, Bighorn Dolomite (Upper Ordovician), northwest Wyoming, v. 29/2, p. 133-142, 6 Figs., 1 Tab.
- Zhang S. and Barnes C. R. (2002) Late Ordovician--Early Silurian (Ashgillian-Llandovery) sea curve derived from conodont community analysis, Anticosti Island, Quebec. *Palaeogeography, Palaeoclimatology, Palaeoecology* 180, 5-32.

## Appendix 1

### **Practical Synergies for Increasing Domestic Oil Production and Geological Sequestration of Anthropogenic CO<sub>2</sub>: An example from the Silurian of the Michigan Basin**

**G. Michael Grammer**<sup>1</sup>, David A. Barnes<sup>1</sup>, William B. Harrison III<sup>1</sup>, Anthony E. Sandomierski<sup>1,2</sup> and Robert G. Mannes<sup>3</sup>

<sup>1</sup>Michigan Geological Repository for Research and Education, Western Michigan University, Department of Geosciences, Kalamazoo, MI 49008

<sup>2</sup>Current Address: ExxonMobil Production Company, Houston, TX 77002

<sup>3</sup>CORE Energy, LLC, 954 Business Park Drive, Suite 1, Traverse City, MI 49686

#### **Abstract**

As oil imports in the United States approach 60% of total daily consumption, more efforts are being expended to maximize recovery from known domestic oil fields. As part of this effort, CO<sub>2</sub> flooding of reservoirs has been proven to be an effective means to increase the recovery of oil bypassed during primary production, albeit often at significant cost due to capture, compression and transportation of adequate CO<sub>2</sub>. At the same time, global and national interest in the viable geological sequestration of anthropogenic CO<sub>2</sub>, a major greenhouse gas when emitted into the atmosphere, is also becoming more significant. In the Michigan Basin, the juxtaposition of the Devonian Antrim Shale natural gas trend, one that contains high levels of associated CO<sub>2</sub>, with the mature Niagaran (Silurian) reef oil play, characterized by reservoirs with high percentages of stranded oil, may provide an economically viable model to combine EOR efforts with the geological sequestration of CO<sub>2</sub>.

Niagaran pinnacle reefs in the Michigan Basin have produced over 450 MMBO since the late 1960's. Due to the complex heterogeneity of the reef reservoirs, however, primary production averages only around 30% with secondary waterflood programs typically capturing an additional 12%. The northern reef trend in the Michigan Basin comprises an immense hydrocarbon resource, located in hundreds of closely-spaced, but highly compartmentalized reef fields in northern Lower Michigan. These geologically complex carbonate reef reservoirs present significant opportunity for enhanced oil recovery operations because of known traps, quantifiable remaining oil, existing

infrastructure and very few secondary recovery projects to date, but also great challenges to modeling for maximum sweep efficiencies and recovery factors during miscible CO<sub>2</sub>/EOR projects.

In the northern reef trend, a local source for subsequent CO<sub>2</sub> flooding is readily available as a byproduct of Antrim Shale production. The annual production of CO<sub>2</sub> separated from Antrim gas is approximately 21 BCF, the majority of which is currently vented directly into the atmosphere. The close proximity of a source of high quality CO<sub>2</sub> from several gas processing plants throughout the northern reef trend, a region with over 800 Niagaran reef fields, provides an economically viable opportunity to combine CO<sub>2</sub> flood EOR operations with geological sequestration of CO<sub>2</sub> greenhouse gases. In this paper, initial results of a pilot project where CO<sub>2</sub> from the Antrim Shale is being injected into several Niagaran reefs are discussed along with reservoir characterization issues associated with these heterogeneous reservoirs. Similar EOR projects throughout the northern reef trend could provide an economic foundation for CO<sub>2</sub> sequestration programs. This is especially the case if they are designed alongside industrial activities that generate easily captured CO<sub>2</sub> emissions streams, such as other gas processing plants or future ethanol plants planned for the region.

### **Introduction**

Geologic sequestration of anthropogenic CO<sub>2</sub> is currently being combined with an EOR program in Silurian-aged reefs in the northern part of the Michigan Basin. This region is especially suitable to combining EOR activities with sequestration of greenhouse gases due to the coincidence of two distinct oil and gas-related plays with associated generation of significant quantities of anthropogenic carbon dioxide. A major northeast-southwest trend of oil and gas fields was developed in Silurian (Niagaran-aged) reefs during the 1970's, known as the "northern" Niagaran reef trend, and today there are over 800 individual reefs known in the Trend (Figure 1). Cumulative production from Niagaran reefs exceeds 450 MMBO and 2 TCF of gas, but production from the fields has declined significantly in the last decade. Many of the reefs have either reached, or are nearing their economic limit in the primary phase of hydrocarbon production, yet only a



few of these have been converted to secondary recovery operations (water flooding or gas re-injection), producing moderate amounts of additional oil.

Coincident with the northern Niagaran reef trend, but in a slightly east-west trending pattern, is the more recent development of significant natural gas production from the Middle Devonian Antrim Shale (Figure 2). Developed in the late 1980's and early 1990's, nearly 8000 low-volume Antrim Shale wells have been drilled, resulting in cumulative natural gas production of approximately 2.5 TCF. Associated CO<sub>2</sub> in the Antrim gas is currently removed at 6 centralized gas-processing plants in the region and the majority of this processed CO<sub>2</sub> is currently vented directly to the atmosphere. The CO<sub>2</sub> removed from the Antrim Shale gas stream is of very high quality (at least 99% pure CO<sub>2</sub>) with only small quantities of associated water and residual methane.

One of the largest gas processing plants in Otsego County has had an average CO<sub>2</sub> production of over 1 BCF/month for the last ten years, or an average of approximately 15 BCF of CO<sub>2</sub> produced each year. Merged production of CO<sub>2</sub> from all Antrim gas processing plants in the region has been averaging about 21 BCF/year. Continued production from this play is estimated for an additional 30-40 years, resulting in total gas recovery of approximately 5 TCF. The total CO<sub>2</sub> content, estimated at 15-30% in Antrim gas, would result in an additional CO<sub>2</sub> production of 375-750 BCF from northern Michigan gas processing plants over the projected life of the play. Here we report on the synergistic value of the current EOR program in Niagaran reefs in the northern Michigan Basin and discuss outstanding reservoir characterization issues that need to be more fully addressed to maximize both the sequestration of CO<sub>2</sub>, and the economic benefits of EOR activities.

### **General Geological Setting**

The Michigan Basin is a roughly elliptical, major intracratonic basin located in the midwest portion of the United States and centered on the Lower Peninsula of the State of Michigan (Figure 3). A structural basin of over 300,000 square kilometers in area, the Michigan Basin also includes the eastern half of Michigan's Upper Peninsula, portions of northern Ohio and Indiana, northeastern Illinois, eastern Wisconsin and

southwestern Ontario, Canada. The Basin is bounded by the persistent, structurally stable areas of the Wisconsin and Kankakee Arches to the west and southwest, the Findlay Arch of Ohio and Algonquin Arch of Ontario to the southeast and east, and the Canadian Shield to the north. Sedimentary deposits in the Basin attain a maximum thickness of nearly 17,000 feet (5200 m) and include sandstones, shales, carbonates and evaporites of Cambrian through Pennsylvanian age. Discontinuous, thin redbeds of Jurassic age occur in the Basin center. A Pleistocene veneer of glacial deposits blankets nearly all of the Lower Peninsula with thicknesses up to 1200 feet (366 meters). Natural outcrops occur in numerous areas around the Great Lakes shoreline as well as in a few inland stream and river valleys. Quarries expose bedrock in areas where the glacial drift is thin or absent. Bedrock (subcrop), structural (depth) and isopach maps can be effectively made for these sedimentary rock formations using well data from over 58,000 oil and gas and other types of wells.

### **Silurian Pinnacle Reefs**

Silurian age (Niagaran) pinnacle reefs exist in two well-defined belts in the subsurface of the Michigan Basin (Figure 1). Although pinnacle reefs from the Michigan Basin were first discovered in 1885 (Shaver, 1977), most reefs were not found until after the development of seismic reflection profiling. The major period of Niagaran reef exploration took place in the 1970's and 1980's, but ongoing refinement of 3-D seismic acquisition and processing has continued to lead to more discoveries in the Basin, especially along the northern (northwestern) trend. To date, there have been over 1100 reefs identified in the northern and southern trends at depths ranging from 3000 to 7000 feet (915 to 2135 meters). The height of the reefs are quite variable, with an average of about 350 feet (107 m), with taller reefs, up to approximately 700 feet (210 m) high found in the northern trend (Figure 4). The diameter or lateral extent of the reefs is quite variable, with smaller but taller reefs in the north and shorter, more broadly developed reefs found in the southern trend. In the northern trend, the aerial distribution of reefs is typically between 40-150 acres, with more laterally extensive reef development (100 to 1000 acres) in the south (Sandomierski, 2007).

Cumulative production from Niagaran reefs throughout the Michigan Basin has exceeded 450 MMBO and 2 TCF of gas with primary recovery efficiencies of 25-35% for the northern trend, and 15-20% for reefs in the southern trend (Brock et al., 1995). Secondary recovery programs, primarily gas re-injection and water injection for pressure maintenance, started in the early 1970's. Brock and others (1995) identified several factors for water flood fields that might also affect EOR and sequestration potential in northern Niagaran reef trend reservoirs. Overall the reefs have generally good injectivity and productivity due to good, albeit highly heterogeneous, reservoir quality and high gravity oil (Gill, 1977). Individual fields have limited lateral extent, many with 3 or fewer wells, comprised of discrete reservoirs that are encased by impermeable evaporites that form regional seals (Figure 4).

### **CO<sub>2</sub>/Enhanced Oil Recovery Operations and Geological Sequestration Potential of northern Niagaran Pinnacle Reefs**

Following the initial discoveries in the late 1960's and '70s, Niagaran reef trend oil reservoirs in Michigan have produced more than 450 MMBO. Of this, more than 270 MMBO has been produced from approximately 2000 wells in the northern reef trend fields from reservoirs at depths ranging from 5,000 to 7,000 feet (1525 to 2135m) mostly in Grand Traverse, Kalkaska, Manistee, and Otsego counties (Figure 2).

Otsego County has produced more than 100 MMBO and significant natural gas from over 320 wells in approximately 125 fields in the reef trend. Currently only a small number of fields in the entire northern reef trend (about 34) are operating under secondary or tertiary production (Tinker, 1983), and approximately half of these fields have achieved significant secondary water flood oil recovery (Brock, and others, 1995). The Chester 18 field in Otsego County is the most successful, having produced more than 9 MMBO in primary recovery and nearly 4MMBO from secondary water flood. From 8 injector and 11 producer wells, this field shows an estimated 13% incremental secondary oil recovery (assuming 30% primary recovery factor) as a result of careful field operations management (Tinker, 1983).

### **CO<sub>2</sub> EOR Programs in northern Niagaran Reefs**

In the mid-1990's, a CO<sub>2</sub>/EOR program was developed by Core Energy LLC in two adjacent Niagaran reef fields in Otsego County, the Dover 33 and 36 fields, utilizing processed CO<sub>2</sub> from produced Antrim gas. An additional reef field CO<sub>2</sub>/EOR project in the Dover 35 field has been in place since early 2004 and two others, the Charlton 30/31 and Charlton 6, are in the initial stages of CO<sub>2</sub> injection for EOR (Figure 5). The Dover 33 field produced 1.3 MMBO through primary production, with decline rates of around 15% since 1971 (Figure 6a). Injection of CO<sub>2</sub> for EOR was initiated in 1996, resulting in an additional 488,800 BO produced from the field through 2006, or about 38% of primary production. Decline rates over the first 10 years of CO<sub>2</sub> injection average around 30%. Cumulative oil production in the field is currently about 1.8 MMBO.

The Dover 36 field was developed in 1973, with primary production of 1.15 MMBO through 1996 when CO<sub>2</sub> injection was initiated (Figure 6b). Primary production declined at an average of 15% over these 23 years. Enhanced oil production from CO<sub>2</sub> injection through 2006 is 288,000 BO, or about 25% of primary production. Cumulative production from the field is around 1.4 MMBO.

Recovery factors represented by the EOR decline curves from the Dover 33 (12% OOIP) and Dover 36 (8% OOIP) fields are the result of only minimal field development and management due to the emphasis on utilization of existing exploration and original production bore holes to reduce development costs. Production from Dover 36 is currently greater than 70 BOPD and increasing. At present, it appears that EUR from the Dover 36 field may be about 34% of primary oil production. Incremental enhanced oil recovery factors that approach primary recovery are theoretically possible given application of existing and emerging technologies for more effective reservoir characterization and exploitation.

### ***Carbon Sequestration Potential in northern Michigan Niagaran Pinnacle Reef Reservoirs***

The association of a substantial anthropogenic CO<sub>2</sub> emissions stream from Antrim Shale gas processing plants, existing CO<sub>2</sub> pipeline and compression infrastructure, and significant potential and ongoing enhanced oil recovery activities in the region make this area ideal for a synergistic combination of EOR activities and geological sequestration of

CO<sub>2</sub> (Figures 2 and 7). Net CO<sub>2</sub> utilization factors in the course of CO<sub>2</sub>/EOR range from 10-50 mcf/bbl or 0.6 to 3 tons CO<sub>2</sub>/bbl of oil recovered (Steve Meltzer, pers. comm.). Given the estimates of gross CO<sub>2</sub> supply presented above, the projected ultimate CO<sub>2</sub>/EOR from Niagaran reef reservoirs (using all Antrim gas processing plants as CO<sub>2</sub> sources) is 25-75 MMBO. Initial estimates of net utilization factors of 6 mcf/bbl for CO<sub>2</sub>/EOR in the two mature flood fields, Dover 33 and 36, suggest that estimates of incremental CO<sub>2</sub>/EOR using Antrim CO<sub>2</sub> may be more optimistic, and as high as 125 MMBO if applied to the entire northern Niagaran reef trend.

Approximately 8 BCF of CO<sub>2</sub> has been injected into five reefs by Core Energy since 1997. Although some CO<sub>2</sub> has been moved from reef to reef, the pipelines and reef reservoir system is a closed system, therefore it is assumed that all the CO<sub>2</sub> originally injected is still contained in one of the reef reservoirs. Therefore about 8 BCF or 465,000 tons of CO<sub>2</sub> has been sequestered during this EOR process.

Based on the geological CO<sub>2</sub> sequestration potential presented above, it is possible that virtually all produced Antrim CO<sub>2</sub> could be effectively sequestered through commercial CO<sub>2</sub>/EOR operations. If CO<sub>2</sub> emission quotas are invoked in the future for the U.S., additional CO<sub>2</sub> disposal costs may be added to Antrim gas processing and production, currently the 10<sup>th</sup> most prolific gas play in the continental United States. The additional cost of Antrim gas production, due to potential CO<sub>2</sub> emissions penalties, may place commercial limits on Antrim gas production. Demonstration of the commercial viability of CO<sub>2</sub>/EOR operations in addition to the sequestration potential available in Devonian saline aquifer targets in the proposed project area (Barnes et al., this volume) will provide local geological sequestration options that may continue to support economic gas production from the Antrim gas play.

### **Reservoir Characterization Issues**

Because of the considerable compartmentalization observed in many of the Niagaran reefs, a major issue that needs to be addressed to fully develop these pinnacle reef reservoirs for combined EOR/CO<sub>2</sub> sequestration programs, is development of a better understanding of the lateral and vertical heterogeneity of the reservoir. A number

of studies have indicated that the Niagaran pinnacle reefs in the Michigan Basin consist of 3-4 major vertical zones, related most often to an overall shallowing of conditions associated with reef development over time (e.g. Mantek, 1973; Huh, 1973; Mesolella et al. 1974; and Sears and Lucia, 1979). In many reefs, these 3-4 zones result in considerable variability in reservoir quality both laterally and vertically. At the present time, the most commonly accepted model for the pinnacle reefs, developed by Huh (1973) shows a lower biohermal stage that transitions into an organic framework reef, which is then capped by supratidal carbonates and evaporites (Figure 8). More recent work by Sandomierski (2007), however, has shown that the reefs may be much more complex than earlier studies have suggested, with multiple stages of episodic growth related to relative sea level fluctuations. These sea level fluctuations, and the associated facies variability, result in a complex reservoir architecture that better defines the heterogeneity observed in the subsurface. To fully evaluate the reservoir quality and distribution in these reefs therefore, it is often necessary to do a fully integrated reservoir characterization analysis including the following: 1) Lithofacies analysis from core and wireline logs; 2) Interpretation of depositional environments and subsequent prediction of the probable scale and distribution of established geobodies; 3) Interpretation of the diagenetic overprint and control on reservoir properties (porosity, permeability and sonic velocity), which is often tied to lithofacies and depositional environment; and 4) Development of a high resolution sequence stratigraphic framework which will define the lateral and vertical reservoir architecture and provide a means to transfer the reservoir model to other reefs in the basin. Of these activities, development of the sequence stratigraphic framework may prove to be the most fundamentally important aspect of reservoir characterization for both CO<sub>2</sub> EOR and sequestration.

### **Developing a Sequence Stratigraphic Framework**

Incorporating the data into a sequence stratigraphic framework is critical to accurate correlation and mapping of individual facies tracts as it provides additional information on the temporal and spatial distribution of facies belts, as well as additional data on probable reservoir geometries. An iterative approach is utilized whereby the probable lateral and vertical distribution and geometries of potential reservoir facies is

determined by the vertical stacking patterns of facies and cycles within the context of dynamic depositional models. The primary fabric of the rock, which is related to depositional environment, and the vertical stacking patterns of the facies provide insight into probable primary and secondary porosity and permeability, diagenetic susceptibility, and the resulting petrophysical characteristics of potential reservoir and seal facies. The end result is that by developing a sequence stratigraphic framework, the operator can enhance the predictability not only of the lithofacies and depositional environments, but also the potential for reservoir-quality porosity and permeability, the petrophysical character, and the inherent 3-D geometries likely to be found in the subsurface.

Sequence stratigraphy is the first stratigraphic method that allows us to interpret, and subsequently predict, the distribution of reservoir-significant, genetically-related chronostratigraphic units. The recognition of genetically-related packages of strata adds a predictive capability to sequence stratigraphy that is lacking in other stratigraphic methods. Through sequence stratigraphy, one is able to recognize different facies that coexisted in the depositional environment during a given period of time. By combining depositional models with time, sequence stratigraphy is capable of documenting the dynamics in a depositional system and, therefore, the distribution and architecture of facies belts, and thus potential reservoirs through time. These two key aspects, the identification of genetically-related sedimentary packages, and the evaluation of depositional systems in a dynamic mode, rather than simply as static systems (i.e. "facies models") results in the major strength of sequence stratigraphy – i.e. the enhanced predictability of sedimentary packages (and therefore probable reservoir geometry), and the prediction of the lateral and vertical continuity of strata across a sedimentary basin.

Sequence stratigraphic interpretation looks at the distribution of genetically-similar depositional systems within the context of a dynamic sedimentary system during the rise and fall of sea level, unlike standard facies models which consider a static model of the system (i.e. a snap-shot in time). By categorizing and differentiating depositional packages that form during rises of sea level (transgressive systems track - TST), from those formed during a highstand of sea level (HST) when the carbonate platform is flooded, or a lowstand of sea level (LST) when sea level has dropped to expose the

platform, one can predict both the facies types, as well as geometries that might be expected in both landward (shoreward) or seaward (basinward) directions. These packages of sedimentary deposits are characterized by a hierarchy of sequences deposited during different frequencies of sea level change. The result is that the sedimentary record is characterized by larger-scale (seismic scale) sequences of LST-TST-HST deposits that are made up of smaller-scale high frequency sequences and cycles (also LST-TST-HST) deposited during higher frequency fluctuations in sea level. Within this hierarchy, these repetitive patterns are typically referred to as 3rd and 4th order sequences (seismic or formation scale), and 5th order, generally shallowing-upward, cycles. These 5th order cycles are generally only 5-10 m (16-33 ft) thick, but are critically important as they often make up the fundamental reservoir (flow) units in carbonates.

### **Petrophysical Characterization**

One of the major tasks in reservoir characterization and modeling is to translate geological information into petrophysical properties that can be extracted from geophysical data sets and/or used to populate sedimentary bodies in reservoir modeling (e.g. Eberli et al., 2004; Masferro et al., 2004). This task is particularly challenging in carbonates, where cementation and dissolution processes continuously modify the mineralogy and pore structure. In extreme cases, this modification can completely reverse the original pore distribution so that grains are dissolved to produce pores, while the original pore space is filled with cement to form the rock. All these modifications alter the physical properties of the rock, thereby resulting in a dynamic relationship between depositional facies and diagenesis which is recorded by physical parameters such as porosity, permeability and sonic velocity (Grammer et al. 2004).

### **Sonic velocity tied to pore architecture**

Establishing a predictable connection between pore type and pore architecture to measured sonic velocity values will help operators more fully recognize, and ultimately predict reservoir type and quality in the subsurface with increased confidence. Because pore geometry is a crucial factor in controlling acoustic properties in carbonates, detailed characterization of pore types and pore architecture through petrographic and image analysis techniques should provide a tool to predict pore architecture, and therefore



permeability of reservoir rocks, through refined analysis and interpretation of the sonic log borehole and seismic data.

Seismic data has proven to be increasingly important in reservoir characterization. High-resolution 3-D seismic surveys produce data sets from which amplitude variations can be used to interpolate between wells. Reservoir saturation is evaluated with AVO (amplitude variation with offset), and time lapse surveys delineate production histories and assist in secondary recovery. Inversions of seismic volumes into a porosity volume can be used to predict high porosity intervals. Because of the degree of uncertainty in these geophysical data, accurate interpretation is dependent upon the understanding of the rock physics in the imaged sediments (Mavko et al., 1998). Although sonic velocity is largely controlled by porosity, many factors such as clay content and mineralogy may complicate the relationship. This is especially true in carbonates where velocity is controlled by the combined effect of depositional lithology and several post-depositional processes that cause a unique velocity distribution (Wang, 1997, Rafavich et al. 1984; Anselmetti and Eberli, 1993).

The poor relationship between porosity and velocity in carbonates results from the ability of carbonates to form cements and certain fabrics with pore types that can enhance the elastic properties of the rock without filling all the pore space. The importance of the pore type on the elastic property, and thus the velocity, is illustrated in Figure 9 which shows that different pore types form clusters in the velocity-porosity diagram. The resulting characteristic pattern observed for every group with the same dominant pore type can explain why rocks with equal porosity can have significantly different velocities. The most prominent velocity contrasts at equal porosities are measured between coarse moldic rocks and rocks with interparticle porosity (Anselmetti and Eberli, 1993). Moldic rocks at 40-50% porosity can have  $V_p$  up to 5000 m/s, whereas rocks with similar amounts of interparticle porosity or microporosity have velocities that can be lower by more than 2500 m/s (Anselmetti and Eberli, 1993).

The complicated relationship between porosity and velocity that is observed, which would also result in a similar porosity-impedance pattern, implies that impedance contrasts between two layers can occur even without a porosity change, i.e. solely as a

result of different pore types and pore system architecture. To further complicate interpretation, two layers with different porosity values can have very similar velocities and may, therefore, exhibit no impedance contrast between them (Grammer et al. 2004). As a result, the scattering in a porosity-velocity diagram has negative implications for seismic inversion and AVO analyses in carbonates. The scattering produces an uncertainty in seismic inversion that most current inversion techniques are not able to reduce. For example, if a single line from a theoretical equation or a best-fit line through the data set is used for inversion, all the velocity values above the line will underestimate porosity and reserves while all the data points below will overestimate porosity and reserves. Similarly, variations in pore type can cause variations in the amplitude with offset that might be more pronounced than variations in saturation or bed thickness. To reduce the uncertainties in seismic inversion and AVO analysis, additional study and development of new theoretical approaches are needed that show the physical relationship between pore types, the rock-frame flexibility, and the elastic behavior in carbonates (Eberli et al., 2004).

The elastic property and resultant sonic velocity of a porous rock is directly related to its rigidity, which in turn is controlled by a variety of parameters such as porosity, the pore structure, mineralogy, saturation, and pressure (Eberli et al., 2004). In carbonates, many of these parameters are in continuous flux because post-depositional dissolution and precipitation processes continuously alter the mineralogy, porosity and pore structure. The result is a wide range of sonic velocity in carbonates (Figure 10), in which compressional wave velocity ( $V_p$ ) ranges from 2000 to 6600 m/s and shear wave velocity ( $V_s$ ) from 600 to 3500 m/s (Anselmetti and Eberli, 1997, 1999). Porosity and pore-types are the main parameters that control velocity in carbonates, whereby variation in pore-type is the main reason for variable velocity at a given porosity. Unlike in siliciclastic sediments, mineralogy and compaction have less effect on velocity. The velocity-porosity relationship is poorly defined showing a typical scatter so that any kind of two-dimensional prediction from velocity to porosity will likely result in large errors (Figure 10).

## **Sequence Stratigraphic Framework and Petrophysical Characterization of Niagaran Reefs**

Sandomierski (2007) and Grammer et al. (2006) have shown that the Niagaran pinnacle reefs in the northern trend of the Michigan Basin may consist of a tripartite hierarchy of sequences, high frequency sequences and cycles that influence lateral and vertical distribution of reservoir flow units. While the overall shallowing-upward trend identified by previous workers is consistent throughout the Basin, Sandomierski (2007) has shown that some northern trend reefs may develop in multiple cycles related to higher frequency fluctuations in relative sea level than has been previously reported. In this model, Sandomierski illustrates that each of the major zones of the reef complex, as reported by others, actually consists of a number of shallowing upward cycles that control reservoir heterogeneity, especially in a vertical sense (see Figure 11).

Correlation between porosity and permeability is notoriously difficult in carbonate reservoirs (Grammer et al. 2004) and most workers suggest there is no correlation between reservoir quality porosity/permeability and facies types within the Niagaran pinnacle reefs (e.g. Wylie and Wood, 2005). More detailed facies analysis on these reefs, however, indicates that there may be a distinct correlation between facies type and measured porosity and permeability (Figure 12), and that prediction of the reservoir quality is therefore enhanced due to the consistency of vertical stacking patterns observed in many of the reefs (Sandomierski, 2007). As illustrated in Figure 11, characterizing the distribution of porosity and permeability relative to the sequence stratigraphic framework shows that porosity and permeability in the reefs may be enhanced near cycle and sequence boundaries as a result of primary facies and subsequent diagenetic modification (Grammer et al., 2006 and Sandomierski, 2007).

Recognition of the sequence stratigraphic framework of the reefs, whether for CO<sub>2</sub> flood/EOR or CO<sub>2</sub> sequestration, is critical because preliminary characterization of pore type and pore architecture and comparison with laboratory measured sonic velocities indicate that some of the facies found in the Niagaran reefs can produce misleading porosity and permeability values from wireline log signatures alone (Grammer et al. 2006). Figure 13 illustrates how, as expected, reef facies with high porosity and permeability have low sonic velocities, and that those with high porosities but low

permeability typically exhibit higher sonic velocity values. There are some facies types, however, that do not follow the predicted pattern and have high porosity and high permeability but also high measured sonic velocities. This anomalous pattern is due to the pore system architecture, and is typical of facies with large isolated vugs and fractures but low matrix permeability as illustrated in Figure 14.

### **Summary**

Anthropogenic CO<sub>2</sub> is being geologically sequestered as part of an ongoing EOR program in Silurian-aged (Niagaran) pinnacle reefs in the northern part of the Michigan Basin. The high volume of regionally available CO<sub>2</sub>, related to processing of produced gas from the coexisting Devonian Antrim play, makes this area a prime candidate for the synergistic combination of EOR activities with the sequestration of a major greenhouse gas. A detailed understanding of the reservoir architecture and petrophysical signatures of various reservoir facies is an important part of a successful CO<sub>2</sub>/EOR program in these reefs. Because of the considerable lateral and vertical variability observed in many of the reefs, optimal placement of injection wells and producers is critical to maximize both the produced hydrocarbons, as well as the volume of sequestered CO<sub>2</sub> (Figure 15). To accomplish this, these reefs need to be analyzed with an integrated reservoir characterization work flow that combines wireline log and rock data with measured petrophysical data to maximize the modeling of these reservoirs.

Whether it is the maximum CO<sub>2</sub> injection rate in an injection well or the productive rate of oil wells, the success or failure of an EOR project is determined largely by the reservoir properties and the proper responses to them. Toward this end, an integrated geophysical-geological-engineering-operational approach would be recommended for designing and operating any Niagaran CO<sub>2</sub> EOR or sequestration project.

Although detailed core or reservoir description information is often not available, or in some cases has not been closely studied prior to start up of some existing projects, it would be advisable to incorporate a geologic perspective on all ongoing projects. This will provide a synergistic effect in that a more detailed geologic understanding may aid

the other disciplines in interpreting well production, choosing recompletion intervals, remaining patient in awaiting well responses or refining OOIP calculations.

The opposite is also true. Ongoing, dynamic operational feedback from production characteristics of wells, test results from new reservoir intervals, GOR behavior of producing wells, pressure buildup responses or indications of reservoir compartmentalization will in turn aid the geologist in deepening his interpretation of the static reservoir framework based upon logs and rock samples.

This type of synergistic approach, therefore, is recommended to provide an increased understanding and interpretation of data from existing fields while also incorporating it with available data for the next potential reservoir to help minimize risk in future EOR/sequestration operations.

## References Cited

- Anselmetti, F.S., and G.P. Eberli, 1993, Controls on sonic velocity in carbonates: Pure and Applied Geophysics, v. 141/2-4, p. 287-323.
- Anselmetti, F.S., and G.P. Eberli, 1997, Sonic velocity in carbonate sediments and rocks, *in* F.J. Marfurt and A. Palaz, eds. Carbonate Seismology: Society of Exploration Geophysicists, Geophysical Development Series no. 6, p. 53-74.
- Anselmetti, F. S., and G. P. Eberli, 1999, The velocity-deviation log: a tool to predict pore type and permeability trends in carbonate drill holes from sonic and porosity or density logs: AAPG Bulletin, v. 83/3, p. 450-466.
- Brock, T., Elenbaas, D. and Schmidt, G., 1995, Secondary recovery in Michigan reefs, summary results, recovery achieved: Engineering Applications for Michigan, Society of Petroleum Engineers, Continuing Education Seminar, 30 p.
- Eberli, G.P., Masaferro, J.L. and J.F. Sarg, eds., 2004, Seismic imaging of carbonate reservoirs and systems, AAPG Memoir 81, 376p.
- Gill, D., 1977, The Belle River Mills Gas Field: Productive Niagaran Reefs Encased by Sabhka Deposits, Michigan Basin, MBGS Special Papers, No. 2, 1977.
- Grammer, G. M., Harris, P. M., and Eberli, G. P., 2004, Integration of modern and outcrop analogs for reservoir modeling – overview and examples from the Bahamas, *in* Grammer, G. M., Harris, P. M., and Eberli, G. P., (eds.), Integration of Outcrop and Modern Analogs in Reservoir Modeling, AAPG Memoir 80, p. 1-22.
- Grammer, G.M., Sandomierski, A.E., Harrison, W.B., III, Barnes, D.A. and Gillespie, R., 2006, New Insight into the Reservoir Architecture of Silurian (Niagaran) Pinnacle Reefs in the Michigan Basin, abstract, Eastern Section AAPG, Buffalo, NY.
- Huh, J.M.S., 1973, Geology and diagenesis of the Salina-Niagaran pinnacle reefs in the northern shelf of the Michigan Basin, unpub. Ph.D. dissertation, University of Michigan, Ann Arbor, 253p.
- Mantek, W., 1973, Niagaran pinnacle reefs in Michigan, Jackson, MI, Consumers Power Company, 32p.
- Masaferro, J.L., Bourne, R., and Jauffred, J.C., 2004, Three-dimensional seismic volume visualization of carbonate reservoirs and structures, *in* Eberli, G.P., Masaferro, J.L. and J.F. Sarg, eds., Seismic imaging of carbonate reservoirs and systems, AAPG Memoir 81, p. 11-41.

Mavko, G., Mukerji, T., and Dvorkin, J., 1998, *The rock physics handbook: Tools for seismic analysis in porous media*; Cambridge, U.K., Cambridge University Press, 329p.

Mesolella, K.J., Robinson, J.D., McCormick, L.M. and Ormiston, A.R., 1974, cyclic deposition of Silurian carbonates and evaporites in the Michigan Basin, *AAPG Bulletin*, v. 58, p. 34-62.

Rafavich, F., C.G.St.C. Kendall, T.P. and Todd, 1984, The relationship between acoustic properties and the petrographic character of carbonate rocks: *Geophysics*, v. 49, p. 1622-1636.

Sandomierski, A. J., 2007, Evaluating controls on the formation and reservoir architecture of Niagaran pinnacle reefs (Silurian) in the Michigan Basin: A sequence stratigraphic approach, Western Michigan University, unpub. M.S. thesis, 189p.

Sears, S.O. and Lucia, F.J., 1979, Reef-growth model for Silurian pinnacle reefs, Northern Michigan trend, *Geology*, v. 7, p. 299-302.

Shaver, R.H., 1977, Silurian reef geometry – new dimensions to explore, SEPM Presidential Address, *Journal of Sedimentary Petrology*, v. 47, p. 1409-1424.

Tinker, G.E., 1983, Design and Operating Factors That Affect Waterflood Performance in Michigan, *Journal of Petroleum Technology*, October, p. 1884-1892.

Wang, Z., 1997, Seismic properties of carbonate rocks, in I. Palaz and K.J. Marfurt, eds., *Carbonate Seismology*: Society of Exploration Geophysicists, Geophysical Development Series no.6, p. 29-52.

Wylie, A.S., and Wood, J., 2005, Well-log tomography and 3-D imaging of core and log curve amplitudes in a Niagaran Reef, Belle River Mills Field, St. Clair County, Michigan, U.S., *AAPG Bulletin*, v. 89, p. 409-434.

### **Figure Captions – Appendix 1**

Figure 1. Distribution of Silurian (Niagaran) pinnacle reef trends in the northern and southern part of Michigan, rimming the Michigan Basin. Modified from Michigan DNR ESRI ArcMap database.

Figure 2. State-wide well penetrations map showing the northern and southern Niagaran reef trend and the Antrim gas play area of northern lower Michigan.

Figure 3. Generalized structure map (top Ordovician Trenton Fm.) showing the elliptical Michigan Basin and associated regional structural highs. The Michigan Basin covers an area of approximately 315,000 km<sup>2</sup> and was filled with more than 5200 m (17,000 ft.) of Paleozoic sediments.

Figure 4. Schematic cross section extending from the shelf edge into the center of the Michigan Basin during Silurian time showing the general distribution of pinnacle reefs and capping evaporites.

Figure 5. Core Energy LLC operations layout in Otsego County, Michigan.

Figure 6 (A and B). Core Energy LLC Niagaran reef fields CO<sub>2</sub>/EOR production decline curves for primary and CO<sub>2</sub>/EOR production in the Dover 33 and Dover 36 fields.

Figure 7. Northern Niagaran reef trend fields and cumulative production. Inset shows Otsego County production and the location of Antrim gas processing plants.

Figure 8. Generalized conceptual model of Niagaran pinnacle reef structure with associated facies. Modified from Gill (1977) after Huh (1973).

Figure 9. Graph of velocity vs. porosity of various pore types of carbonates with an exponential best fit curve through the data for reference. Different pore types cluster in the porosity-velocity field, indicating that scattering at equal porosity is caused by the specific pore type and its resulting elastic property. From Grammer et al., 2004, as modified from Anselmetti and Eberli, 1993.

Figure 10. Compressional wave velocity and porosity of pure carbonates compared to the time average and Woods equations. A large scattering of velocity values exists at equal porosities, and a large range of porosity at a given velocity. This scattering introduces uncertainty in seismic inversions. Modified from Anselmetti and Eberli, 1999.

Figure 11. Details of a Niagaran reef in the northern reef trend showing facies variability (different color) and stacking patterns, as well as the sequence stratigraphic framework and hierarchy. In some reefs, porosity and permeability tend to increase towards the top of both large and smaller (higher frequency) cycles.



Figure 12. Porosity and permeability distribution from a northern reef trend pinnacle reef illustrating how porosity and permeability values cluster with detailed facies analyses. Modified from Sandomierski (2007).

Figure 13. Laboratory measured porosity vs. permeability and porosity vs. p-wave velocity for a Niagaran reef from the northern reef trend. Most of the data fall within expected ranges, with high porosity/high permeability samples exhibiting slow p-wave velocities (samples 5 and 15) and high porosity/low permeability samples exhibiting high p-wave velocities. Samples 8 and 9 are anomalous, exhibiting high porosity and permeability, but also high p-wave velocities. This anomaly is the result of large (cm scale), but localized vugs and fractures within an overall tight matrix. See also Figure 14.

Figure 14. Thin section photomicrographs of anomalous samples in Figure 13. Sample 8 (3524 ft.) and Sample 9 (3540 ft.) both exhibit high porosity and permeability values, but have anomalously high measured sonic velocities as well. This is due to the pore system architecture, which is characterized by large (mm to cm scale) isolated vugs and fractures but with very low matrix porosity.

Figure 15. Schematic diagram of Niagaran pinnacle reefs illustrating the importance of well placement for maximum sweep efficiency for EOR and sequestration of CO<sub>2</sub>. Modified from Gill (1977).

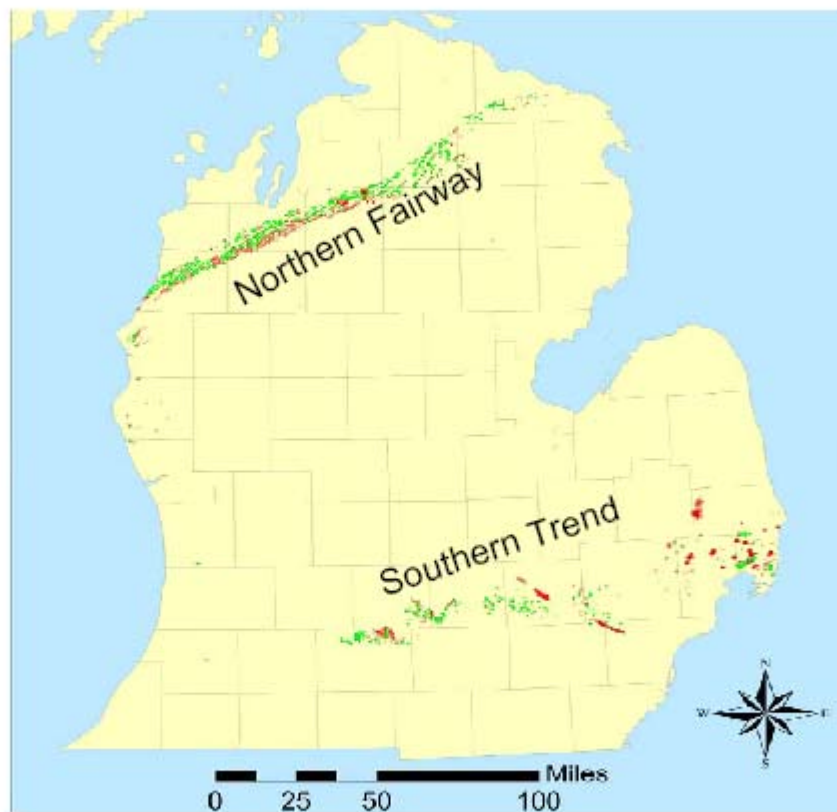


Figure 1

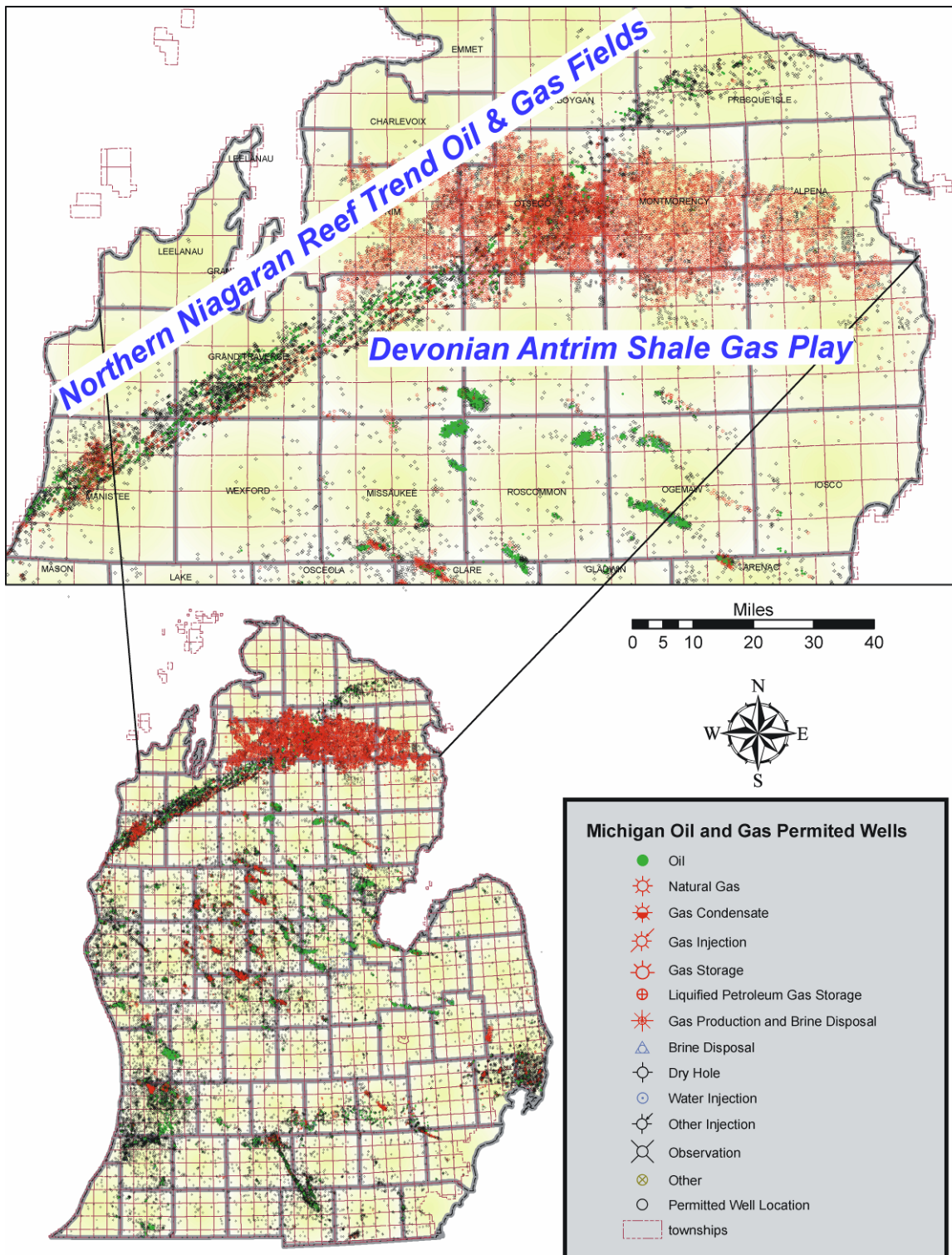
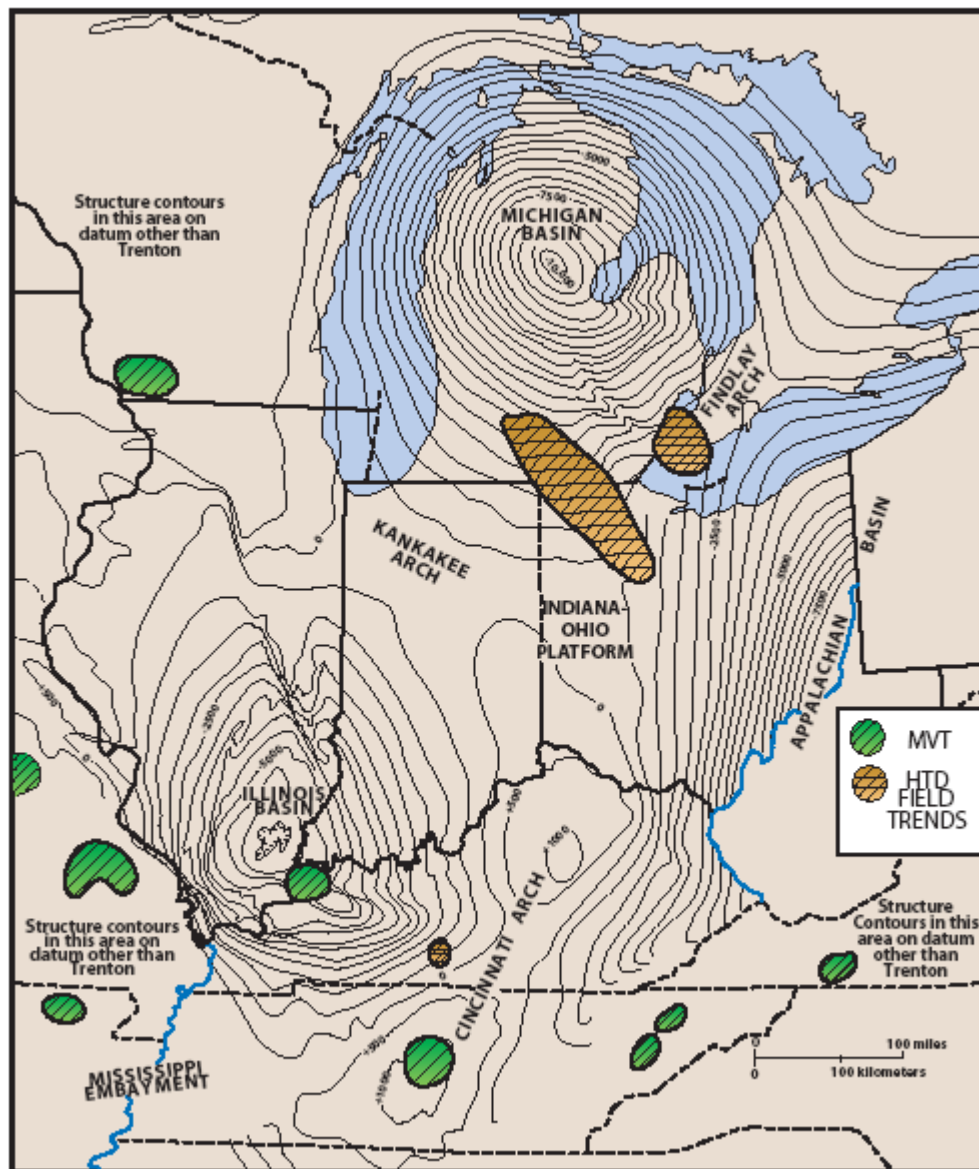


Figure 2



Modified from Keith and Wickstrom, 1992

Figure 3

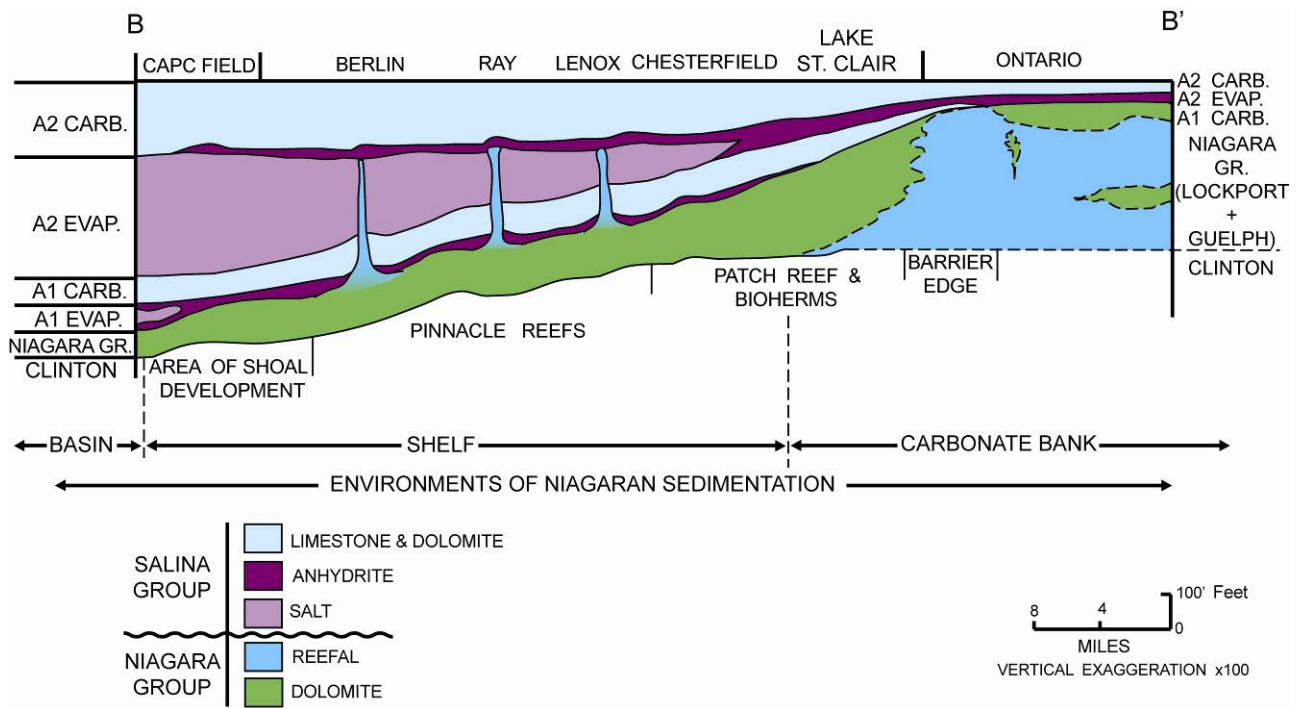


Figure 4

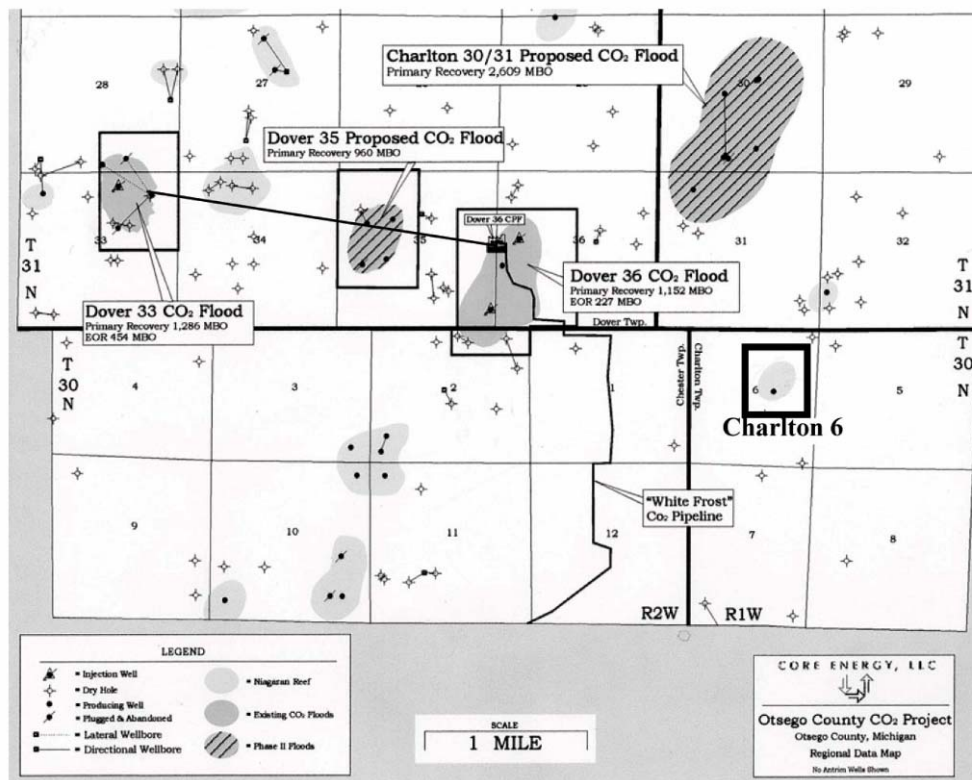


Figure 5

### Dover 33 Niagaran Reef Field, Otsego County, Michigan Enhanced Recovery with CO2

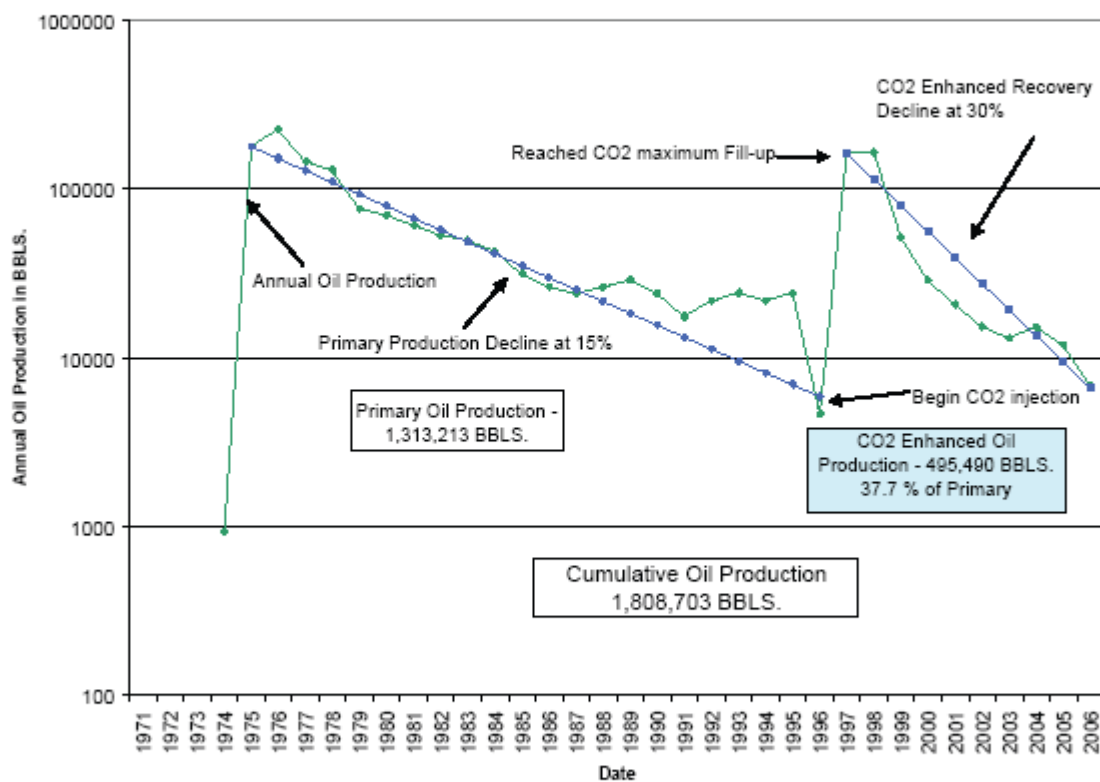


Figure 6a



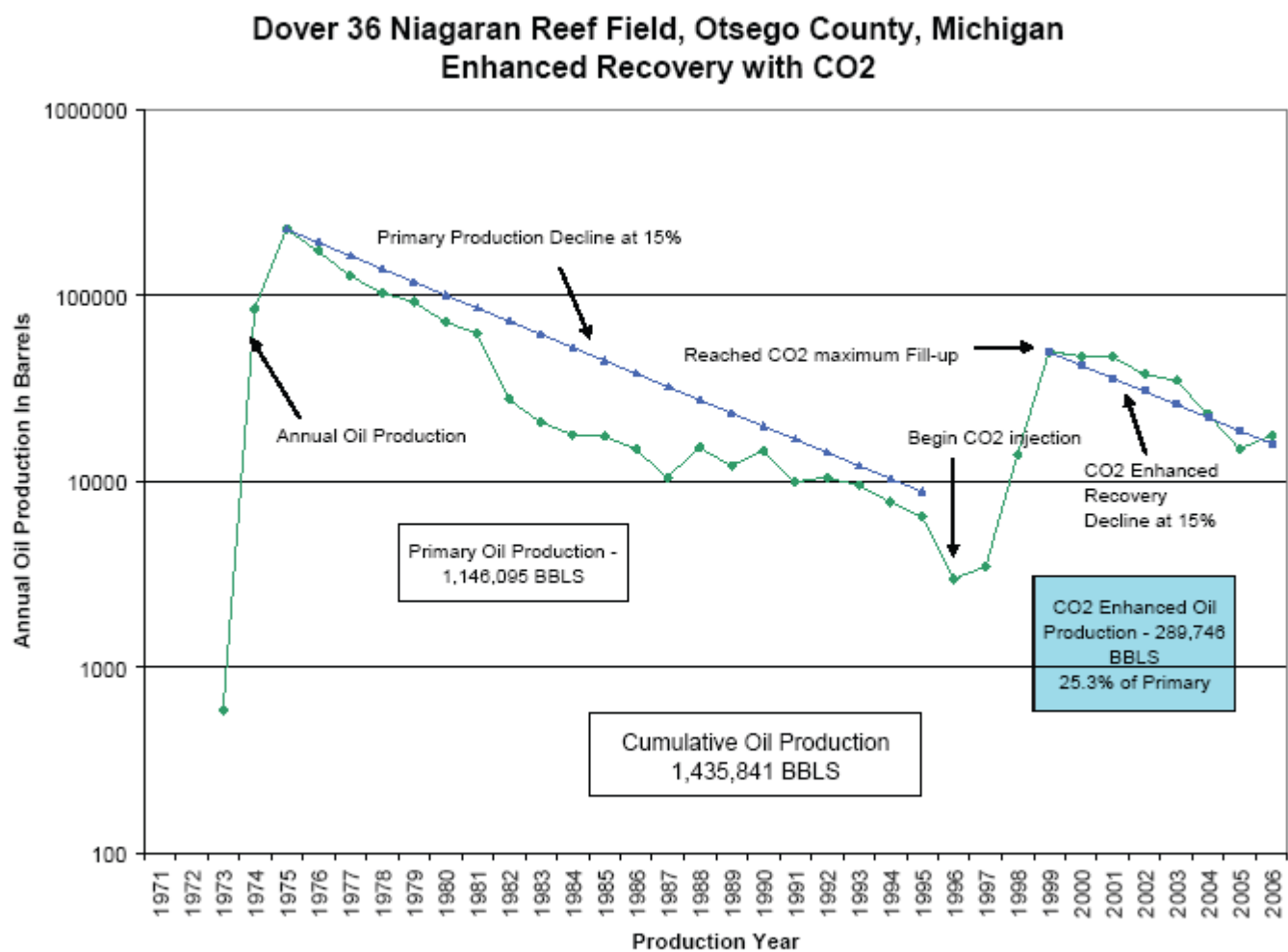


Figure 6b



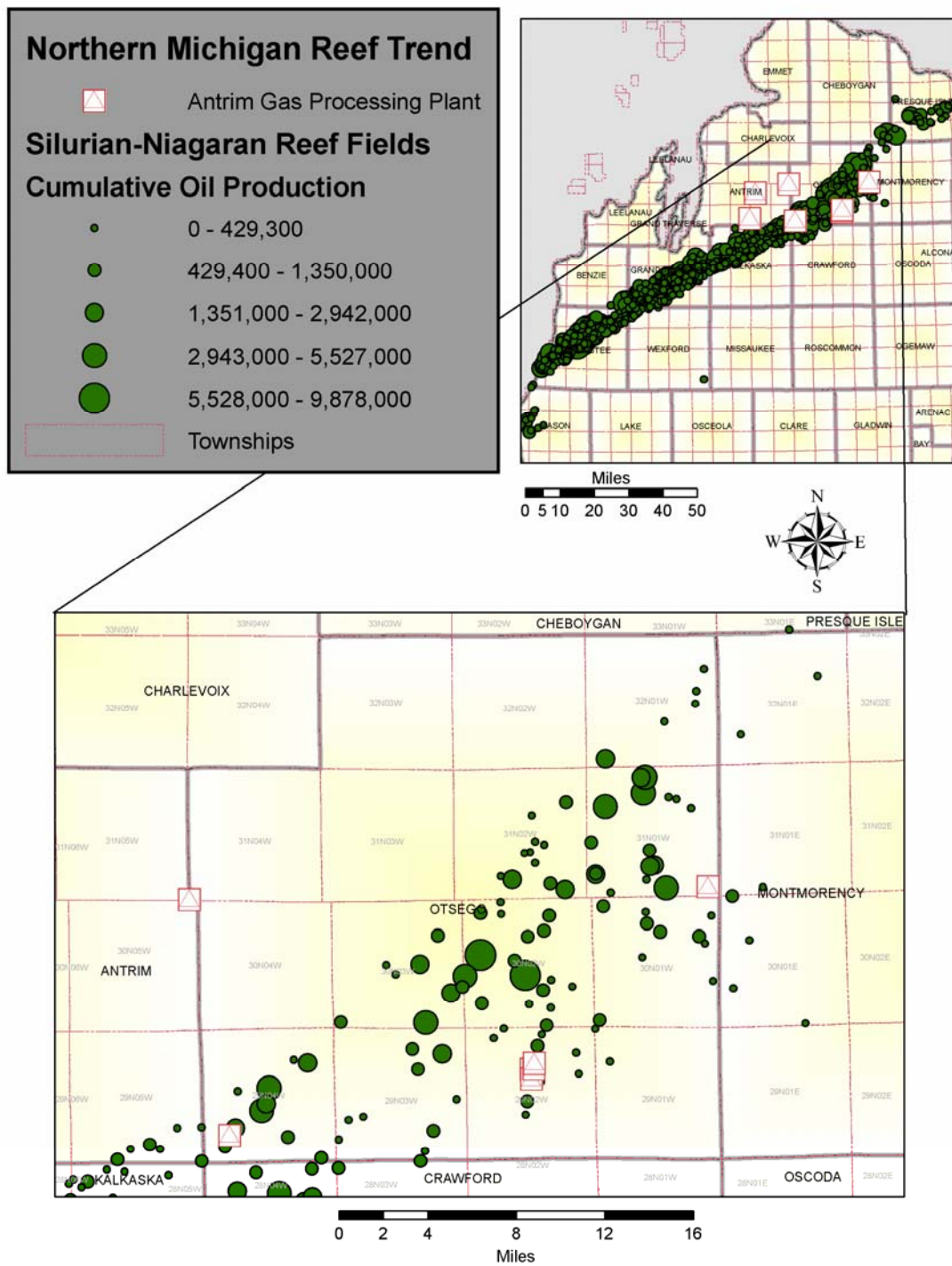


Figure 7



## Velocity vs. porosity in carbonates

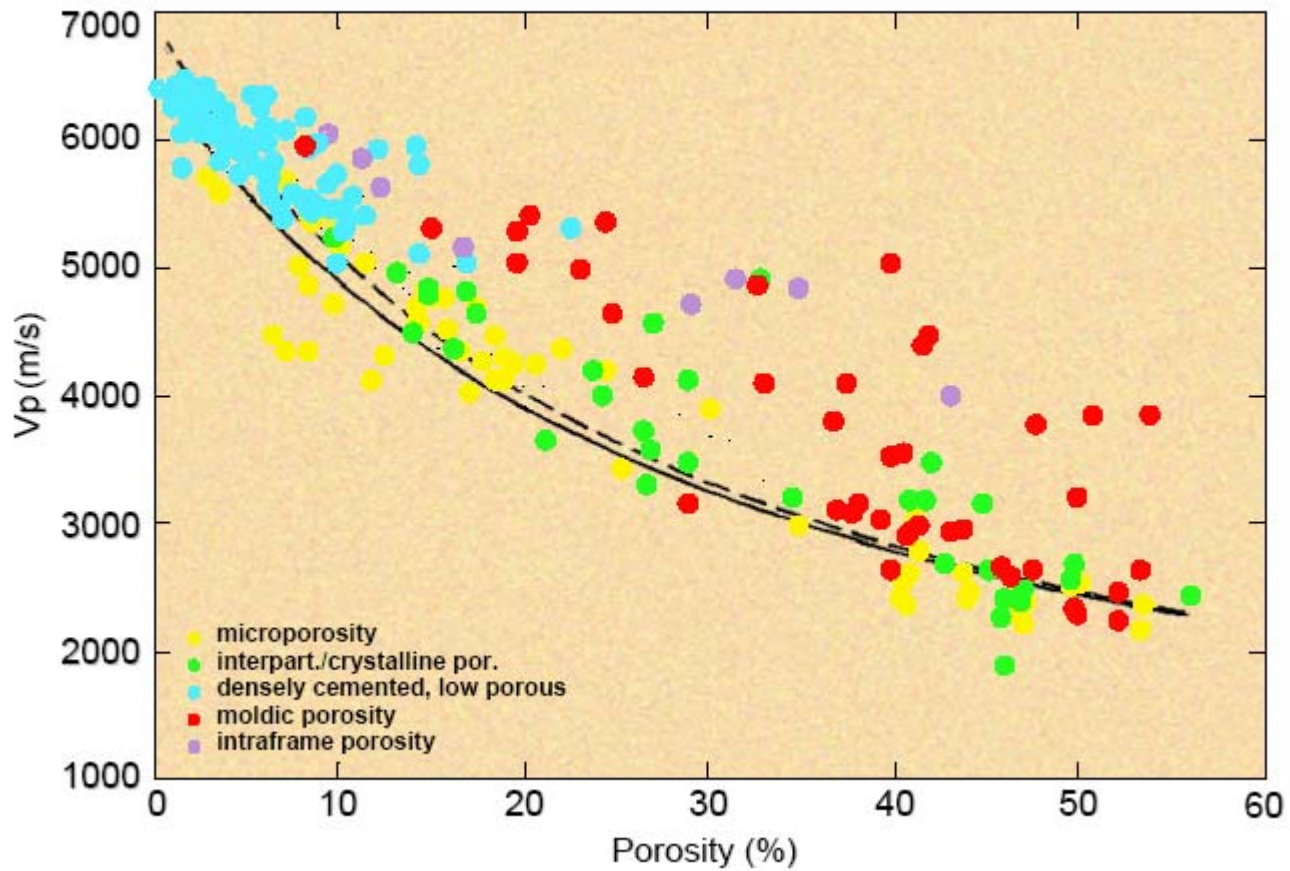


Figure 9

Figure 10.

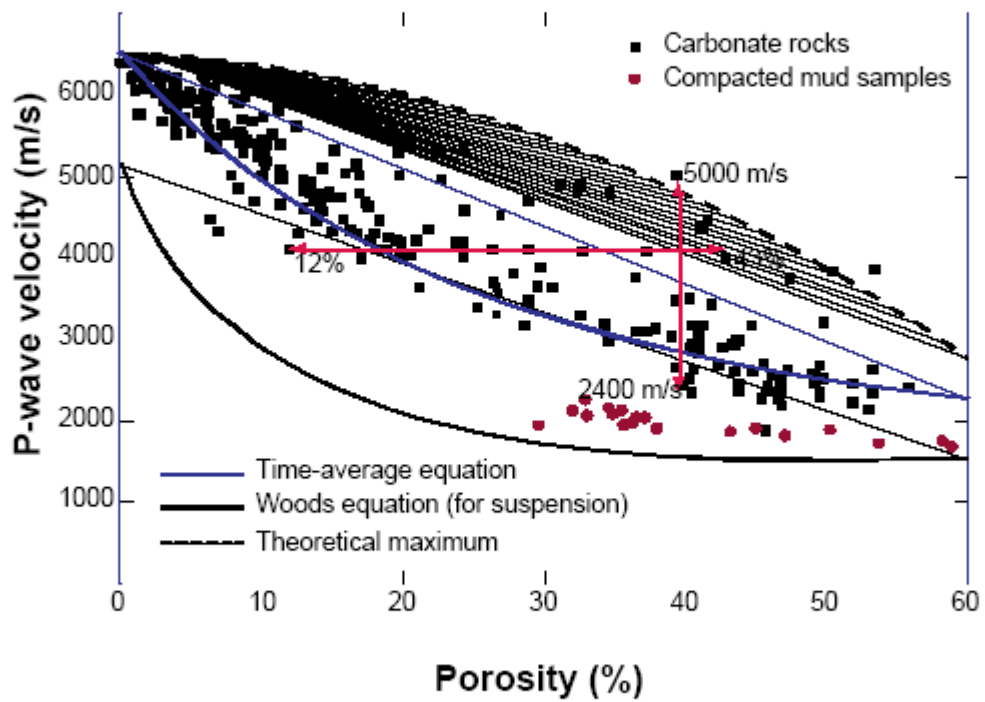


Figure 10

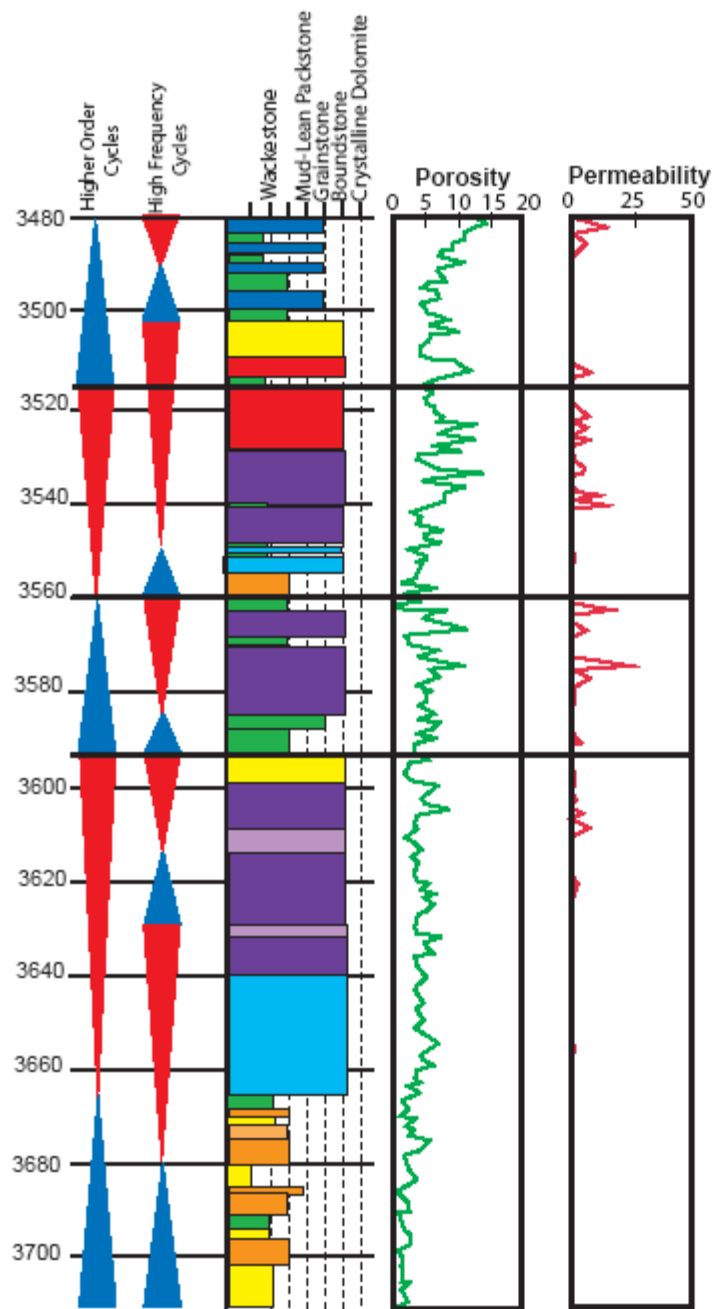


Figure 11

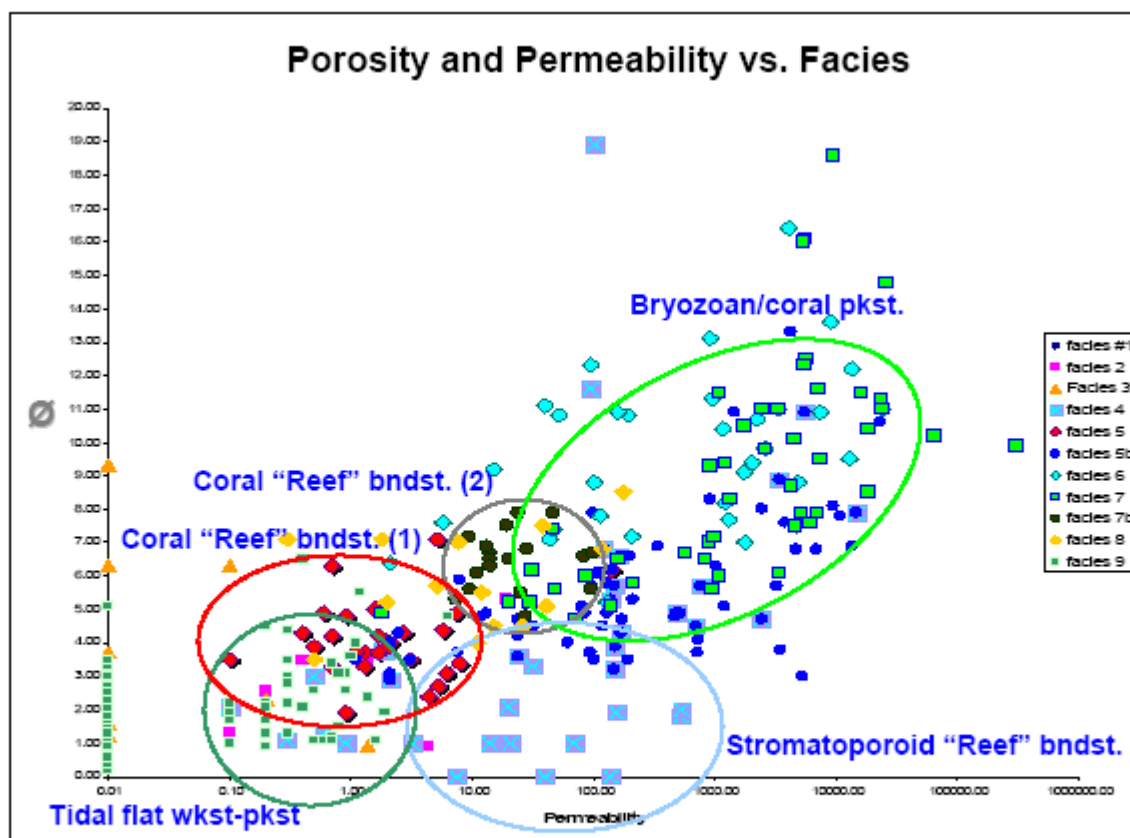


Figure 12

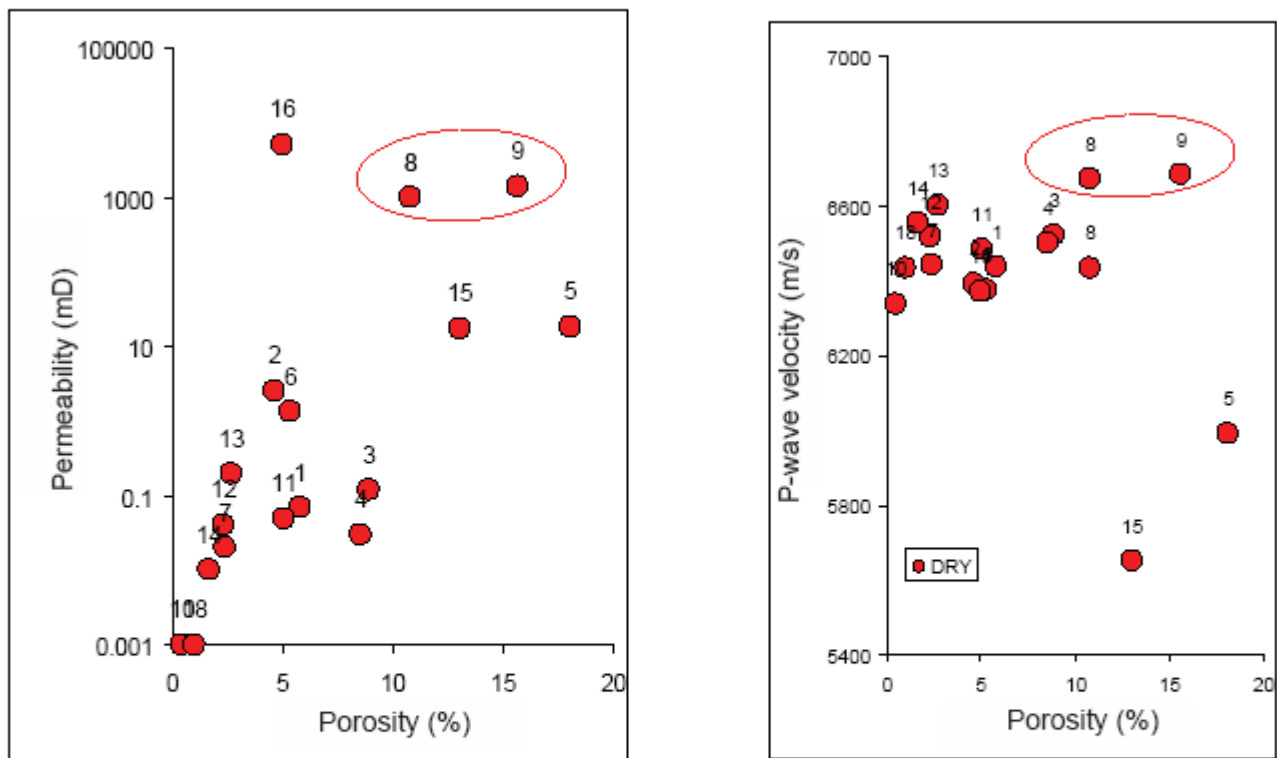
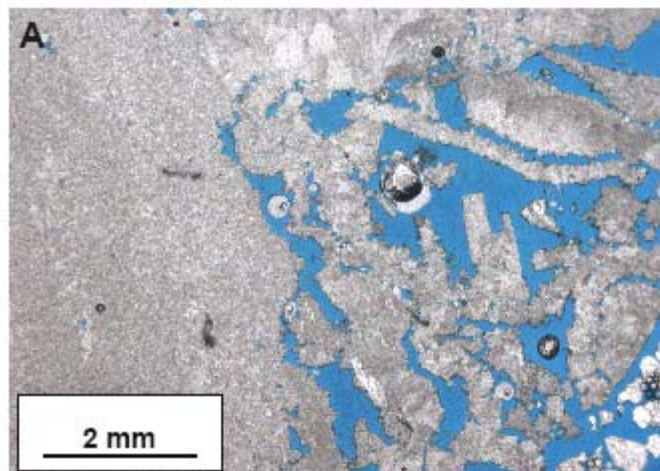


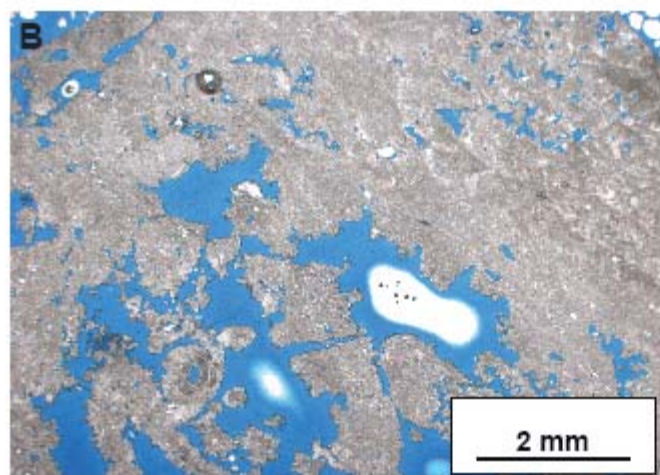
Figure 13





Large isolated vugs and fractures  
Low matrix porosity

Sample 8  
3524 ft. (Niagaran reef)  
 $\phi = 10.8\%$   
 $K = 990 \text{ mD}$   
 $V_p = 6240 \text{ m/s}$



Large isolated vugs and fractures  
Low matrix porosity

Sample 9  
3540 ft. (Niagaran reef)  
 $\phi = 15.6\%$   
 $K = 1368 \text{ mD}$   
 $V_p = 6660 \text{ m/s}$

Figure 14





## APPENDIX 2

### INITIAL SUMMARY OF CURRENTLY AVAILABLE GEOLOGIC DATA (TASK 2)

#### **Ordovician - Trenton-Black River Production Analysis Data and Graphs** (Prairie du Chien, Trempealeau generally not productive)

#### **DISCOVERY**

- 1884 – Drilling begins on Findlay-Kankakee Arch in Indiana and Ohio
  - Indiana-Lima trend
  - 100,000 wells
  - 500 MBO Bowling Green Fault Zone (Albion-Scipio analog)
- 1917 – SW Ontario – Dover Field
  - narrow, elongate, east-west trending dolomitized reservoir with synclinal expression
  - highly variable dolomitization
  - 4 separate pools
  - production from 2800-3200'
  - 249 KBO and 12.8 BCF CUM
- 1920 – Dundee Township, Monroe County, Michigan
  - First Trenton oil in Michigan
  - Noncommercial
- 1936 – Deerfield Field, Monroe County Michigan
  - First Commercial Trenton oil in Michigan
  - Along the Lucas-Monroe monocline
    - Extension of Bowling Green Fault zone in Ohio
  - Dolomite lenses in upper 125' of Trenton Group
  - 1959 – 40 wells drilled on 360 acre field
  - 1959 – 608 KBO CUM
- 1954 – Northville Field, Washtenaw, Oakland and Wayne Counties, Michigan
  - drilled as gravity prospect
  - faulted anticline
  - production from
    - Dundee (Devonian)
    - Salina-Niagaran (Silurian)
    - Trenton-Black River (Ordovician)
      - Fractured and dolomitized limestones
      - East flank of structure
      - Production is fault associated
- 1955-58 – Albion-Scipio, Calhoun & Hillsdale Counties Michigan

1955 - Scipio Discovery Well – Houseknecht No. 1 (Sec 10, T5S-R3W – Hillsdale Co.)  
 Originally drilled for Devonian gas - Dry  
 Deepened on advice of family psychic friend  
 1/57 - Encountered oil @ 3900'  
 Comp @ 140 BOPD and “considerable” gas  
 9/57 – Confirmation well – Stephens No. 1 (Sec 10, T5S-R3W – Hillsdale Co.)  
 Spetacular blowout – hit lost circulation @ 3769' (235' into Trenton)  
 Shut-in – craters began to form around location  
 Flowed for 25 hours @ 15 MMCFGPD  
 11/58 – Albion Discovery well Rosenau No. 1 (Sec 23, T3S-R4W, Calhoun Co.)  
 Comp @ 200 BOPD  
 Subsequent drilling discovered Pulaski (1959), Barry, Sponseller, Van Wert, Cal-Lee Fields – All part of the Albion-Scipio Trend  
 1986 - 961 wells drilled, 573 still producing  
 1989 – 330 Trenton penetrations in Albion Field  
 631 Trenton penetrations in Scipio Field

12/82 – Stoney Point Field Discovery (sub-parallel to Albion-Scipio 5 miles east)  
 JEM Casler No. 1-30 (Sec 30, T4S-R2W, Jackson Co.)  
 Encountered dolomite reservoir 115' into Trenton @ 3910'  
 Hit lost circulation @ 4248', casing set  
 Tested @ 2000 BOPD from perfs 4161'-4179'  
 BHP drop never exceeded 3 psi  
 Put on production @ 220 BOPD (1/83)  
 1983 –1987 – 210 wells drilled around Stoney Point Trend  
 1987 – 75 wells oil and gas producers in Stoney Point Trend

## **STRATIGRAPHY**

Trenton – Limestone, brown-gray, fossiliferous with carbonaceous partings  
 Top-of-Trenton Unconformity:  
 Rooney (1966) – southward thinning of Trenton toward Findlay arch in Ohio  
 DeHaas and Jones (1984,1989) – Exposure and karsting to produce caverns  
 Keith (1985) and Gray (1983) – dismissed any top-of-Trenton unconformity, considered this surface to be a marine hardground

Black River – Limestone, tan-gray, lithographic; altered to porous dolomite

### **TRENTON-BLACK RIVER TRAP**

#### Deerfield Field

Lucas-Monroe monocline (extension of Bowling Green Fault Zone)

#### Northville Field

Faulted anticline

#### Albion-Scipio Trend and Stoney Point Trend

Stratigraphic traps, limited development of porous, fractured dolomite reservoirs within the tight regional Trenton-Black River limestone northwest-southeast, left-lateral strike slip faulting (en echelon faults) offset 2.5 miles

Reactivated basement faults, primarily Precambrian, w/ additional reactivation during Late Ordovician-Early Silurian?, Late-Silurian-Early Devonian?, Mississippian?

Synclinal sag-like compartments related to down-dropping over partly extensional, en echelon breaks in the underlying section

Diagenetic porosity development (dolomitization) near faults  
Sharp contacts between dolomite and regional limestone  
Albion-Scipio, Stoney Point Fields– no anticlinal closure

### **TRENTON-BLACK RIVER SEAL**

- (1) Overlying Utica Shale
- (2) Non-porous, finely crystalline, ferron “cap dolomite” at the top of the Trenton Group
- (3) Non-dolomitized regional Trenton-Black River limestone
- (4) Trace fluorite, sphalerite, barite mineralization observed as late-stage pore fillings

### **TRENTON-BLACK RIVER CHARACTERISTICS**

#### **Porosity**

Vuggy, cavernous  
Intercrystalline  
Open fractures, often solution enlarged  
2-5% normal  
8-12% present but uncommon

#### **Permeability**

Extremely variable (0.01 – 8000 md)  
Generally low (85% of samples < 10 md)

Porosity/Permeability plots show no uniform relationship

### **Capillary Pressure**

High entry pressures in cap dolomite (confirms seal)

High entry pressures in Trenton-Black River = moderate to poor reservoir

rocks

### **Log Signatures**

Lost circulation – most wells cased and then logged

Gamma ray – neutron log typical

Neutron porosities range 2-10% (4-6% most common)

Modern gamma-ray logs, porosity of 26% observed at Utica Shale baseline

Many wells show < 0% neutron porosity = no cement behind casing

Base of zone usually at gas/oil contact

Thin shale layers acted as flow barriers during dolomitization, so most

Reservoirs located below persistent shale layers - particularly true for “E” Shale (Best developed in northern portion of Albion Field)

and Black River Shale (Best developed in southern portion of Albion Field)

Typical log – Figure 18 in Hurley and Budros

### **Fractures**

Dominant trend N30W

Secondary trend east-west (Finnigan’s Finger north of Haskell Unit)

Open, partially filled, and filled

Filling = saddle dolomite w/ calcite and anhydrite locally present, trace amounts of MVT minerals

### **Lost Circulation Zones/Caves**

Some zones encountered in cap dolomite (seal)

30% of wells in Albion-Scipio encountered lost circulation

54% of wells in Stoney Point encountered lost circulation

Bit drops up to 62’ reported in Albion-Scipio - rare

Bit drops up to 8’ reported in Stoney Point – rare

DeHaas and Jones (1984, 1989) propose cave development related to karsting responsible for lost-circulation zones; however, few others agree with this relationship due to:

- 1.) bit drops rare, most zones solution-enlarged fractures or vuggy rock
- 2.) Trenton-Black River arbitrarily divided into 4 levels w/ no true geological relationship to caves and lost-circulation zones

- 3.) Synclinal depression across field persists through Early Devonian - Cave formation would collapse under 1500' of overburden
- 4.) Geochemical data shows reservoir dolomites precipitated from hot solutions, some dissolution porosity is a late-stage event
- 5.) No cave features such as flowstone, cave sediments, cave pearls observed
- 6.) Core shows no karst features at Trenton/Utica contact – rather phosphatic and pyritic mineralization suggest a hardground (same as top-of-Trenton contact in Indiana)
- 7.) If caves formed during Ordovician – then Utica Shale should have filtered down into subsurface and this is not observed.

It appears that Mammoth Cave analog is not correct, rather, lost-circulation zones were probably developed by fracturing and dolomitization in a hydrothermal setting in a burial environment (Hurley and Budros)

## RESERVOIR COMPARTMENTS

Determined by:

- Structure Maps
- Fluid Contacts
- Oil and Gas Ratios
- Bottom-hole Pressures
- Lateral Well Drilling Data

Inter-well Scale shows en echelon synclinal compartments

Field Scale shows free gas cap with 150'-200' oil column

Pulaski Break – Major non-dolomitized discontinuity of fluid levels between Albion and Scipio Field

Stoney Point Field – 4 major compartments based on BHP's and decline rates

Albion Field – 3 major compartments based on BHP's and decline rates

Albio, Scipio and Stoney Point Fields – subtle east-west permeability barriers due to fracture zones that have undergone mylonitization and/or pervasive cementation

Finnigan's Finger – east-west production due to incomplete late-stage crystallization

Compartment Boundaries vs. Lost Circulation Zones

- Most lost circulation zones on up-dip (south) side of barriers between Group 2 and 4, and Groups 1 and 2 (Figure 27, Hurley and Budros)

Lost circulation zone decrease southward in Group 2 Suggesting that dolomitizing fluids move upward along east-west fracture zones

Dolomites also formed on undersides of shales suggesting upward fluid flow

Stoney Point - Dolomites/lost circulation zones concentrated in lower part

### **ORIGIN OF DOLOMITE**

- 1) Burgess (1960) – Reservoir dolomite was a secondary mineral formed as Cambrian and Lower Ordovician water moved up along the fracture zone (analogs- Dover and Colchester Fields in Ontario)
- 2) Ells (1962) – Magnesium-bearing waters ascending through fractures responsible to dolomitization (Albion-Scipio Field similar to Mississippi Valley-type [MVT] lead-zinc mineral deposits)
- 3) Beghini and Conroy (1966) – Reservoir formed by pre-Black-River Group water that moved through faults and fractures to produce secondary dolomite
- 4) Buehner and Davis (1968) – Reservoir is epigenetic dolomite related to a fault system
- 5) Shaw (1975) – Described a mineral assemblage (including sphalerite) in Albion-Scipio cores similar to MVT mineral deposits. He noted 2-phase fluid inclusions in Albion-Scipio dolomites. Pore filling saddle dolomites precipitated from fluids at minimum of 80 degree C temperature. He identified a liquid-hydrocarbon phase in some fluid inclusions indicating hydrocarbons were present at time of cementation. Proposed a model of replacement dolomitization and development of intercrystalline porosity during Middle to Late Silurian by waters percolating through fractures. Magnesium is sourced from underlying Prairie du Chien dolomite or Trempealeau formations. Second phase - during Lower to Middle Devonian as hot fluids from basin center created cavernous porosity, subsequent collapse, and precipitation of MVT assemblage.
- 6) Ardrey (1978), DeHaas and Jones (1984, 1989) Diagenesis of Trenton-Black River in Albion-Scipio area due to exposure (top of Trenton Unconformity). Dolomitization is the result of mixing models based on the observation that Trenton formation water is less saline than water in shallower horizons; therefore, it could not be of hydrothermal origin.
- 7) Taylor and Sibley (1986) – They identified 3 major types of dolomite (1) regional dolomite not associated with Field, (2) Cap dolomite that occurs in

the top 40 feet (related to interaction of the Trenton with Fe-rich fluids formed during the de-watering of the overlying Utica Shale) (3) fracture-related dolomite (formed during deeper burial at approximately 80 degrees C based on geochemical results)

- 8) Budai and Wilson (1986) – They identified various MVT accessory minerals including pyrite, calcite, anhydrite, barite, celestite, sphalerite, and fluorite in association with saddle dolomite cements. They proposed a hydrothermal model with Paleozoic and Precambrian basement rock as sources of iron, sulfur, and other trace metals.
- 9) Hurley and Cumella (1987) – They proposed a model based on carbon, oxygen, and strontium isotopes fluid-inclusion geothermometry, brine geochemistry and regional hydrologic constraints. Dolomitizing fluids were Silurian-Devonian hypersaline sea water that moved down fracture zones to meet with hot limestone-dissolving fluids moving up from the basement. These fluids mixed in a pattern that is consistent with the distribution of dolomite reservoirs and lost-circulation zones.

### **SOURCE ROCK**

Trenton Black River Sequence is the primary source

Shaley layers have TOC's 20-25 wt%

Burial history indicates maturity reached in the Carboniferous for the central basin area

TAI (visual kerogen) and pyrolysis (Tmax) indicate thermally maturity for oil and gas

Utica Shale (above Trenton – traditionally considered source) – TOC's too low

### **HYDROCARBONS**

Paraffinic

41-43 degree API

0.002% Sulfur

0.974 cp Viscosity (at reservoir conditions)

GOR's – 400 – 600 scf/STB

Cloud Point – 70 degree F

Free gas cap at time of discovery

### **WATER CHARACTERISTICS**

Connate water dense, CA-rich brine

North of Albion - 234,000 mg/L Total dissolved solids



South of Scipio – 196,000 mg/L Total dissolved solids  
Formation water resistivity approximately 0.03 ohm-m at 104 degree F (BHT)

### **RECOVERY MECHANISMS**

#### Original Recovery

- Solution-gas drive
- Gas cap expansion
- Gravity drainage
- Limited water drive

#### Current Recovery

- Stoney Point Field – Pressure is still high (approximately 1100 psig)
- Albion-Scipio Field
  - Pressures down to 100-150 psig
  - Gravity drainage now main mechanism

Volumetric Calculations meaningless – unable to accurately estimate porosities

Material Balance Calculations suggest:

- Scipio Field – 170 MMB OOIP
- Albion Field – 120 MMB OOIP
- Stoney Point Field – Not Available

#### Secondary Recovery

- Pilot Waterflood of the Haskell Unit (near south end Scipio Field) – discouraging results
- Marathon Oil – drilled a number of horizontal wells with considerable promise

### **EXPLORATION TECHNIQUES**

Originally - Advice of psychic after dry hole exploring for Devonian gas

Early - “Trendology”

- Linear Fracture Zone (northwest – southeast)

- Top-of-Trenton synclinal sag (up to 60’) recognized in producing wells

1960’s - early 70’s – Gravity defined basement fault along Scipio Trend

- Limited drilling success

- Dolomite porosity mutes density contrast between regional limestone and reservoir Dolomite

1970’s - Magnetics used to detect basement discontinuities and faults

- Albion-Scipio does not appear as an individual feature on magnetic maps

Recently – Micromagnetic surveys and resistivity profiles have been employed

- Significance not yet proven

- Reflection-seismic currently the primary method – Problems:

- Variable till (overburden) thicknesses produce noise and statics problems

- Secondary porosity (dominant reservoir component) not detected by P-waves

Reservoir dolomites (2-5% porosity) have similar acoustic impedance as regional limestones  
Reservoir geometries hard to image  
Reflection-seismic Trenton-Black River discoveries based on  
    Disruptions (sags) at Trenton event  
    Internal waveform changes  
    Disruption of lower events  
    Recognition of faults from offsetting events and/or diffractions  
Soil gas geochemistry studies above Scipio field showed no correlation between soil gas and producing parts of the field (despite Stoney Point Field discovery)  
LANDSAT – effective as a regional tool but interpretations of individual anomalies subjective  
Stoney Point Field - Soil-gas geochemistry

## **DEVELOPMENT**

Albion-Scipio Trend  
    Initial Maximum Allowable 150 BOPD and/or 200MCFGPD  
    7/1/60 - Maximum Allowable reduced to 125 BOPD and/or 165 MCFGPD  
    7/1/61 - Maximum Allowable reduced to 100 BOPD and/or 150 MCFGPD  
        (applies only to wells drilled in center of NW qtr of SE qtr of 40 acre unit)  
    Current – Oil allowable lifted, gas allowable 150 MCFGPD  
    Developed on 20 acre spacing  
    Decline rate 15% per year  
Stoney Point Trend  
    Maximum Allowable 150 BOPD and/or 175 MCFGPD  
    Drilling window maximum is 10 acres per 40-acre unit  
    Developed on 40 acre spacing  
    Decline rate 15% per year  
Subsurfacing mapping useful as development tool  
    % dolomite in Trenton-Black River sequence  
    Hydrocarbon shows in Trenton-Black River sequence  
    Isopach Traverse Limestone (Devonian) to top of Salina Group (Silurian)  
        showing thick of synclinal sag over productive part of field

## **Trenton – Black River Trend: Production Analysis**

### General Observations

1. Production data for the Trenton – Black River trend varies in quality and completeness. The State of Michigan did not require complete production data reporting until xxx. Digital data bases developed by the state beginning in 1981 generally do not include data before that date or data before and after that date may be cataloged in different groupings.
2. Production data are often grouped by lease hold and not necessarily by either individual well or by geological producing unit (e.g. – Albion Scipio 1 – 7 South Units). There is no means to separate the data and recalculate results based upon more geologically based, flow-unit parameters.
3. Initial potential data was never recorded for most wells in the trend. Only long-term and/or average data are available in most instances. Data is often duplicated as leasehold results and trend summaries. However, it is seldom clear as to exactly what data are included.
4. The State of Michigan imposes a 200 barrel-per-day maximum allowable on production which often distorts the true capabilities/performance of the affected wells.
5. During the beginning stages of field development, many operators produced the oil and flared the gas. Complete gas production data were only recorded during the later stages of field development as oil production declined and the gas cap was blown down to extend the economic life of the field.
6. Graphs of “Cumulative Oil and Cumulative Gas Production by Field” show an expected exponential decline in field size. “Gaps” in the curve are “filled” by “trend data” which give a distorted view as to the particular field sizes discovered. When these trends are omitted (difficult to accurately identify) a pattern emerges showing a few very large fields discovered (Albion-Scipio Trend), a large number of 1-5 well size fields discovered, and only a few intermediate field sizes discovered. Dr. Christopher Swezey of the U.S.G.S. interprets this to mean that there are still intermediate sized Trenton-Black River fields to be found. He calculates that as much as 723 million barrels of oil, 2,002 billion cubic feet of gas, and 112 million barrels of NGL’s may yet remain. The play is not resource limited as much as it is technology limited. It represents the greatest single remaining potential reserves for a particular reservoir in the State of Michigan.
7. Most fields have produced more oil than gas. However, there are 5 fields in the trend that have produced more gas than oil. These are: Albion-Pulaski-Scipio Trend, Albion-Scipio 3 South, Albion-Scipio 4 South, Albion-Scipio 5 South, and Northville.

8. Only Stoney Point field has produced more brine (bbls) then gas (BOE).
9. Cumulative Oil Production can be divided into approximately 5 main groups:
  - a.) **>10,000,000 bbls**  
Albion-Pulaski-Scipio Trend, Scipio-Fayette-Moscow, Stoney Point, Pulaski-Homer Twp, Albion Twp.
  - b.) **500,000 – 6,000,000 bbls**  
Adams Twp, Sheridan Twp, Lee Twp, Hanover, Albion-Scipio 6 South, Albion-Pulaski-Scipio Trend, Albion-Scipio 5 South, Northville, Dearfield, Albion-Scipio 3 South, Albion-Scipio 4 South
  - c.) **5,000 – 50,000 bbls**  
Albion-Scipio 2 South, Reading Section 25, Albion-Scipio 1 South, Northville?, Henrietta, Tekonsha, Lee Section 34 (Black River), Freedom, Reading, Medina, Springport, Green Oak
  - d.) **500 – 5,000 bbls**  
Rattle Run, Summerfield, Albion-Scipio 7 South, Huron, Hanover Section 13, Summerfield Section 07, Macon Creek, Summerfield Section 19, Blissfield, New Boston, Newburg, Cadmus, Olivet, Sumpter
  - e.) **0 - 60 bbls**  
Ridgeway Section 01, Winterfield
10. Cumulative Gas Production can be divided into approximately 5 groups:
  - a.) **>100,000,000 MCF**  
Albion-Pulaski-Scipio Trend
  - b.) **6,000,000 – 100,000,000 MCF**  
Scipio-Fayette-Moscow Trend, Pulaski-Homer Twp, Stoney Point, Albion Twp, Northville, Albion Scipio 4 South
  - c.) **1,000,000 – 6,000,00 MCF**  
Adams Twp, Albion Scipio 5 South, Albion-Pulaski-Scipio Trend, Albion Scipio 3 South, Reading Section 3 South, Reading Section 25, Albion Scipio 1 South, Albion Scipio 6 South, Sheridan Twp
  - d.) **300,000 – 1,000,000 MCF**  
Albion Scipio 2 South, Hanover, Lee Section 34 (Black River), Lee Twp
  - e.) **50,000 – 300,000 MCF**  
Cadmus, Winterfield, Green Oak, Blissfield
11. There is little correlation between “Years of Production” vs. “Cumulative Oil Production by Field” or “Year of Discovery.” Longest producing fields (most years of production) range from discovery dates of 1935 (Deerfield), 1947 (New Boston), 1954 (Northville), 1961 Springport, and 1967 (Green Oak). However, these fields do not reflect the greatest cumulative oil totals. Instead, accumulations from these fields are similar to those from fields having produced

for the fewest years (Reading Section 25 – disc 1999, Henrietta – disc 1979, Albion-Pulaski-Scipio Trend – disc 1981). Fields reflecting “Maximum Oil Accumulation” are associated with “Years of Production” intermediate in range (Scipio-Fayette-Moscow Trend – disc 1957, Albion Twp – disc 1959, Albion-Pulaski-Scipio Trend – disc 1960, Pulaski-Homer Twp – disc 1959, Stoney Point – disc 1984, Albion-Scipio6 South – disc 1982, Adams Twp – disc 1967, Sheridan Twp – disc 1967). The lack of correlation between “Years of Production,” “Cumulative Oil Production by Year” and “Year of Discovery” leads one to speculate that fields of varying reservoir types and production capabilities, overprinted by the learning curve of discovery, have been mixed into a single data base. Approximately four groups can be identified within this data base:

(1) > 30 years of production; Deerfield, Northville, Springport, New Boston,

(2) 20 – 30 years of production; Green Oak, Freedom, Ridgeway Section 01, Summerfield, Albion-Scipio 1 South, Albion Scipio 3 South, Hanover, Scipio-Fayette-Moscow, Tekonsha, Albion Twp, Albion-Pulaski-Scipio Trend, Macon Creek, Medina, Pulaski-Homer Twp, Stoney Point,

(3) 10 – 20 years of production; Blissfield, Lee Section 34 (Black River), Albion Scipio 2 South, Albion Scipio 5 South, Cadmus, Albion Scipio 6 South, Northville, Albion Scipio 4 South, Adams Twp, Lee Twp, Olivet, Sheridan

(4) 0 – 10 years of production; Reading, Albion Scipio 7 South, Summerfield Section 19, Winterfield, Rattle Run, Reading Section 25, Summerfield Section 07, Huron, Henrietta, Newburg, Sumpter, Albion-Pulaski-Scipio Trend, Hanover.

12. There appear to be four distinct groups of “Field Size” in comparison to “Year Discovered.”

(1) 1935 -1960; Deerfield, Sumpter, Huron, New Boston, Freedom, Northville, Ridgeway Section 01, Scipio-Fayette-Moscow Twp, Summerfield, Albion Twp, Hanover, Pulaski-Homer Twp, Tekonsha, Albion-Pulaski-Scipio Trend,

(2) 1960 – 1967; Macon Creek, Medina, Springport, Blissfield, Adams Twp, Green Oak, Lee Twp, Sheridan Twp,

(3) 1969 – 1984; Olivet,, Reading, Henrietta, Newburg, Albion Scipio 1 – 6 South, Northville (Gas Storage), Albion Scipio 7 South, Stoney Point,

(4) 1985 – 1999; Winterfield, Cadmus, Lee Section 34 (Black River), Rattle Run, Hanover Section 13, Summerfield Section 07, Summerfield Section 19, Reading Section 25. Each group displays a general trend of increasing field size through time. This “re-setting of the curve” may reflect discovery of differing field types followed by increasing knowledge of how to explore and develop these new types.

13. Nearly one-half of the Trenton – Black River fields produce only oil (Albion-Scipio 7 South, Deerfield, Freedom, Henrietta, Macon Creek, Medina, New Boston, Newburg, Northville, Olivet, Reading, Ridgeway Section 01, Springport, Summerfield, Summerfield Section 07, Summerfield Section 19, Tekonsha, Hanover Section 13, Huron, Rattle Run, Sumpter) .
14. The other half of the Trenton – Black River fields produce both oil and gas (Albion-Pulaski-Scipio Trend, Scipio-Fayette-Moscow, Pulaski-Homer Twp, Stoney Point, Albion Twp, Northville, Albion-Scipio 1-6 South, Adams Twp, Reading Section 28, Sheridan Twp, Hanover, Lee Section 34 (Black River), Lee Twp, Cadmus, Winterfield, Green Oak, Blissfield) .
15. Winterfield is the only field in the trend to produce only gas. This is primarily a Dundee Formation field producing both oil and gas from that interval. Only one well in the field penetrates the deeper Trenton – Black River Formations producing gas from those intervals.

#### Current Activity

Data from the first 4 years of the Albion – Scipio field which are contained in the Albion – Scipio Field Folio Series is currently being entered into a computer data base. These data are lease based and reported upon a monthly schedule. It is thought that these data more accurately reflect initial production conditions and are more consistently reported. These data will be analyzed when data entry is complete.

1. Fields from each category defined above will be correlated to the newly developed index covering data quantity, quality and availability for each field. Fields in each category ranking high in data coverage will be selected for detailed study.

Representative Well Summaries (Trenton/Black River)

**HOWARD DUNLAP No. 1**  
**James O. Kelly**  
**Drilling Contractor – Union Rotary Corporation (Rotary)**

**Field:** Exploratory Extension - Albion field – Oil & Gas – Black River  
**API #:** 21-025-22108-00-00  
**Permit#:** 22108  
**Location:**  
**Township:** Lee  
**County:** Calhoun  
**Well:** SE NW SE Sec. 22, T1S – R5W  
990' from north line, 990' from west line of quarter section  
**Datum:** GL - elevation 930'  
**Logging Datum:** RKB – 943' (3' above rig floor 940')  
**Spud:** 01/31/1960  
**Completed:** 03/03/1960  
**Cored:** No Cores  
**DST:** DST #1  
4,230' – 4,320' (top Trenton formation), open 1 hr, gas to surface in 17 min, recovered 40' mud, ICIP – 1,053#, FCIP – 1,256#  
DST #2  
4,414' – 4,474' (base Trenton formation), open 1 ½ hrs, gas to surface in 2 min, est. 5.5 MCFGPD, blew down to 1,800 MCFGPD, ICIP – 1,725#, FCIP – 1,055#  
**Csg:** 8 5/8" @ 955' w/ 300 sxs cmt  
5 1/2" @ 4,580' w/ 230 sxs cmt  
**TD:** Drlr - 4,910' (St. Peter?, Prairie Du Chien formation)  
Lgr - 4,912' (St. Peter?, Prairie Du Chien formation)  
**PBTD:** 4,660' (Black River formation)  
**Perfs:** 04/20/1960  
Perfs 4,457' – 4,463'  
03/15/1960 - sand frac w/ 2,000 gals acid plus 500 bbls oil & 5,000# sand  
Perfs 4,488' – 4,498' w/ 40 shots, treated w/ 5,500 gals acid  
06/21/1960 - sqzd all perfs, CO to 4,660',  
Perfd 4,580' – 4,660', treated with 10,000 gals acid and 5,000 gals water  
Perfd 4,600' – 4,636', Vibra-fracd w/ #10 charges  
**IP:** "Excessive gas" – restricted (State proration) to 16 BOPD  
**Current Status:** 09/28/1961 – P&A

**BLAIR No. 1**  
**Turner Petroleum Company and McClure Oil Company**  
**Harry Roberts - Rotary 0' – 3,680'**  
**McClure Drilling Corporation – Cable Tool 3,680' – 3,826'**

**Field:** Exploratory Extension – Oil – Trenton formation  
Opened the “Pulaski field” portion of the trend between the Albion and Scipio field areas

**API #:** 21-  
**Permit#:** 21273  
**Deepened Permits** 10/22/1963 - #1454 Projected TD 3,900'  
05/15/1969 - #1599 Projected TD 3,920'

**Location:**  
**Township:** Pulaski  
**County:** Jackson  
**Well:** SE NW SW Sec. 20, T4S - R3W  
990' from north line, 990' from west line or quarter section

**Datum:** GL - elevation 1,008'  
**Logging Datum:** Rotary Table (RT) – 1,012.5' (4.5' above GL)  
**Spud:** 11/26/1958  
**Completed:** 01/09/1959  
**Cored:** No Cores  
**Csg:** 8 5/8" @ 224' w/ 200 sxs cmt  
5 1/2" @ 3,680' w/ 25 sxs cmt

**TD:** Drlr - 3,826' (in Trenton formation)  
Lgr - 3,832' (in Trenton formation)

**Shows:** 3,766' – 3,768' - Show of gas (40 MCFG)  
3,777' - Gas (gauged 70 MCFG)  
3,795' - Gas (gauged 100 MCFG)  
3,810' – 3,815' - Oil in bailer  
3,815' – 3,820' - Spray of Oil (est. 700 MCFG & 25-30 BOPD)  
3,820' – 3,826' - Increase Oil and Gas – Well Flowing to Pits

**Contacts:** Gas/Oil – 3,766'  
Oil/Water – 3,810'

**Original Perfs:** Open Hole Completion (Top Trenton formation)  
**IP:** Before acid – FARO 160 BOPD restricted (State proation)  
**Deepened TD:** 12/13/1963 – 3,910'  
Treated open hole 3,844' – 3,890'  
Treated open hole 3,815' – 3,832'  
8/23/1963 - 3,000 gals 15% HCl  
12/13/1963 – 3,000 gals 15% HCl

**Deepened TD:** 05/10/1969 – 05/16/1969 - 3,826'  
**IP:** 6/18/1969 - 500 gals mud acid – IPP 115 BOPD  
**Current Status:** 11/27/1963 – Reworked; McClure Oil Company interest to Patrick Petroleum Company 09/25/1991 – P&A complete



**ORVILLE HERGERT #2**  
**McClure Oil Company**

**Field:** Albion Scipio 5 South  
**API #:** 21-059-22196-00-00  
**Permit#:** 22196  
**Location:**  
**Township:** Scipio  
**County:** Hillsdale  
**Well:** SE SW SE Sec. 25, T5S - R3W  
330' north of section south line, 990' east of section west line  
**Datum:** GL - elevation 1182.6'  
**Logging Datum:** RKB - 1192' (9.4' above GL)  
**Spud:** 03/05/1960  
**Completed:** 04/25/1960  
**Cored:** Core #1 - 3,892'-3,938' (Recovered 44.33')  
Core #2 - 3,938.5'-3,988' (Recovered 49.5')  
Core #3 - 3,988'-4,038' (Recovered 51')  
Core #4 - 4,038'-4,060' (Recovered 24')  
Bleed green oil - no fractures  
**Csg:** 9 5/8" @ 1010' w/ 400 sxs cmt  
5 1/2" @ 4021' w/ 175 sxs cmt  
**TD:** Drlr - 4060' (Black River formation)  
Lgr - 4058' (Black River formation)  
**Perfs:** Open Hole Completion 4021' - 4060' (Black River formation)  
**IP:** After acid - FARO 51 BO in 3 hours on 4/64" choke;  
pinched flow to 150BOPD; 5/03/60 Treated 4021 - 4060'  
w/ 500 Mud Acid + 2500 Regular Acid  
**Current Status:** Abandoned 08/07/90  
05/02/91 - Approved P&A

**J.C. TURNER #1**  
**Continental Oil Company**  
**Drilling Contractor; Original Hole – Parker Drilling Company**  
**Drilling Contractor; Well Deepened – E.F. Moran (Rotary)**

**Field:** Exploratory – First Trenton Test in Area  
**API #:** 21-025-09261-00-00  
**Permit#:** 9261  
**Location:**  
**Township:** Albion  
**County:** Calhoun  
**Well:** NE SE NE Sec. 15, T3S R4W  
990' from south line, 330' from east line of quarter section  
**Datum:** GL - elevation 1,022'  
**Logging Datum:** DB – 1,032' 6" (10' 6" above ground level)  
**Spud:** 12/05/1941  
**Completed:** 12/27/1941  
**Deepened:** 05/04/1943  
**Re-Completed:** 06/18/1943  
**Cored:** Core #1 – No Record  
Top Devonian Traverse Limestone – 1,600'  
Core #2 – 1,625' – 1,632' (Recovered 7' – Saved 2'6")  
Core #3 – 1,633' – 1,640' (Recovered 6' – Saved 1')  
Core #4 – 1,640' – 1,643' (Recovered 1')  
Core #5 – 1,644' – 1,646' (Recovered 16')  
Core #6 – 1,662' – 1,676' (Recovered 14')  
Core #7 – 1,647' – 1,694' (Recovered 15'3")  
Core #8 – 1,694' – 1,712' (Recovered 18')  
Core #9 – 1,712' – 1,730' (Recovered 17'9")  
Core #10 – 1,730' – 1,748' (Recovered 16.33')  
Top Dundee formation – 1,800'  
Core #11 – 1,800' – 1,805' (Recovered 4'2" –  
Drld 1,748' – 1,800')  
Core #12 – 1,805' – 1,810' (Recovered 5')  
Core #13 – 1,810' – 1,828' (Recovered 17'9" – Saved 17'1")  
Core #14 – 1,841' – 1,859' (Recovered 17'4" – Saved 16'8")  
Core #15 – 2,170' – 2,188' (Recovered 17' -  
Drld 1,859' – 2,170')  
Top Bass Island formation – 2,182'  
Core #16 – 2,188' – 2,206' (Recovered 16'6" – Saved 14'10")  
Top Salina formation – 2,233'  
Top Niagaran formation 2,687' (?)  
Core #17 – 2,845' – 2,881' (Recovered 10'10" – Saved 8'10")  
Core #18 – 2,863' – 2,881' (Recovered 5'8")

Core #19 – 23 – No Cores Labeled with these numbers  
Top Ordovician Cincinnati Series – 3,326’  
Top Ordovician Utica Shale – 3,662’  
Top Ordovician Trenton formation– 3,952’  
Core # 24 – 3,948’ – 3,966’ (Recovered 16’6” – Saved 14’7”)  
3,950’ – 3,964’ - Saturated, Bleeding oil  
3,959’ – 3,964’ - Best Porosity  
Core #25 – 3,966’ – 3,979’ (Examined 12’6”)  
Core #27 – 3,997’ – 4,015’ (Examined 17’)  
Core #28 – 4,015’ -4,033’ (Examined 16’8”)  
13” @ 395’  
8 1/4” @ 1,582’  
**Original TD:** 12/27/1941 - 1,609’  
**Deepened TD:** Permit # 365 – 02/17/1943 – to 4,000’  
Permit # 374 – 04/30/1943 – to 4,500’  
05/04/1943 - Drlr - 4,286’  
05/04/1943 - Lgr – 4,281’  
**Perfs:** Traverse Limestone Gas Pay:  
1,600’ – 1,605’ 3-5,000,000 CFG  
1,605’ 3,004,000 CFG  
1,607.5’ - 5,000,000 CFG  
1,609’ - 10,500,000 CFG  
**IP:** Trenton formation Dry, Plugged Back to Traverse Limestone  
1,600’ – 1,605’ - FARO 10,200,000 CFGPD  
**Current Status:** 04/04/43 – Dry Hole (Trenton)  
07/09/1943 - P&A – Traverse Limestone (Gas)

**CASLER # 5-30**  
**JEM Petroleum Corporation**  
**Drilling Contractor - James Bigard Drilling Co.**

**Field:** Stoney Point  
**API #:** 21-075-36587-00-00  
**Permit#:** 36587  
**Location:**  
**Township:** Hanover  
**County:** Jackson  
**Well:** SE NW SE Sec. 30, T4S – R2W  
981' from north line, 986' from west line of quarter section  
**Datum:** GL - 1,105' elevation  
**Logging Datum:** RKB - 1,117.6' (12.6' above GL; 1,115.6' Rig Floor)  
**Spud:** 10/25/83  
**Completed:** Drlg - 11/05/83, Well – 11/19/83  
**Cored:** Core #1 - 4,081' – 4,088.4' (Cut 9', Recovered 7.4')  
Core #2 - 4,097' – 4,118' (Cut 21', Recovered 21')  
Core #3 - 4,118' – 4,134' (Cut 16', Recovered 16')  
Core #4 - 4,134' – 4,166' (Cut 32', Recovered 32')  
Core #5 - 4,166' – 4,190.4' (Cut 24', Recovered 24.4?)  
**Lost Circulation** 4,235' – drilled blind to 4,256'(TD)  
**Csg:** 11 3/4" @ 397' w/ 150 sxs cmt  
8 5/8" @ 2,065 w/ 150 sxs cmt  
5 1/2" @ 4,256' w/ 350 sxs cmt  
**TD:** Drlr - 4,256' (Black River formation)  
**Perfs:** 11/15/83 - 4,207' - 4,212' (Black River formation) w/ 4 spf  
**IP:** FARO 220 BOPD; 45° API grav; 89.6 MCFGPD;  
H<sub>2</sub>S – 67 grains/100 cu. ft.; BHP 465 psi @ 4,209'  
**Current Status:** 6/19/2001 – Shut In  
12/11/2002 – Permittee Changed to:  
Whiting Oil and Gas Corporation

**HAROLD I. MANN #6**  
**The Ohio Oil Co.**  
**Marathon Oil Co. (MOC)**  
**Drilling Contractor – McClure Drilling Corp. (Rotary)**

**Field:** Albion Scipio 5 South  
**API #:** 21-059-22381-00-00  
**Permit#:** 22381  
**Deepen Permit #:** 1544  
**Location:**  
**Township:** Scipio  
**County:** Hillsdale  
**Well:** SE NW NE Sec. 23, T5S - R3W  
990' from north line, 990' from west line of quarter section  
**Datum:** GL - elevation 1173.6'  
**Logging Datum:** RKB – 1,175'  
**Spud:** 5/12/1960  
**Completed:** 6/01/1960  
**Cored:** Core #1 – 3,939' – 3,965' (Recovered 26')  
Core #2 – 3,966' – 3,993' (Recovered 27')  
Core #3 – 3,994' – 4,035' (Recovered 40.5')  
Core #4 - 4,036' – 4,088' (Recovered 50.6')  
**Core/Log Depth** Core #1, 2, 3 - 4.5' shallow to log  
Core #4 - 6.5' shallow to log  
**Csg:** 9 5/8" @ 1,010' w/ 625 sxs cmt  
5 1/2" @ 4,150' w/ 250 sxs cmt  
**TD:** Drlr. - 4,150, Lggr - 4,154' (Black River Formation)  
**Completion:** 6/03/1960 - Perfd 4,071' – 4,085' w/ 57 shots  
Pre-acid FARO 250 BOPD  
Acidized w/ 500 gals MCA and 3,500 gals 15% RA  
After Acid FARO 125 BOPD restricted  
**Current Status:** P&A – 8/10/94

**PAUL TAYLOR 1-35**  
**Marathon Oil Company**  
**Drilling Contractor – Bigard Drilling Co. (Rotary)**

**Field:** Exploratory – Albion Area  
**API #:** 21-023-31348-00-00  
**Permit#:** 31348  
**Location:**  
**Township:** Quincy  
**County:** Branch  
**Well:** NW NE NE Section 35, T6S, R5W  
330' from north line, 920' from east line of quarter section  
**Datum:** GL - elevation 1,030.2'  
**Logging Datum:** RKB – 1,042.9' (12.7' above GL)  
**Spud:** 11/28/1976  
**Completed:** 12/10/1976  
**Cored:** Core #1 – 3,090' – 3,101'  
(Core Barrel Jammed - Cut 11', Recovered 8")  
Core #2 – 3,101' – 3,159'  
(Cut 58', Recovered 59.9' - Picked-up 1.9' of Core #1)  
Core #3 – 3,361' – 3,420' (Cut 59', Recovered 59')  
**Csg:** 11 3/4" @ 320' w/ 245 sxs cmt  
8 5/8" @ 1,525' w/ 165 sxs cmt (Pulled 660')  
**TD:** Drlr - 3,730" (Prairie Du Chien formation)  
Lgr - 3,729' (Prairie Du Chien formation)  
**Perfs:** Dry Hole – No Perfs  
**IP:** 12/10/1976 – Well plugged; 50 sxs cmt @ 3,000', 50 sxs cmt @  
1,900', cut 8 5/8" csg and pulled, 50 sxs cmt @ 690', 75 sxs cmt @  
325', 10 sxs cmt @ 30', Cut csg 3' below GL, welded steel plate  
on top, filled rat hole to surface  
**Current Status:** D&A – Plugged 12/10/1976

**W.F. and Florence M. Rosenau No. 1**  
**Tom Mask and McClure Oil Company**  
**Harry Roberts (Rotary 0' – 3,955')**  
**McClure Oil Company (Cable Tool 3,955' – 4,084')**  
**McClure Oil Company (Rotary 4,084' – 4,329')**

**Field:** Albion Field – Oil – Black River Formation Discovery  
**API #:** 21-025-21195-00-00  
**Permit#:** 21195  
**Location:**  
**Township:** Albion  
**County:** Calhoun  
**Well:** NW NW SW Sec. 23, T3S, R4W  
330' from north line, 330' from west line of quarter section  
**Datum:** GL - 986.5'  
**Logging Datum:** RKB – 991.3'  
**Spud:** 10/04/1958  
**Completed:** 12/15/1958  
**Cored:** Core #1 – 3,892'-3,938' (Recovered 44.33')  
Core #2 - 3,938.5'-3,988' (Recovered 49.5')  
Core #3 – 3,988'-4,038' (Recovered 51')  
Core #4 – 4,038'-4,060' (Recovered 24')  
**Csg:** 8 5/8" @ 368' w/ 155 sxs cmt  
5 1/2" @ 3,902' w/ 35 sxs cmt  
4" lnr (452') @ 4,300' w/ 120 sxs cmt  
**TD:** Drlr - 4,314' (Black River formation)  
Lgr - 4,324' (Black River formation)  
**Lost Circulation:** 3,930' – 3,940'  
4,085'- lost tools w/ 2,800 MCF & spray of oil  
**Perfs:** 01/24/1959 – Perfd 4,218' – 4,238' w/ 101 shots  
01/25/1959 – Treated w/ 500 gals mud acid  
01/28/1959 – Perfd 4,172' – 4,192' w/ 101 shots  
01/28/1959 – Treated perfs 4,172' – 4,238' w/ 250 gals mud acid  
and 1,500 gals regular acid  
**IP:** Before Acid – FARO 168 BOPD  
After Acid FARO 45 BOPD restricted (State proration)  
**Reworked:** 10/11/1960 – 10/25/1960  
Sqzd all perfs, perfd 4,182' – 4,192' w/ 40 shots, treated w/ 1,000  
gals mud acid, 10,000 gals regular acid, IPP 75 BOPD, no water,  
State allowable 40 BOPD  
**Current Status:** 02/23/1961 – Reworked  
05/03/1961 – Plugged Back  
07/10/1961 - Converted to BDW (Pay Zone Abandoned – Plugged  
back to Niagaran formation for brine diposal)  
09/09/1987 – P&A Approved

**VIRGIL W. SKINNER #1**  
**The Ohio Oil Co.**  
**Marathon Oil Co. (MOC)**

**Field:** Albion Scipio  
**API #:**  
**Permit#:** 21833  
**Deepen Permit #:** 1544  
**Location:**  
**Township:** Scipio  
**County:** Hillsdale  
**Well:** NW SE SE Sec. 23, T5S - R3W  
1021' from south line, 990' from east line of quarter section  
**Datum:** GL - elevation 1112.2' (1113')  
**Logging Datum:** RKB - 1124.2' (1125' - 12' above GL)  
**Spud:** 09/13/1959  
**Completed:** 10/08/1959 (Original Hole)  
**Cored:** Core #1 - 3,875' - 3,898' (Recovered 21.6')  
Core #2 - 3,898' - 3,945.5' (Recovered 44.7')  
Core #3 - 3,945.5' - 4,003' (Recovered ?)  
**Csg:** 10 3/4" @ 730' w/ 480 sxs cmt  
7" @ 3,592; w/ 100 sxs cmt  
4 1/2" lnr @ 4,001' w/ 85 sxs cmt  
**Original TD:** Drlr - 4,003' (Trenton formation ?)  
**Original Perfs:** 10/13/1959 3,912' - 3,928' w/ 64 holes (Trenton formation ?)  
10/14/1959 - Treated perfs 3,912' - 3,928' w/ 1,500 gals. acid  
After acid - FARO 218 BO  
**DST #1** 3,900' - 3,950' (2) GS in 8 min, Steady blow throughout, Rec. 1 1/2  
bbls OGCM, IBHP 1540# in 1/2 hr., FBHP 1584# in 1/2 hr., Rec.  
335' oil and 325' O&GCM  
**DST #2** 3,950' - 4,000' (1/2) GS in 2 min., Steady blow, Shut-in 1 hr.,  
Rec. 225' GCM, ICIP 1560#, FCIP 1560#, IBHP 1872#, IFP 52#,  
FFP 124#, FBHP 1872# in 1/2 HR.  
**Spud Re-complete:** 10/10/1966  
**Final TD** 4,025'  
**Re-completed:** 10/18/1966 (Deepened Hole)  
**Completion:** 10/14/1959 - perfd 3,912' - 3,928' w/ 64 shots  
11/22/1966, Squeezed perfs 3,912' - 3,928' w/ 200 sxs cmt,  
deepened hole to 4,025', Acidized open hole 4003' - 4,025' w/  
2000 gals. acid, IP (permitted) 110 BOPD, Completed open hole  
**Current Status:** 08/05/1994 - Approved P&A



**ROBERT SPONSELLER #1**  
**C.J. Simpson**  
**Drilling Contractor – D.B. Lesh Drilling Co. (Rotary)**

**Field:** Exploratory Extension – Oil – Base of Black River formation  
Opened “North Adams field” (southern extension of Scipio field)

**API #:**

**Permit#:** 22180

**Location:**

**Township:** Adams

**County:** Hillsdale

**Well:** NW NW NW Sec. 4, T6S – R2W  
330’ from north line, 330’ from east line or quarter section

**Datum:** GL - elevation 1,171’

**Logging Datum:** RKB – 1,181.8’

**Spud:** 03/27/1960

**Completed:** 04/15/1960

**Cored:** No Cores

**Csg:** 8 5/8” @ 1,001’ w/ 450 sxs cmt  
5 1/2” @ 4,078’ w/ 150 sxs cmt

**TD:** Drlr - 4,099’ (Base of Black River formation – Pipe strap  
correction at TD – 4,099’ drlg depth = 4,087’ csg depth)  
Lgr - ’ ?? (Base of Black River formation)

**Bit Drop:** **4,098’ – 4,099’**  
Kelly dropped free for 6”, completely lost circ of drlg fluid, no  
blowback to surface, pumped fresh water into lost circ zone at rate  
of 3 bbls per min, well remained dead, ran 5 1/2” csg w/ formation  
packer shoe @ 4,078’ (Black River formation), regained circ above  
packer, cmtd w/ 150 sxs cmt

**DST:** **DST#1**  
3,760’ -3,951’, 1 hr 50 min, recovered 150’ gas & 45’ mud, no  
shows, ICIP – 86# in 15 min, FCIP – 86# in 1/2 hr  
**DST #2**  
3,255’ – 3,292’, 2 hrs, recovered 720’ mfresh water & 720’ salt  
water, ICIP – 835# in 30 mon, FCIP – 785# in 30 min

**Perfs:**

**IP:** FARO 720 BO in 24 hours through a 6/64” chk

**Current Status:** 08/08/2000 – P&A

**Stephens No. 1**  
**Aurora Gasoline and McClure Oil Company**  
**Drilling Contractor – McClure Oil Company**  
**(Rotary 0' – 3,769'; Cable Tool 3,769' – 3,772')**

**Field:** Exploratory – Oil & Gas – Scipio Field Confirmation - Trenton  
**API #:** 21-059-20676-00-00  
**Permit#:** 20676  
**Location:**  
**Township:** Scipio  
**County:** Hillsdale  
**Well:** SE SW NE Sec. 10, T5S R3W  
330' from south line, 990' from west line of quarter section  
**Datum:** GL - 1,018'  
**Logging Datum:** RKB – 1,030' (12' above GL)  
**Spud:** 08/13/1957  
**Completed:** 09/18/1957  
**Cored:** No Core  
**Csg:** 13 3/4" @ 57'  
8 5/8" @ 203' w/ 200 sxs cmt  
5 1/2" @ 3,756' w/ 550 sxs cmt  
**TD:** Drlr - 3,928'  
Lgr - 3,927'  
**Perfs:** Open Hole Completion  
**IP:** Lost Circulation @ 3,769 1/2' Blew out, Flowed out-of-control for 25 hours, FARO 100 BO per hour and 15-20,000 MCFG, Initial Production before acid - 165 BOPD restricted (State proration)  
**Reworked:** **10/11/1961 – 10/13/1961**  
Sqzd w/ 1,200 sxs cmt,  
CO to 3,928' - New TD, perfd 3,834' – 3,867' w/ 92 shots, treated w/ 250 gal mud acid and 250 gals regular acid, FARO 36 MCFGPD  
**10/30/1962 – 11/09/1962**  
Sqzd w/ 2,400 sxs cmt, CO to 3,875', perfd 3,859' -3,867' w/ 32 shots, treated w/ 500 gals regular acid, swbd, FARO 5 bbls oil and 80 bbls water / 12 hours, Sqzd w/ 4,185 sxs cmt, cmt job failed, POP as gas well, CP 800#, TP 1,000#  
**09/28/1964 – 10/06/1964**  
CO to TD (3,928'), Deepened to 3,930' – New TD, treated w/ 2000 gals acid, recovered gas, sqzd twice, Deepened to 3,953' New TD, set pkr, treated w/ 2000 gals acid at 2,953' - 3,926', no results, perfd 3,736' – 3,740' w/ 16 shots, Gauged 150 MCFGPD  
**Current Status:** 09/11/1992 – P&A completed

**VANWERT #1**  
**McClure Oil Company**  
**Drilling Contractor – McClure Drilling Corporation**  
**(Rotary 0' – 4,000', Cable Tool 4,000' – 4,021')**

**Field:** Exploratory Extension - Scipio Field – Oil – Black River formation  
**API #:** 21-059-21751-00-00  
**Permit#:** 21751  
**Location:**  
**Township:** Adams  
**County:** Hillsdale  
**Well:** SE SE SE Sec. 8, T6S – R2W  
330' from south line, 430' from east line of quarter section  
**Datum:** GL -  
**Logging Datum:** RKB – 1,153' above SL  
**Spud:** 08/04/1959  
**Completed:** 09/09/1959  
**Cored:** No Cores  
**Csg:** 8 5/8" @ 366' w/ 300 sxs cmt  
5 1/2" @ 4,000' w/ 185 sxs cmt  
**TD:** Drlr - 4,021' (Black River formation)  
Lgr - (Black River formation)  
**PBTD:** 3,996'  
Well reported making "some" bottom hole water  
Plugged Back 4,022' – 4,007' with gravel  
Plugged Back 4,007' – 3,996' with lead wool  
**DST:** DST #1  
3,873' – 3,921', open 40 min, recovered gas to surface in  
4 1/2 min, recovered OCM in 15 min, flowed oil in 33 min,  
"lots" of gas, IBHP - 1,574#, FBHP - 1,548# in 30 min,  
IFP - 934#, FFP - 960#  
DST #2  
3,949' – 4,000', open 90 min, recovered gas to surface in 3  
min, flowed oil in 23 min, flowed 50 bbls oil to tanks in 1  
hour, IBHP - 1,574# in 30 min, FBHP – 1,560# in 30 min,  
IHMP – 1,872#, FHMP 1,872#, IFP – 338#, FFP – 418#  
**Perfs:** 09/11/1959 – perfd 3,984' – 3,990' w/ 24 shots  
(Black River formation)  
**IP:** Before Acid – FARO 50 BO per hour on DST,  
After Acid - FARO 720 BOPD  
09/14/1959 – Treated 3,984' – 3,990' w/ 500 gals Mud Acid,  
FARO 30 BO per hour  
**Reworked:** 02/21/1965 – 04/05/1965

Present TD – 3,998', Sqzd perfs 3,984' – 3,990' w/ 100 sxs cmt (02/14/1965), sqzd perfs again w/ 200 sxs cmt (02/15/1965), shut down 24 hrs, 500 bbls fluid - 50% oil, treated w/ 2000 gals 15% acid, swbd So & Gas, 50# Pressure, Pumped 30 – 35 BOPD

**09/20/1967 – 09/26/1967**

Perfd 3,920' – 3,936' w/ 12 shots, acidized, IPP 6 BOPD

**05/08/1968**

Perfd 3,920' – 3,936' w/ 12 shots, treated w/ 750 gals 15% acid, IPP 6 BOPD

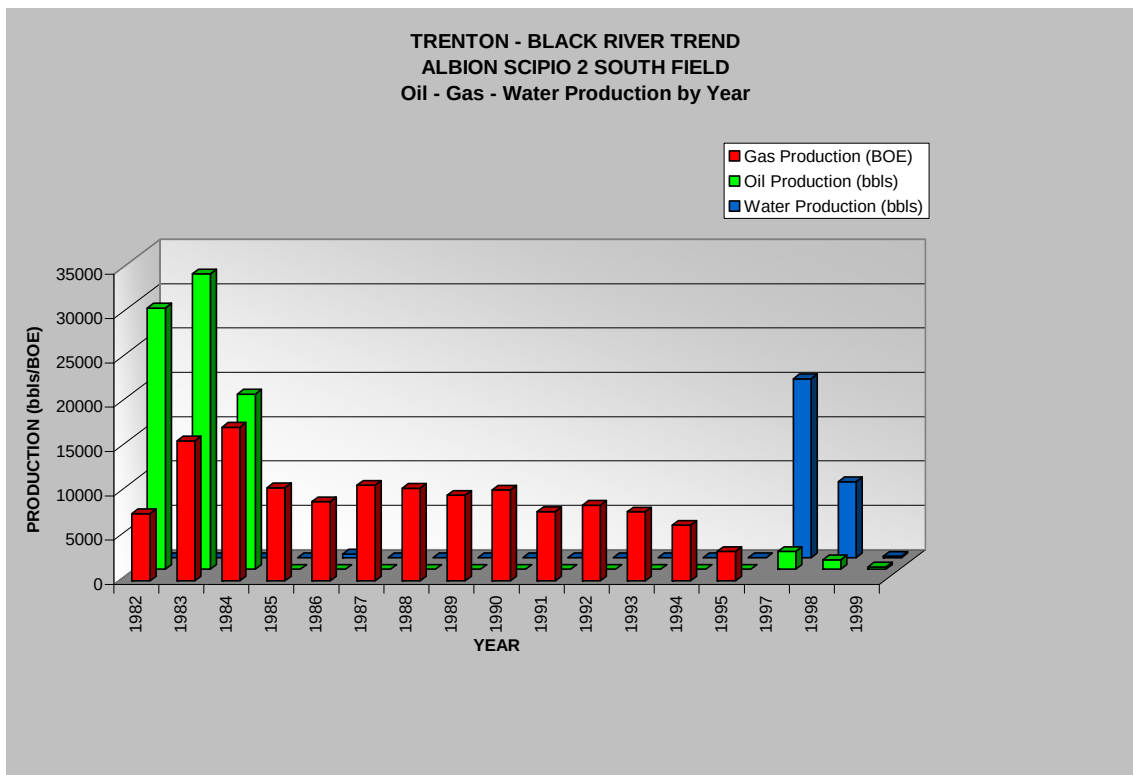
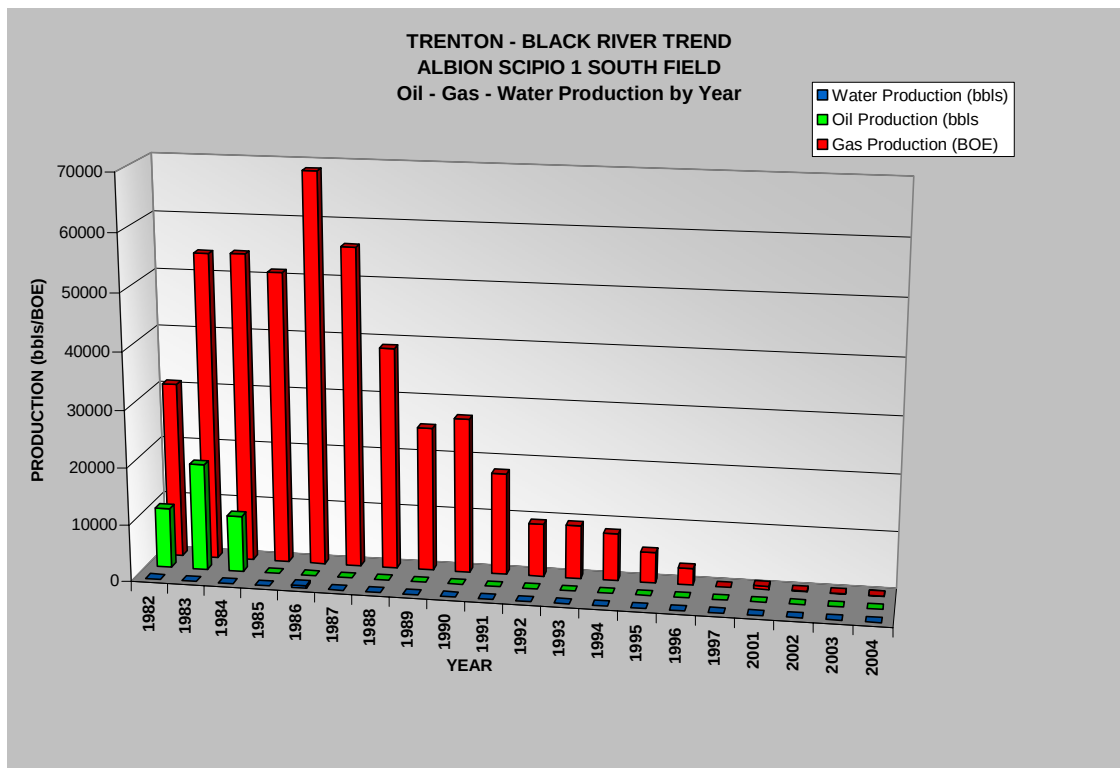
**Current Status:**

08/26/1967 – 09/01/1967 - To Patrick Petroleum Company

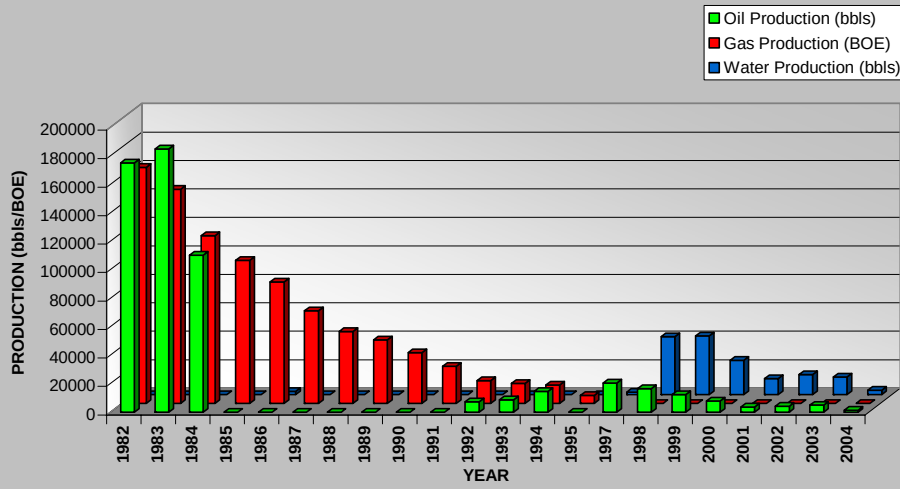
07/.25/1969 – P&A complete

**WINTER No. 1**  
**McClure Oil Company and Perry Fulk**  
**Drilling Contractor – McClure Drilling Corporation**  
**(Rotary 0' – 4,236', Cable Tool 4,236' – 4,242')**

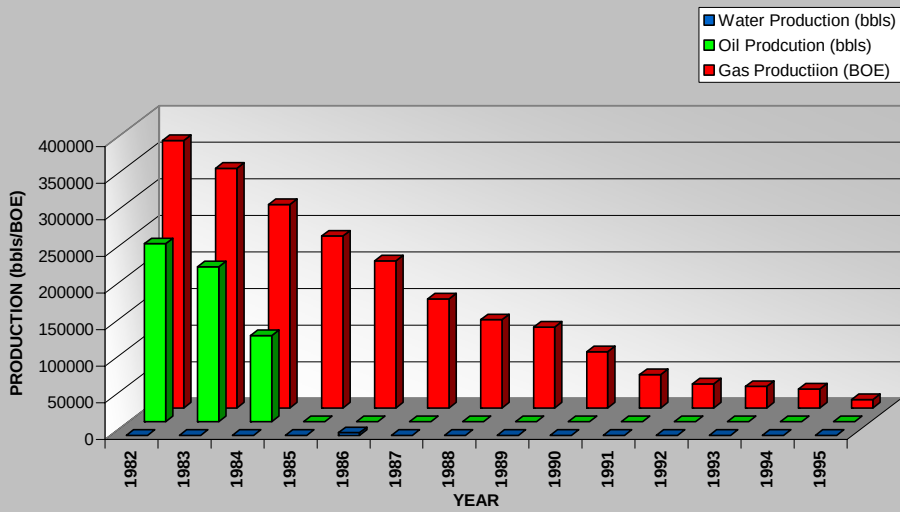
**Field:** Exporatory Extension – Albion Field – Oil - Trenton  
**API #:** 21-025-22205-00-00  
**Permit#:** 22205  
**Location:**  
**Township:** Sheridan  
**County:** Calhoun  
**Well:** NW NE NE Sec. 19, T2S – R4W  
330' from line, 990' from east line of quarter section  
**Datum:** GL - elevation 968.3'  
**Logging Datum:** RKB – 980.1' (1.6' above Rig Floor – 978.5')  
**Spud:** 03/13/1960  
**Completed:** 05/19/1960  
**Cored:** No Cores  
**DST:** (Preliminary Report – Lost Circulation 4,185' – 4,194')  
DST 4,179' – 4,236' (Trenton formation), open 30 min, recovered  
gas to surface in 3 min, mud in 4 min, oil in 7 min, flowed oil for  
14 min, ICIP - 1,806#, FCIP - 1,806# in 30 min, IFP – 1,520#,  
FFP – 1,700#, IHMP – 2,000#, FHMP – 2,000#  
**Csg:** 9 5/8" @ 1,005' w/ 590 sxs cmt  
5 1/2" @ 4,236' (TD) w/ 135 sxs cmt  
**TD:** Drlr - 4,236' (Rat hole ? to 4,242')  
Lgr - 4,229'  
**Deepened TD:** 4,242'  
**Perfs:**  
**IP:** Before Acid – FARO 30 BO per hour,  
After acid – FARO 40 BO in 1 hr 15 min  
(Preliminary Report – FARO 102 BO in 1 hr on 3/4" choke)  
5/24/1960 – treated 4,232' – 4,242' (deepened TD) w/ 500 gals  
mud acid, FARO 150 BOPD  
**Current Status:** 07/31/1980 – P&A complete



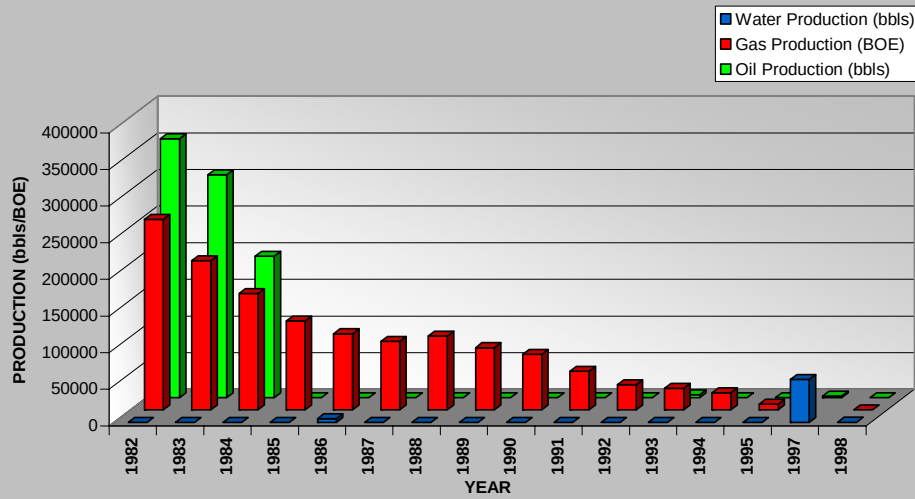
**TRENTON - BLACK RIVER TREND**  
**ALBION SCIPIO 3 SOUTH FIELD**  
 Oil - Gas - Water Production by Year



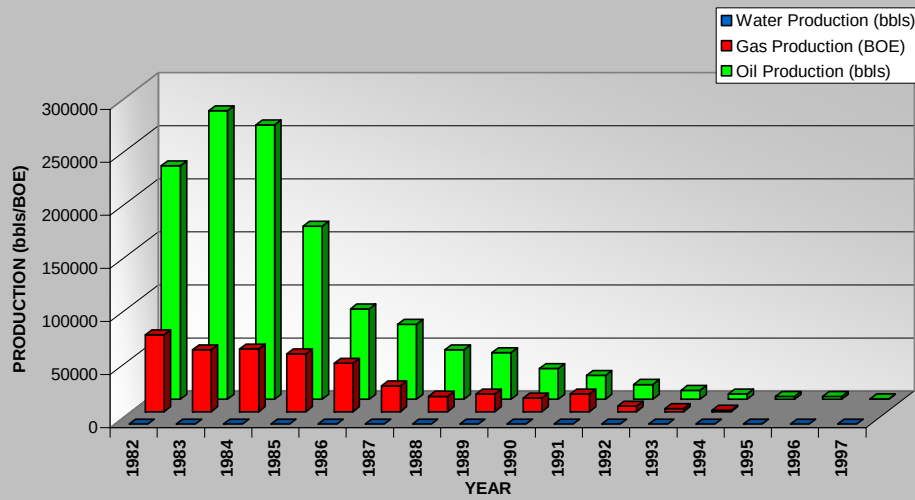
**TRENTON - BLACK RIVER TREND**  
**ALBION SCIPIO 4 SOUTH FIELD**  
 Oil - Gas - Water Production by Year (1982 - 1995)



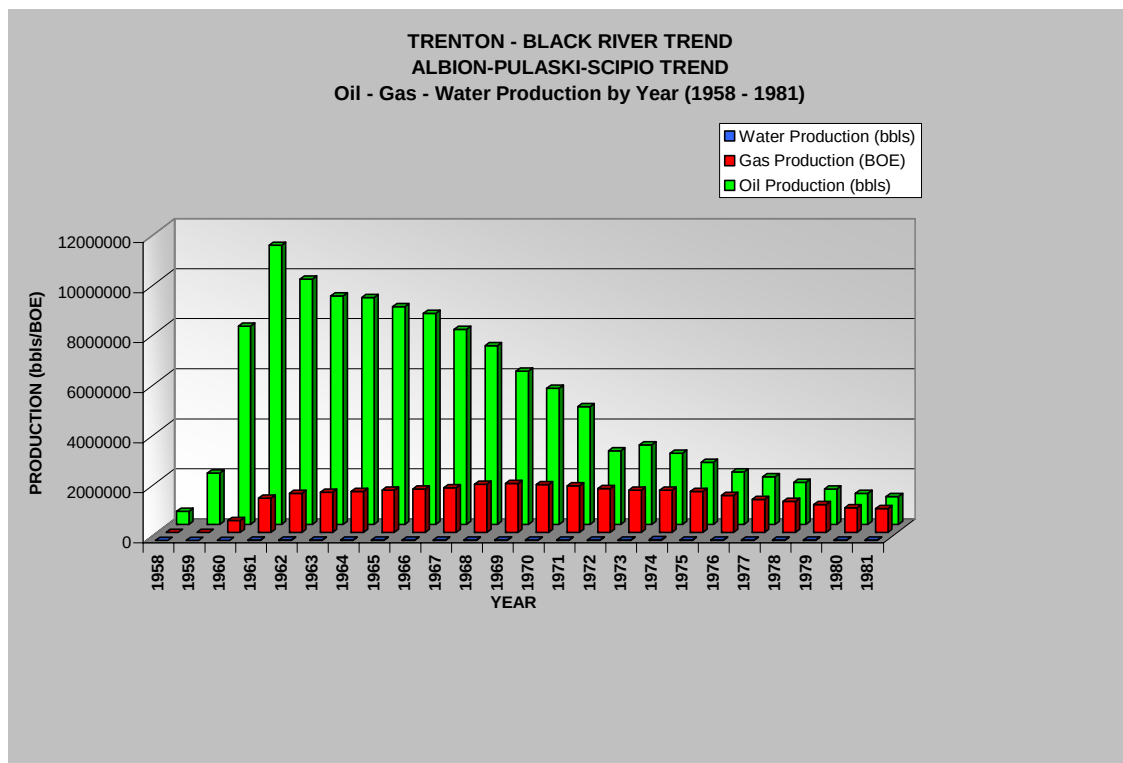
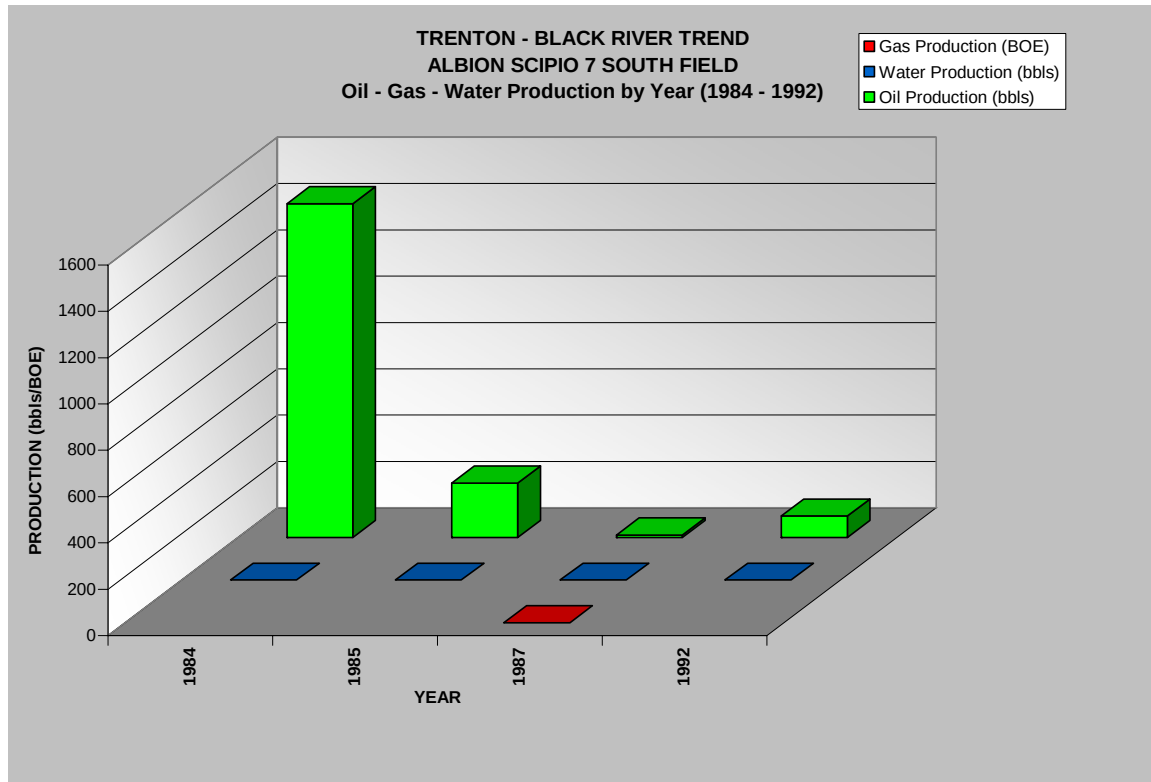
**TRENTON - BLACK RIVER TREND**  
**ALBION SCIPIO 5 SOUTH FIELD**  
**Oil - Gas - Water Production by Year (1982 - 1998)**

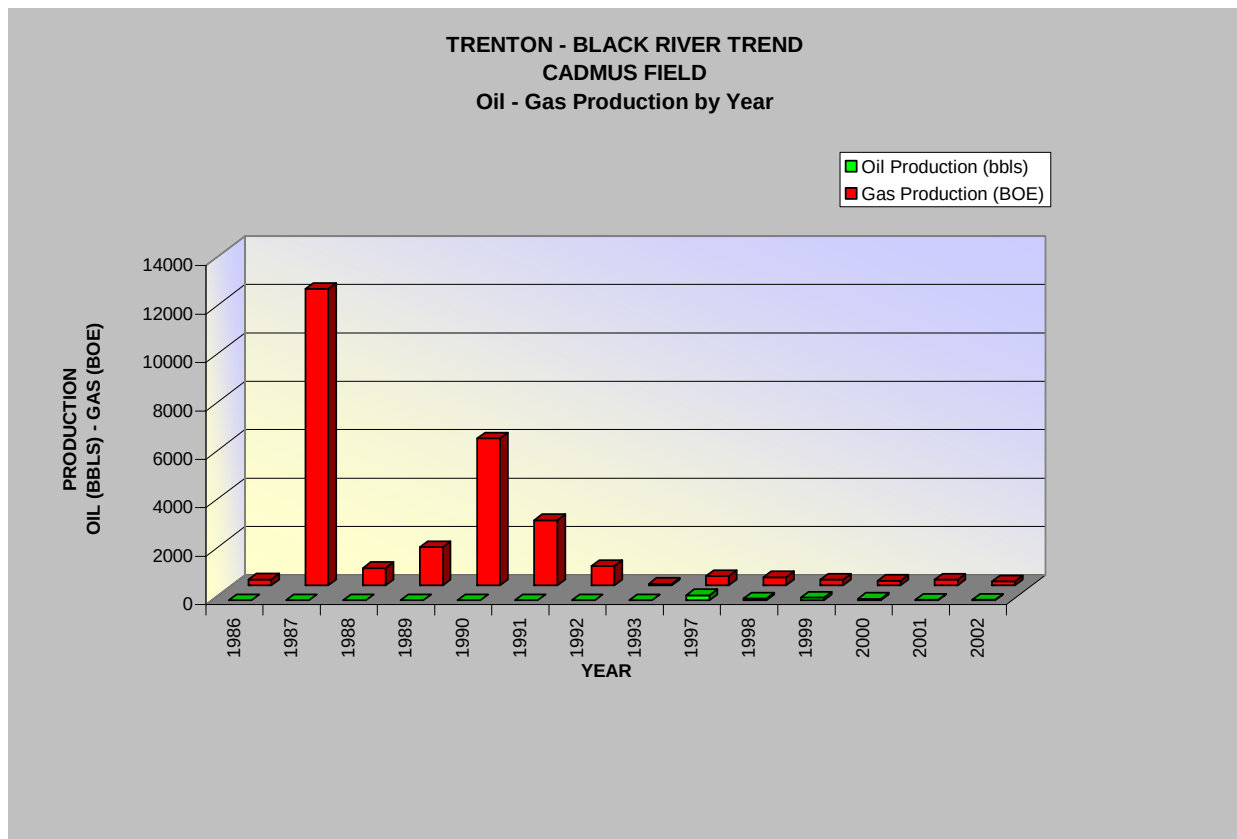
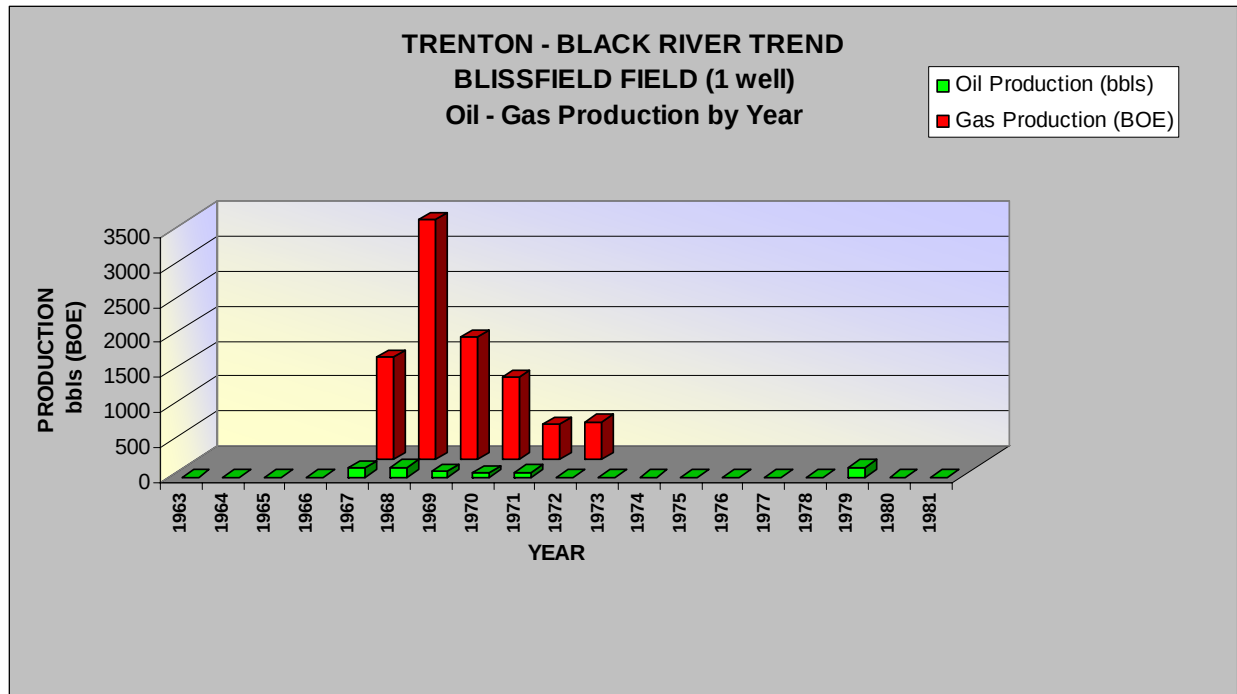


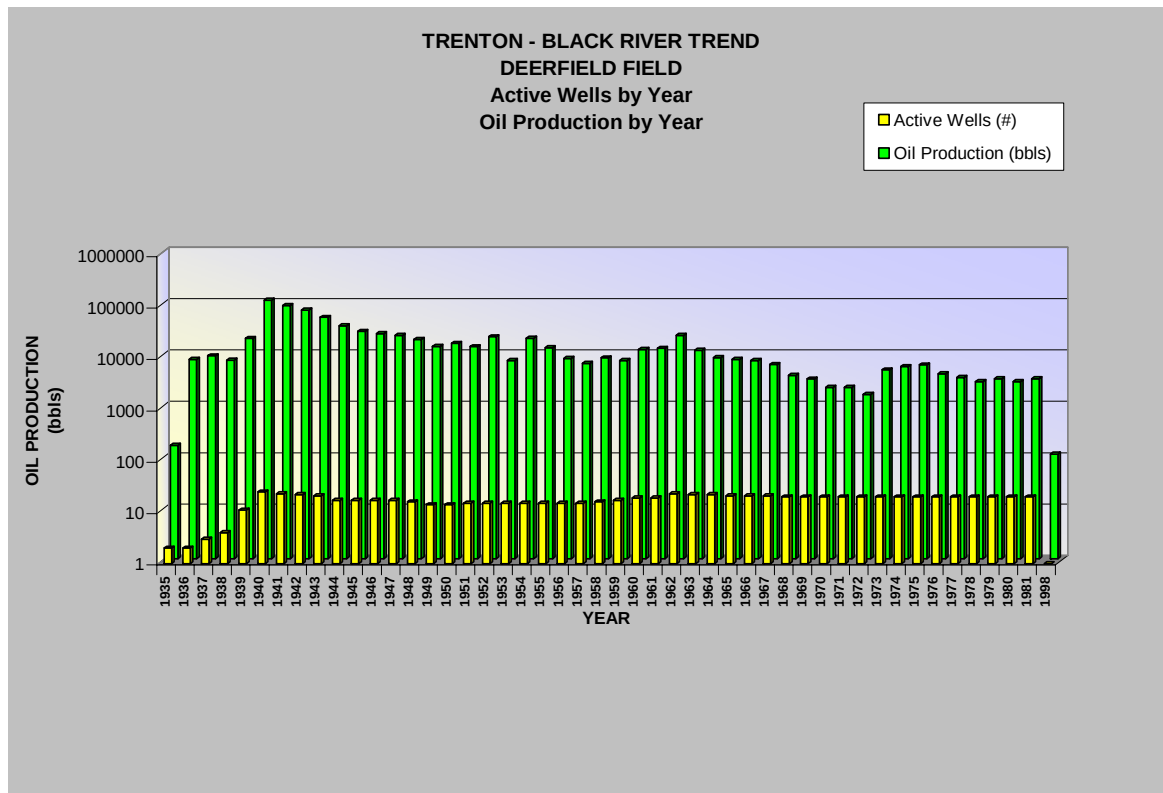
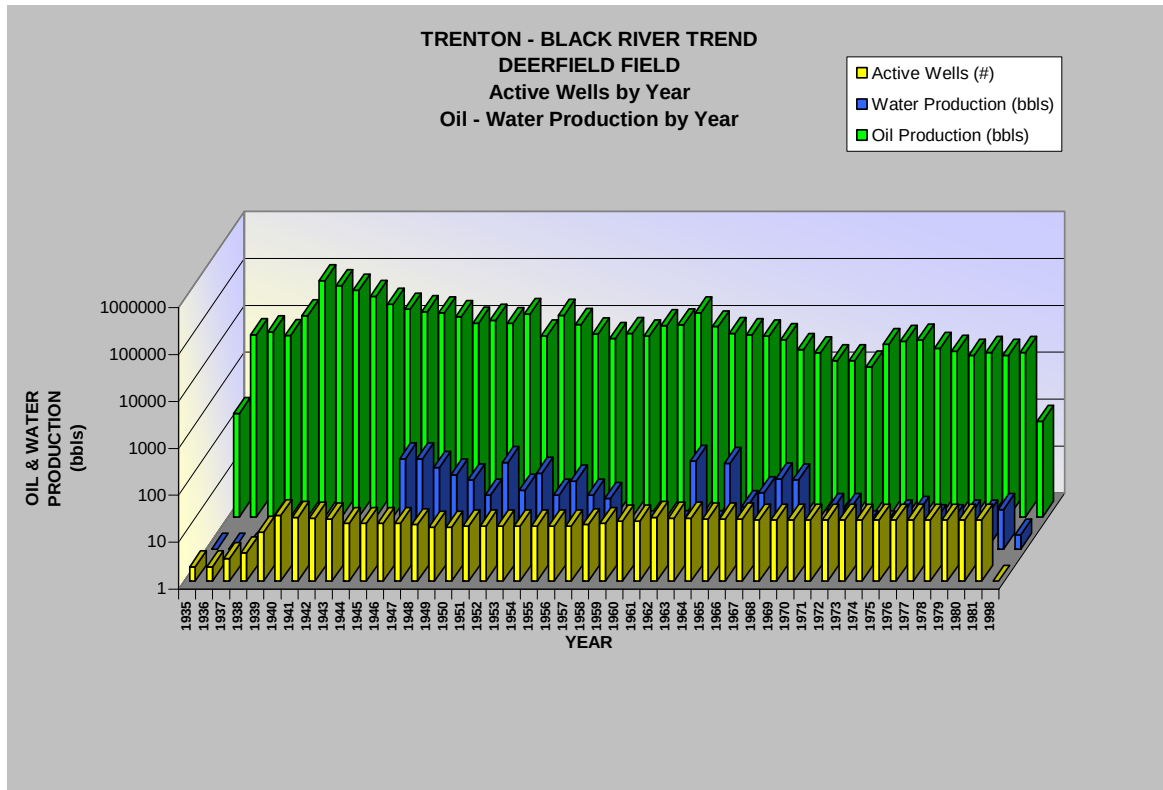
**TRENTON - BLACK RIVER TREND**  
**ALBION SCIPIO 6 SOUTH FIELD**  
**Oil - Gas - Water Production by Year (1982 - 1996)**

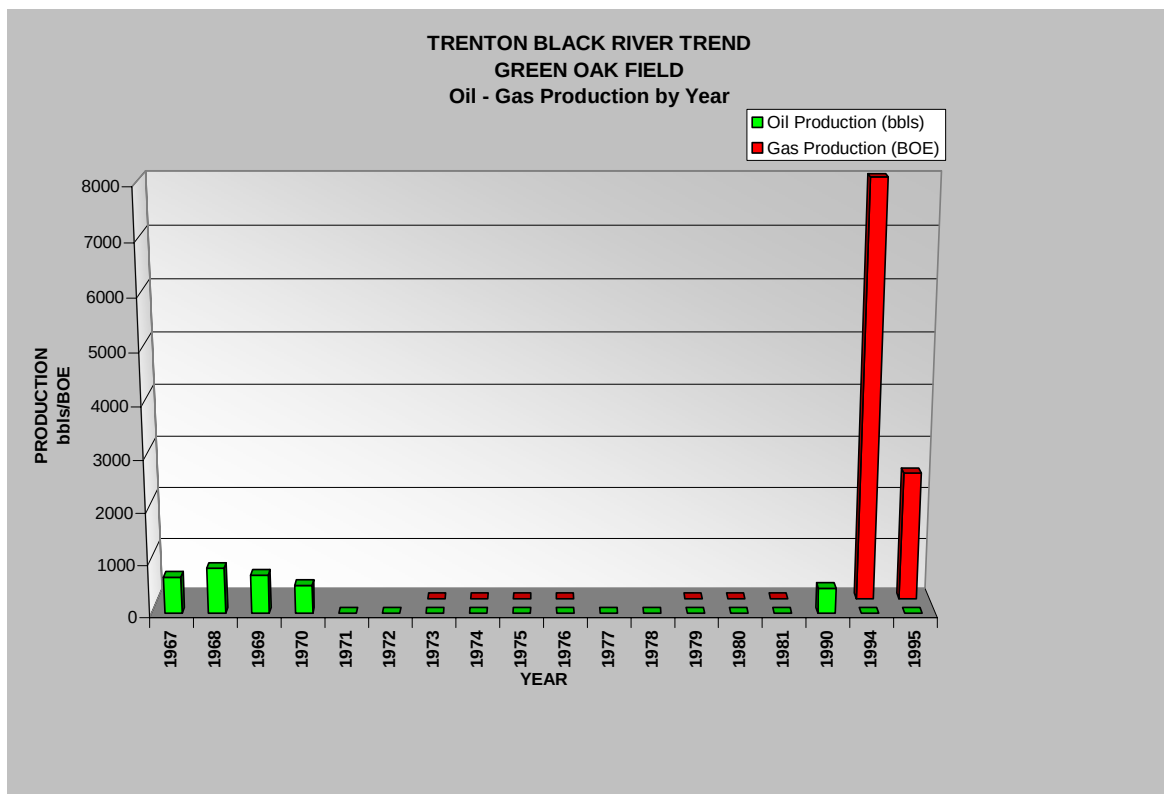
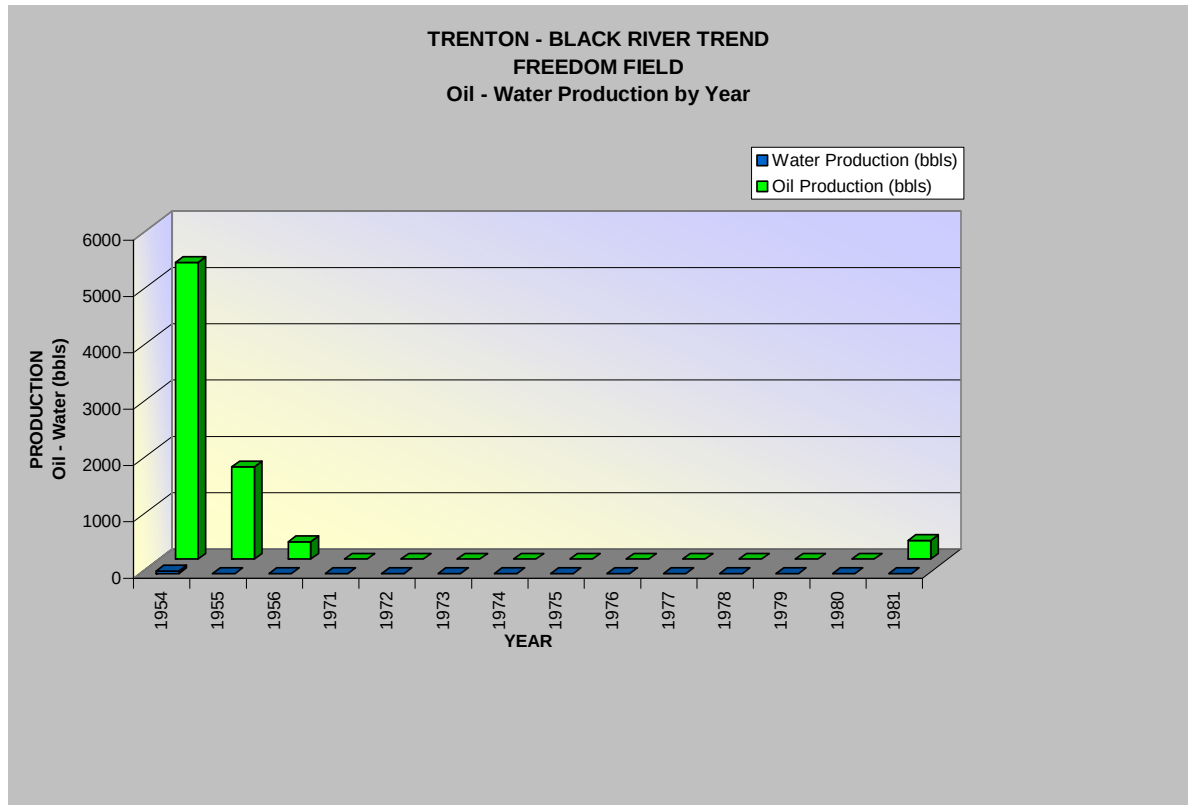


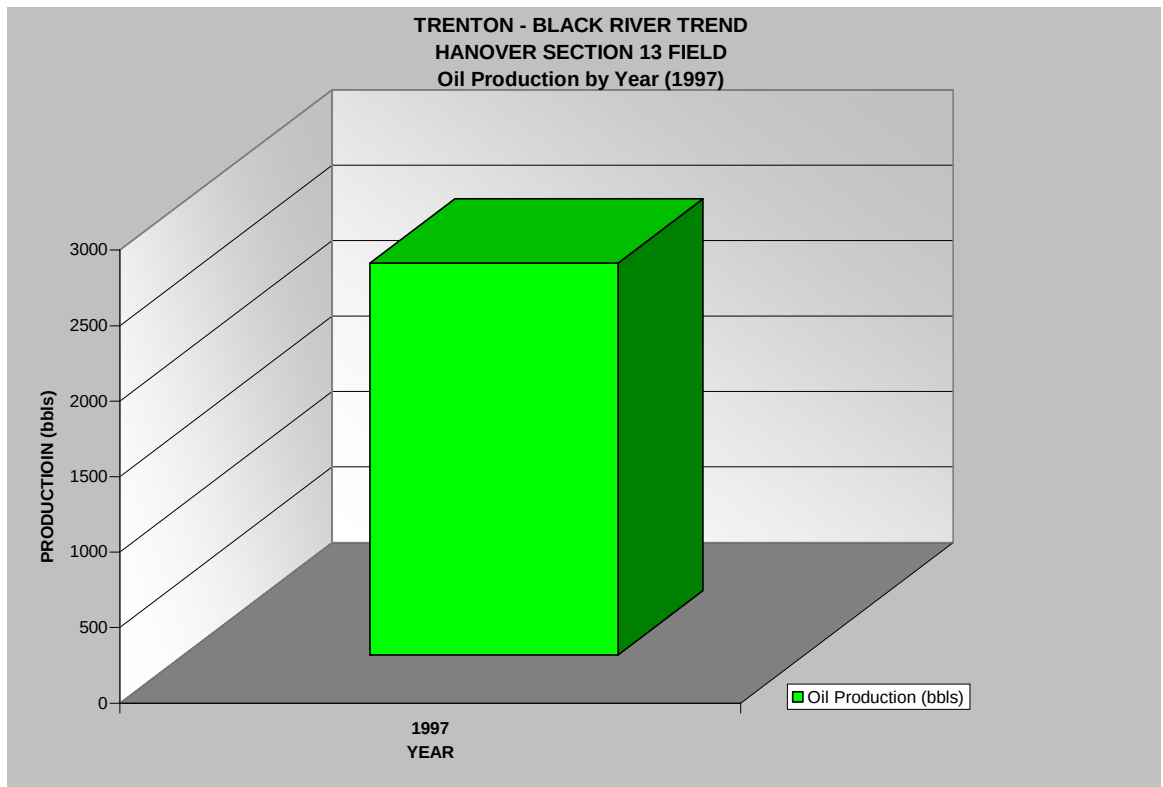
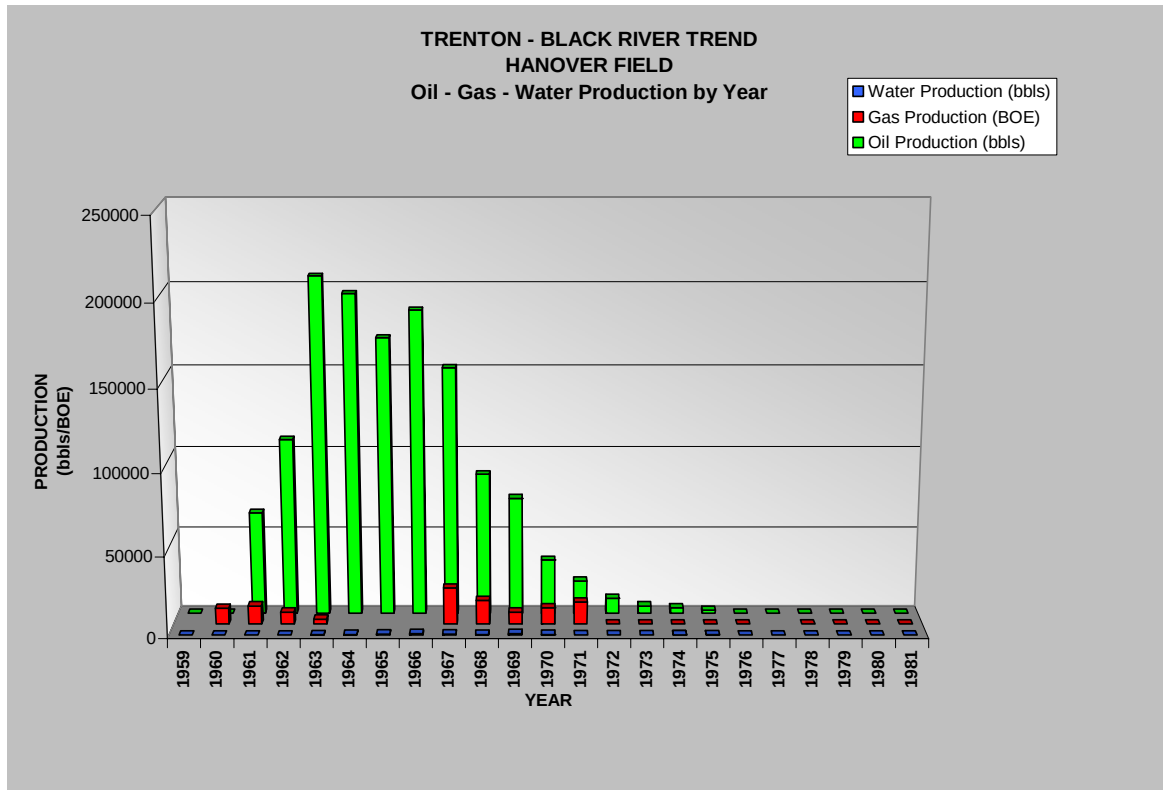


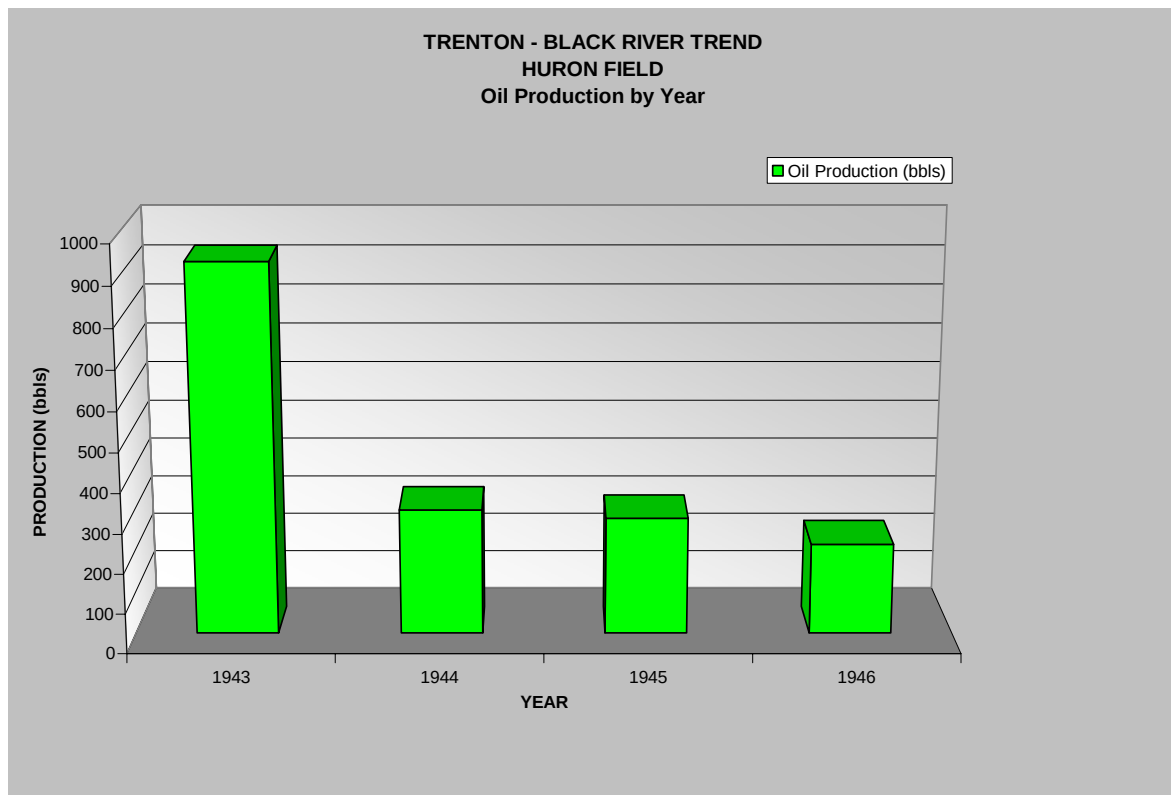
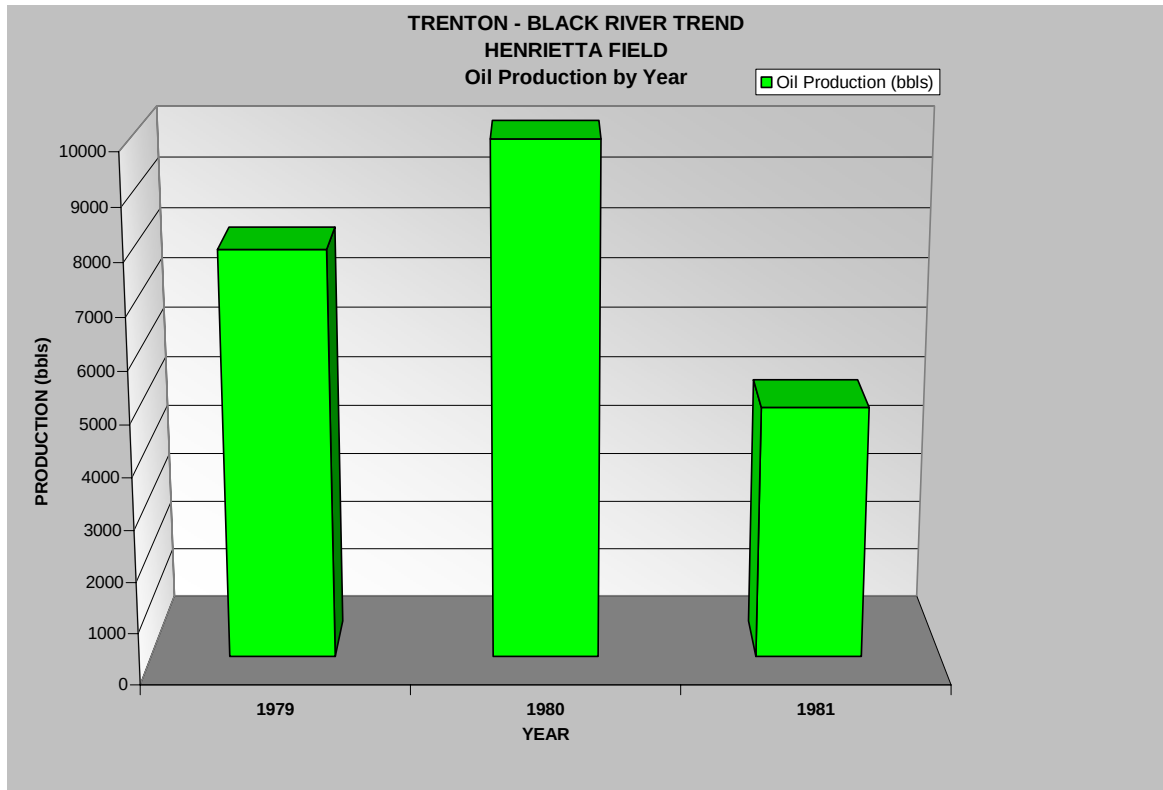


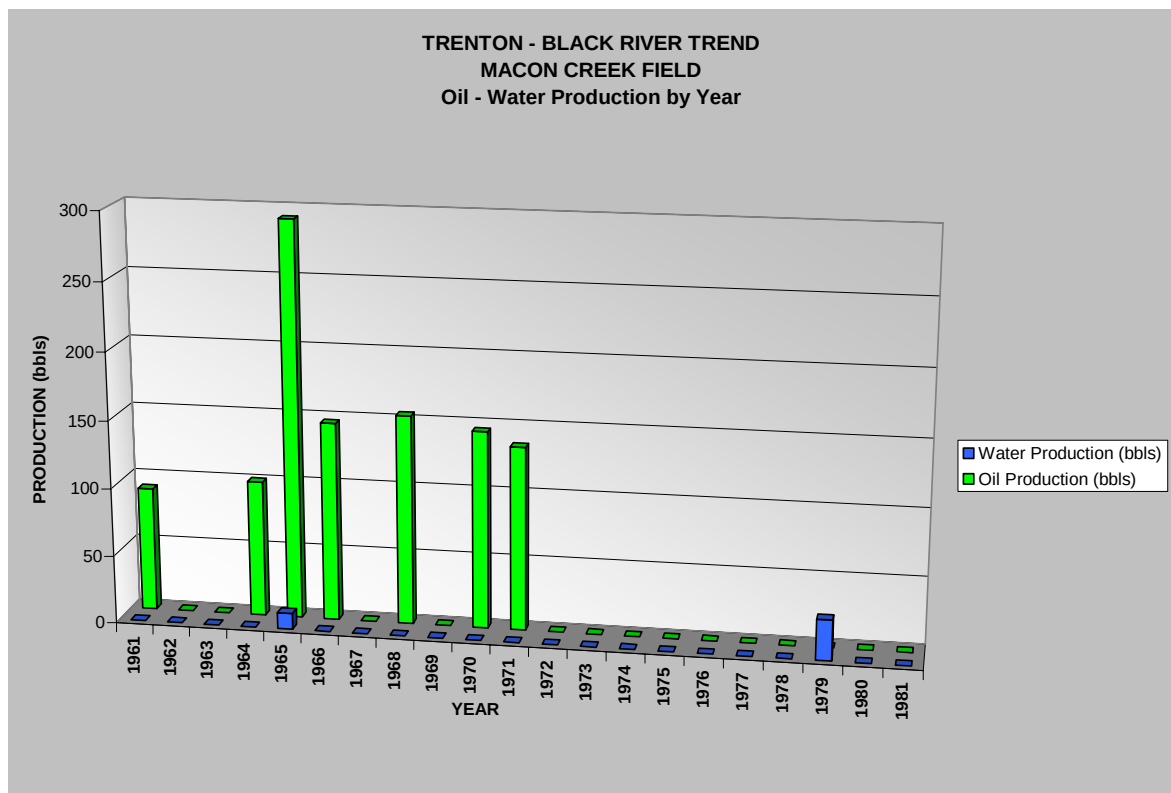
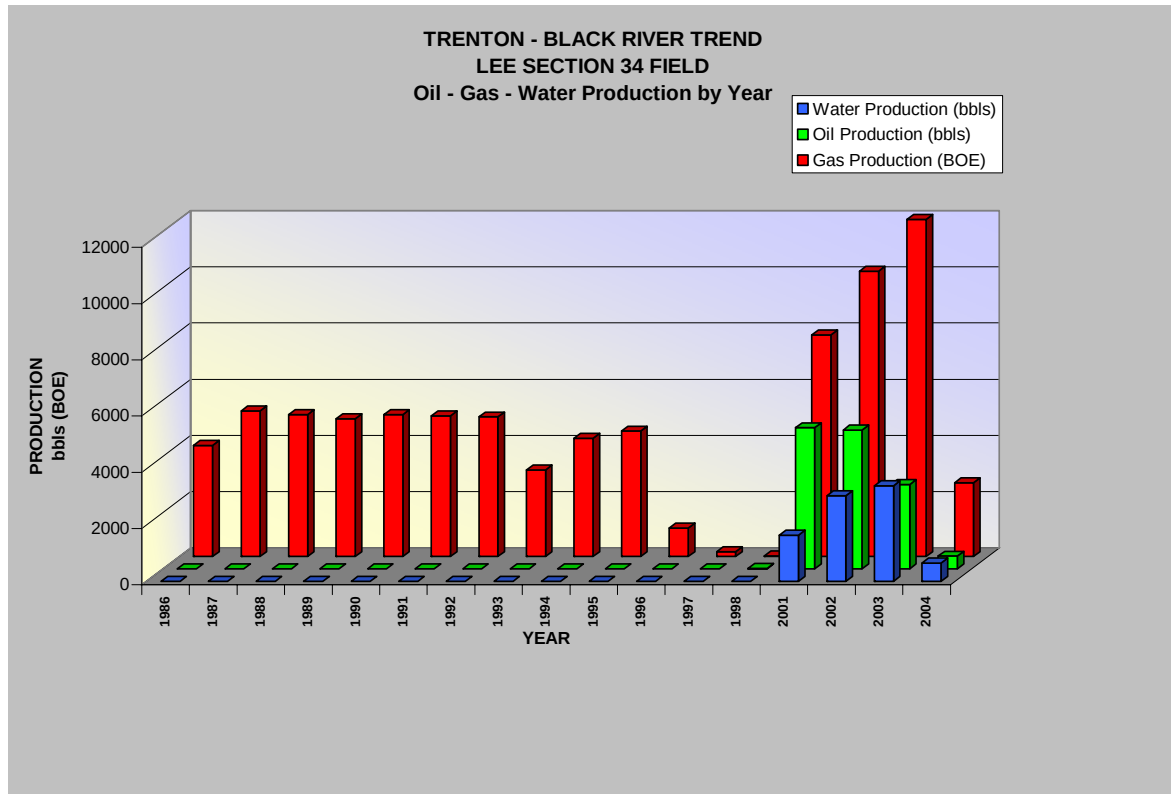


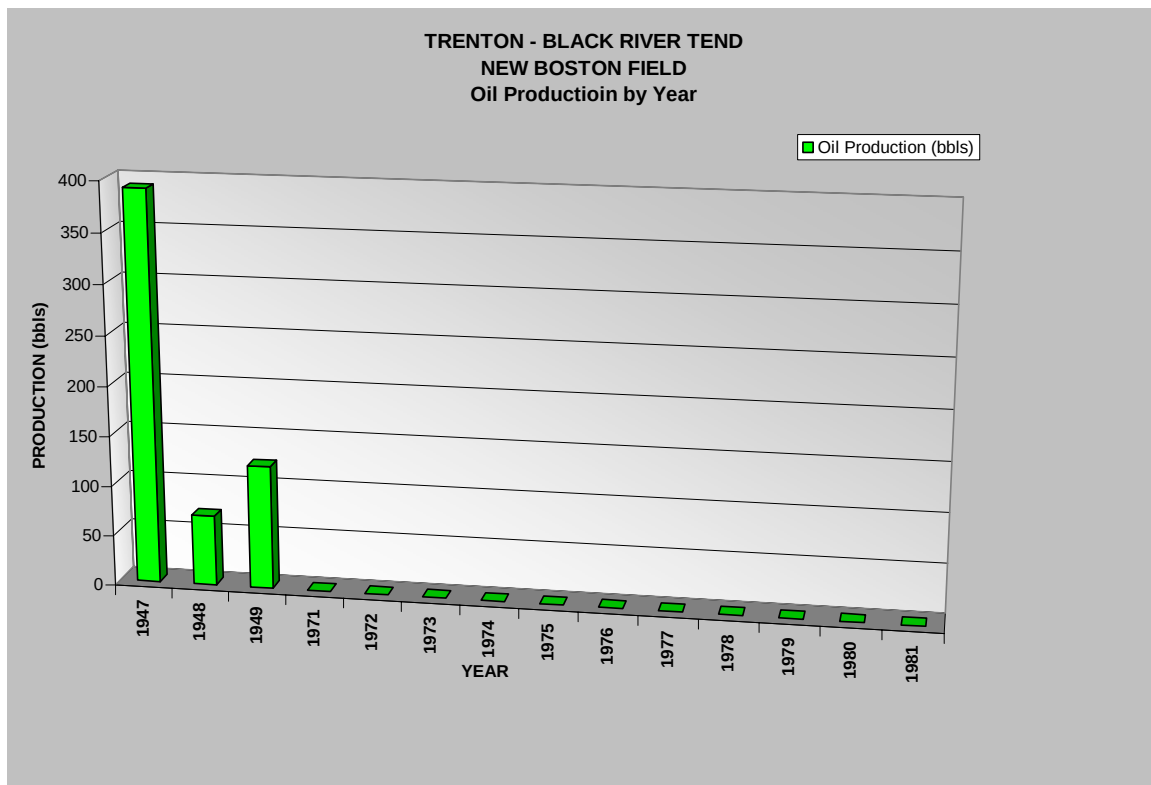
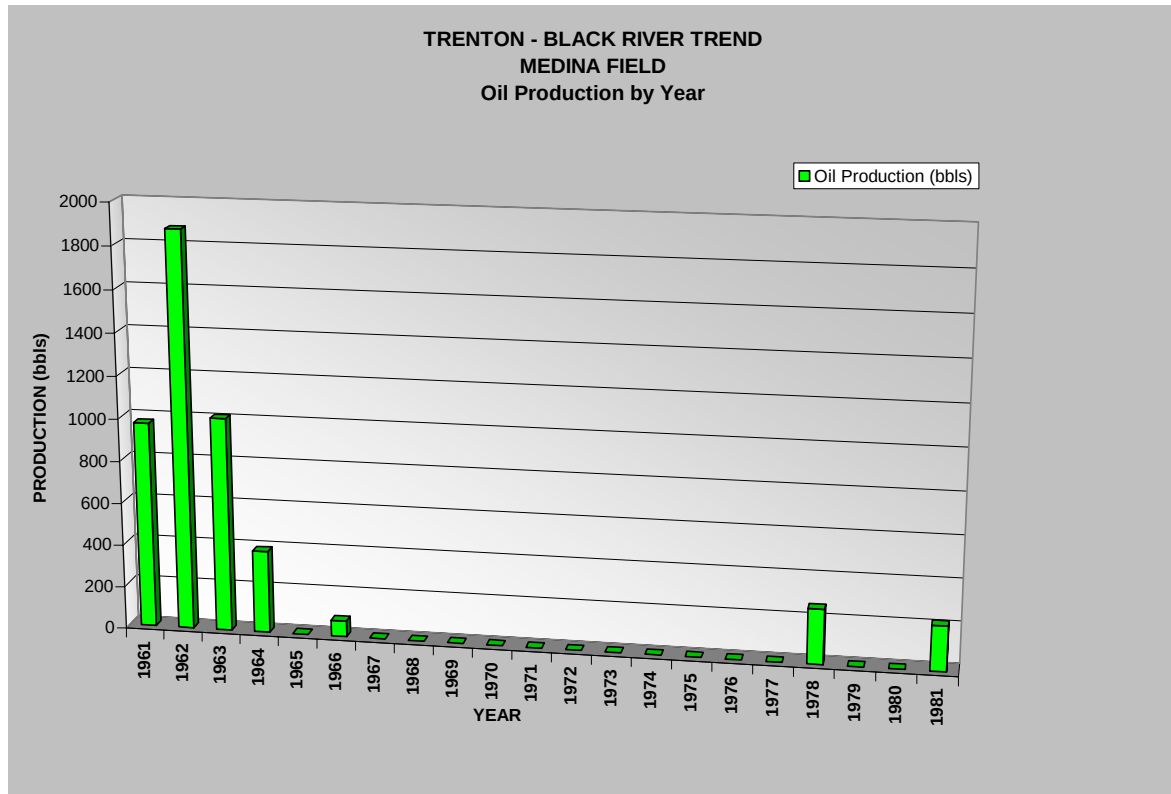




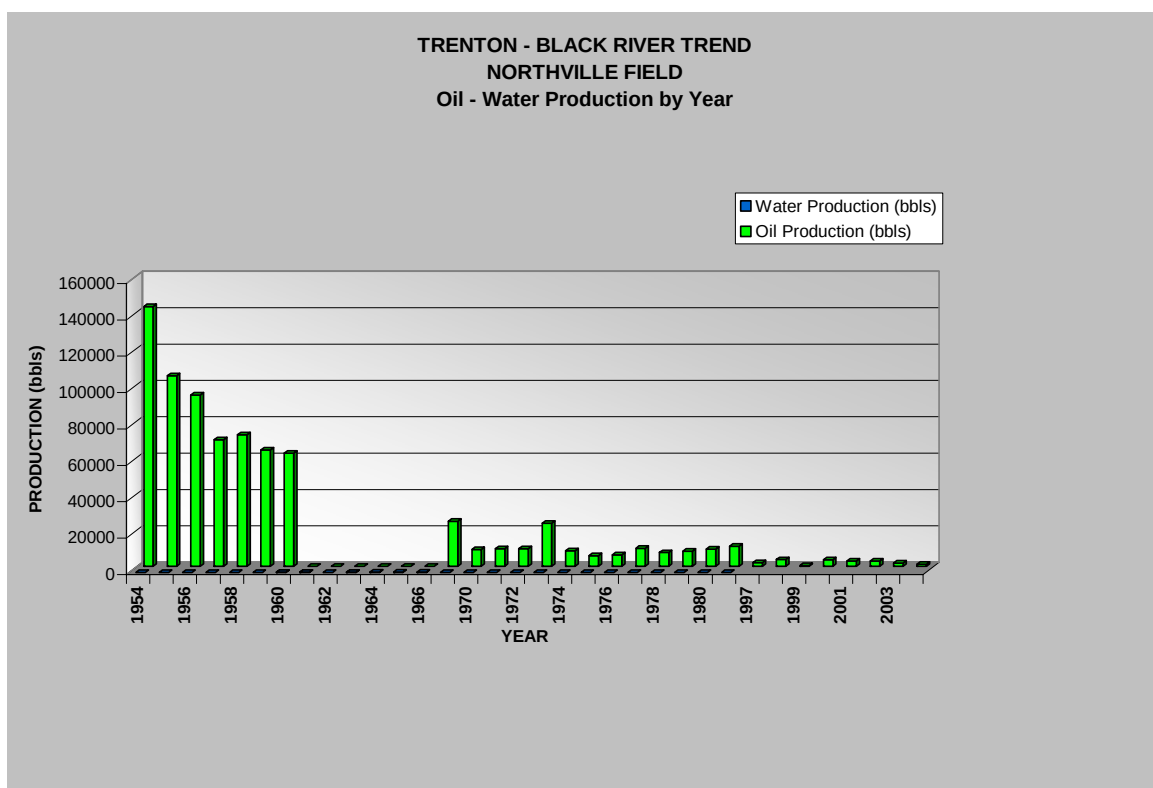
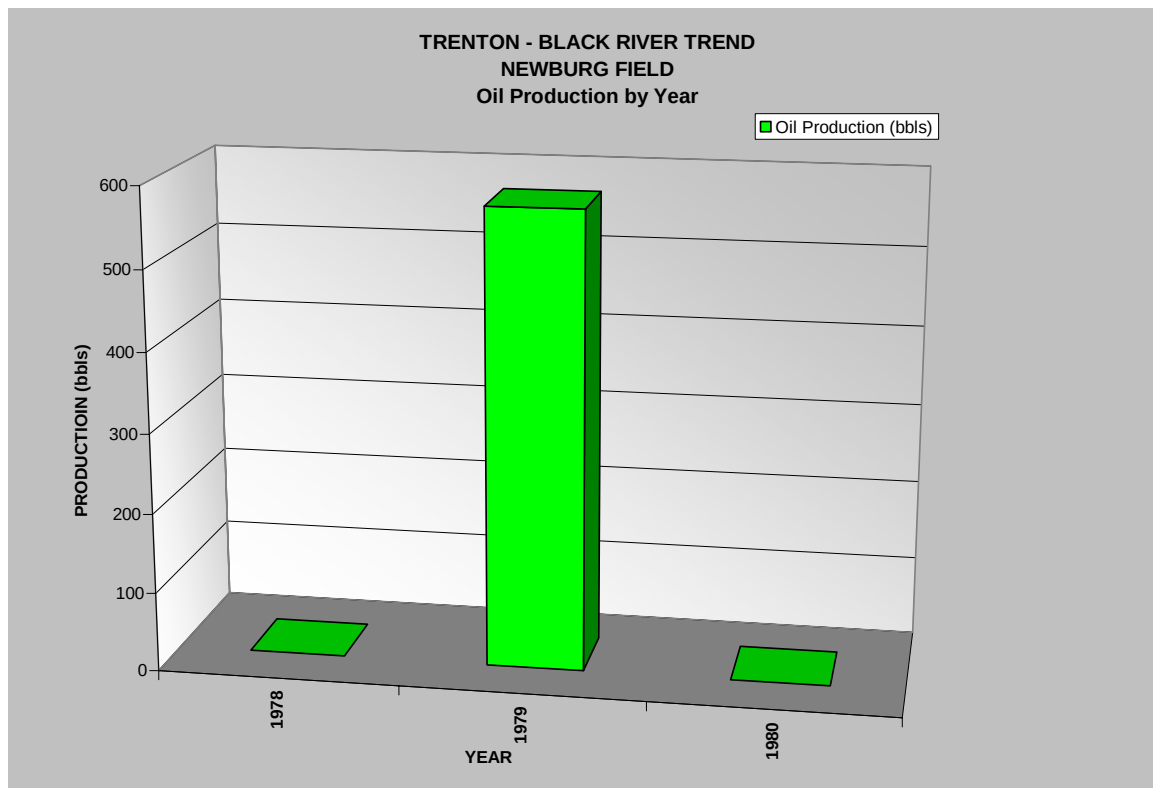


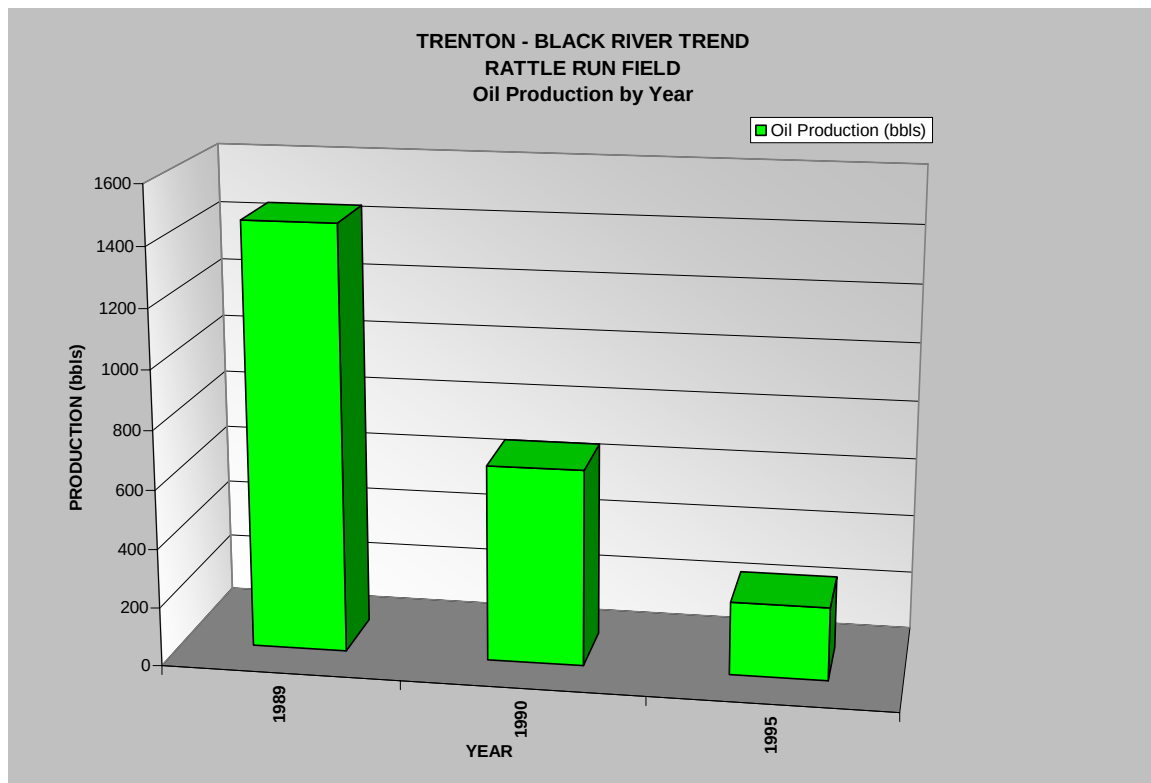
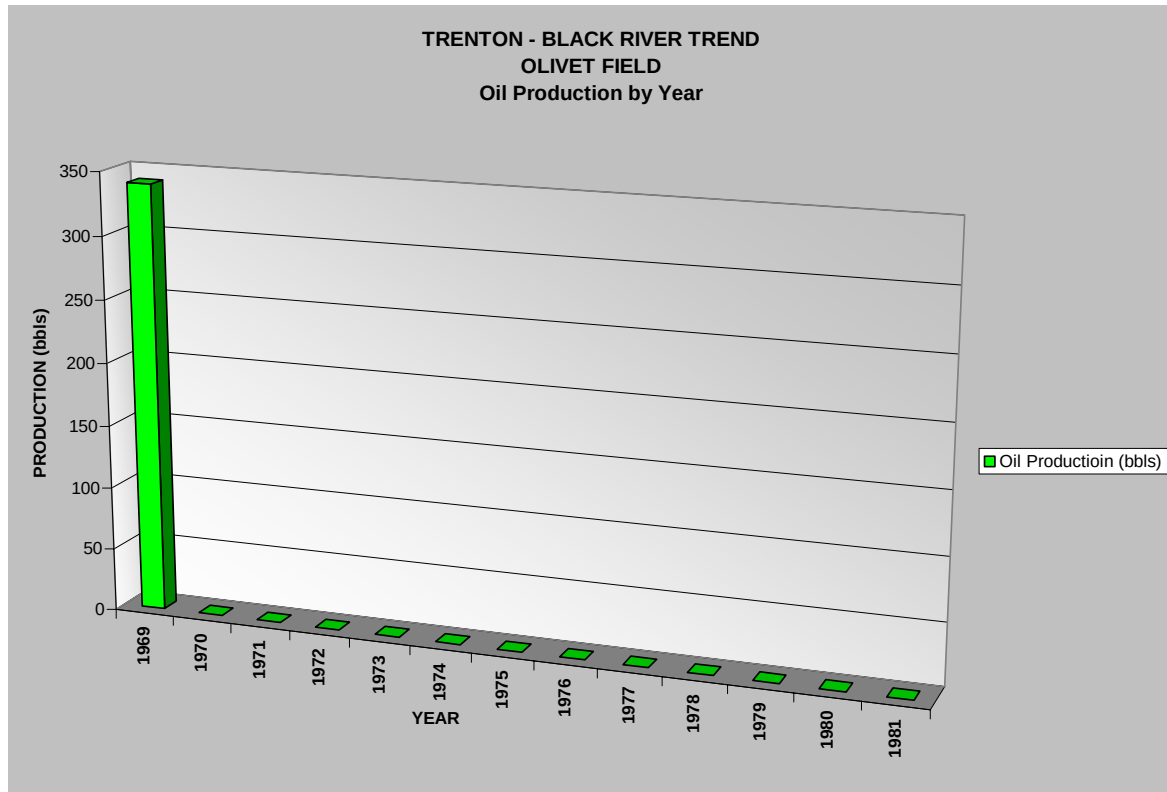


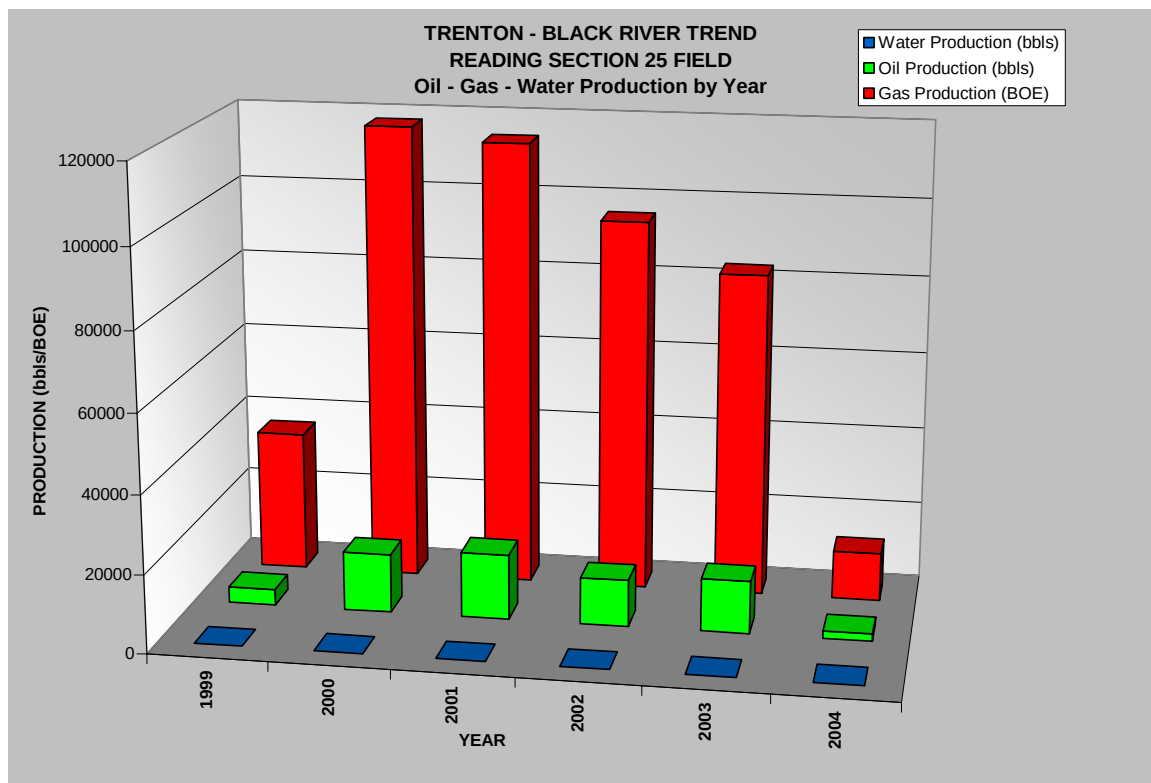
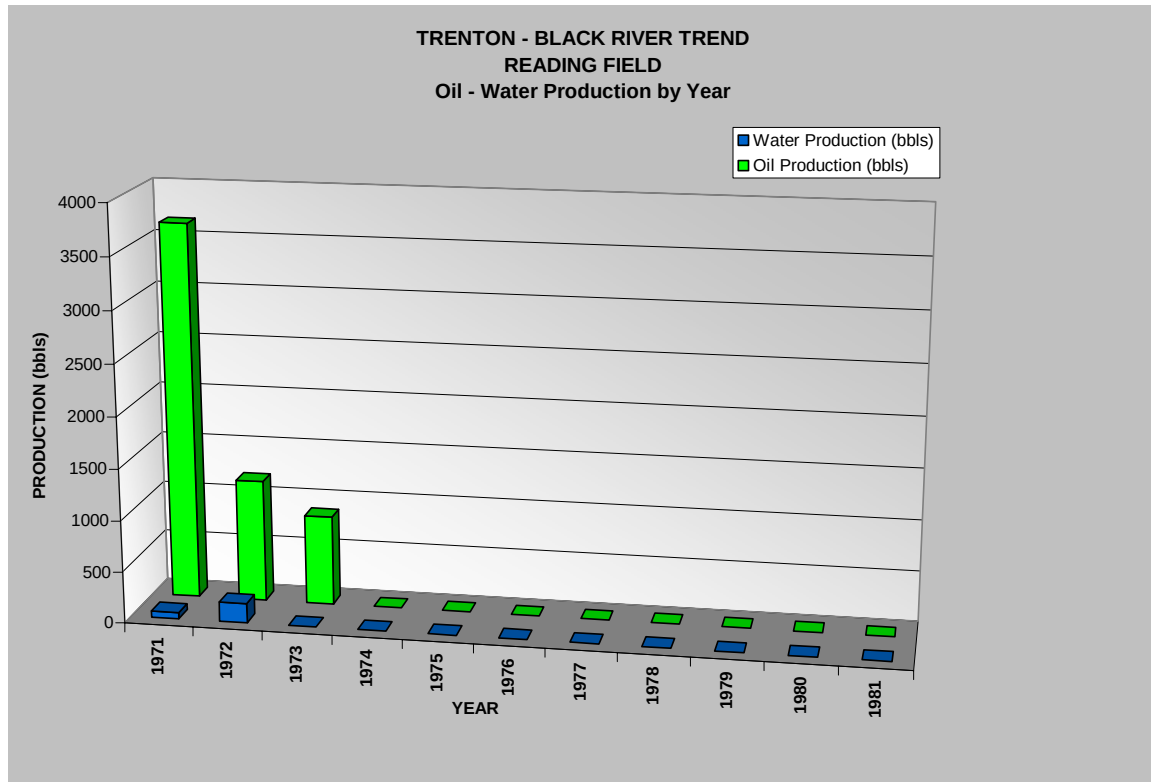




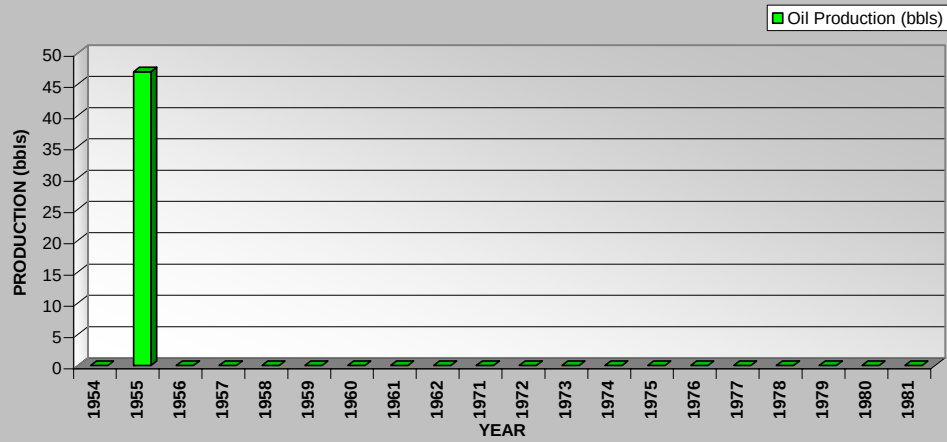




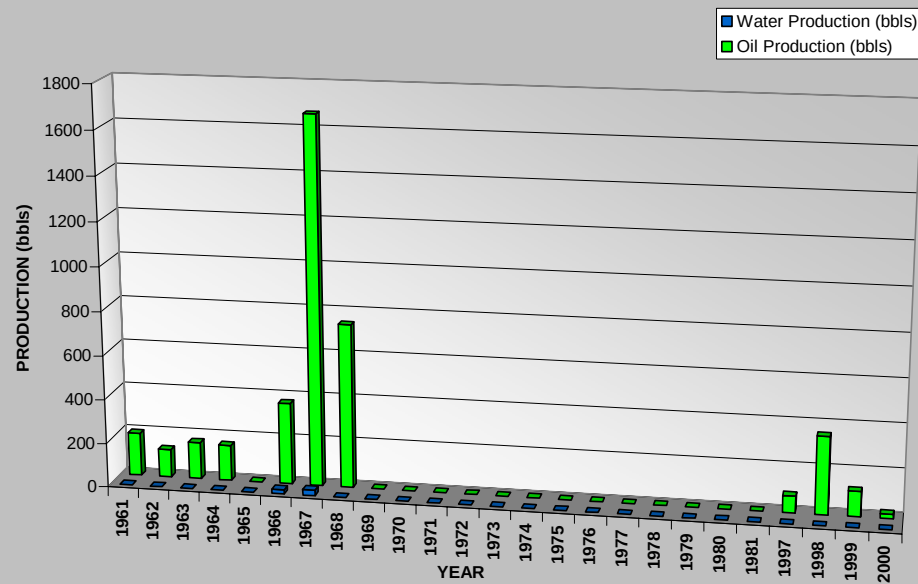




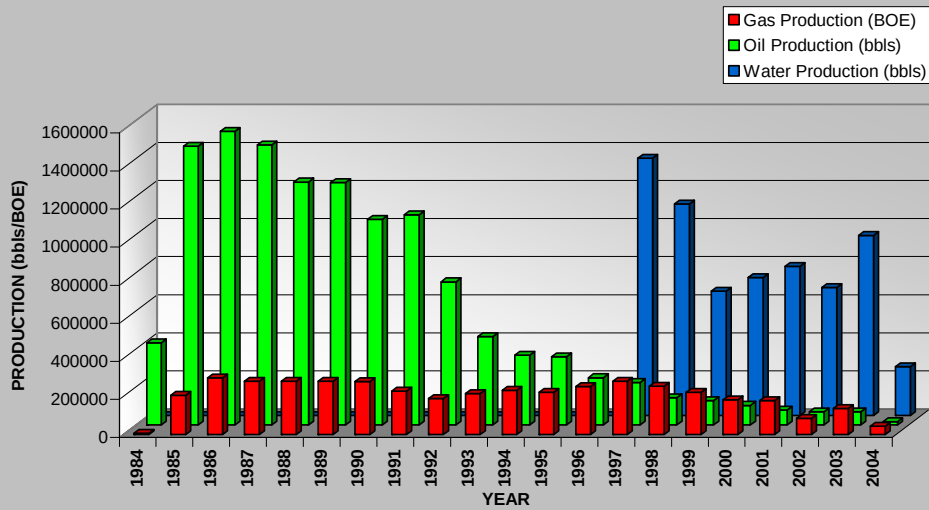
**TRENTON - BLACK RIVER TREND  
RIDGEWAY SECTION 1 FIELD  
Oil Production by Year**



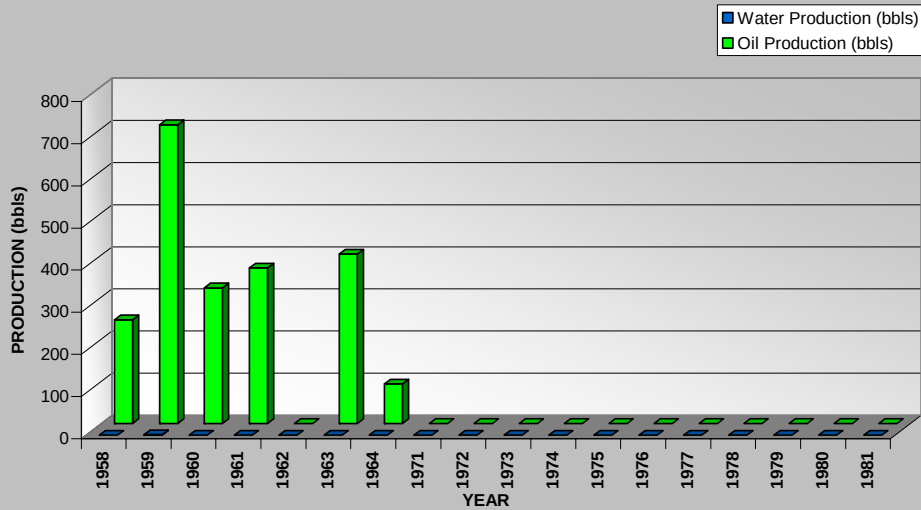
**TRENTON - BLACK RIVER TREND  
SPRINGPORT FIELD  
Oil - Water Production by Year**

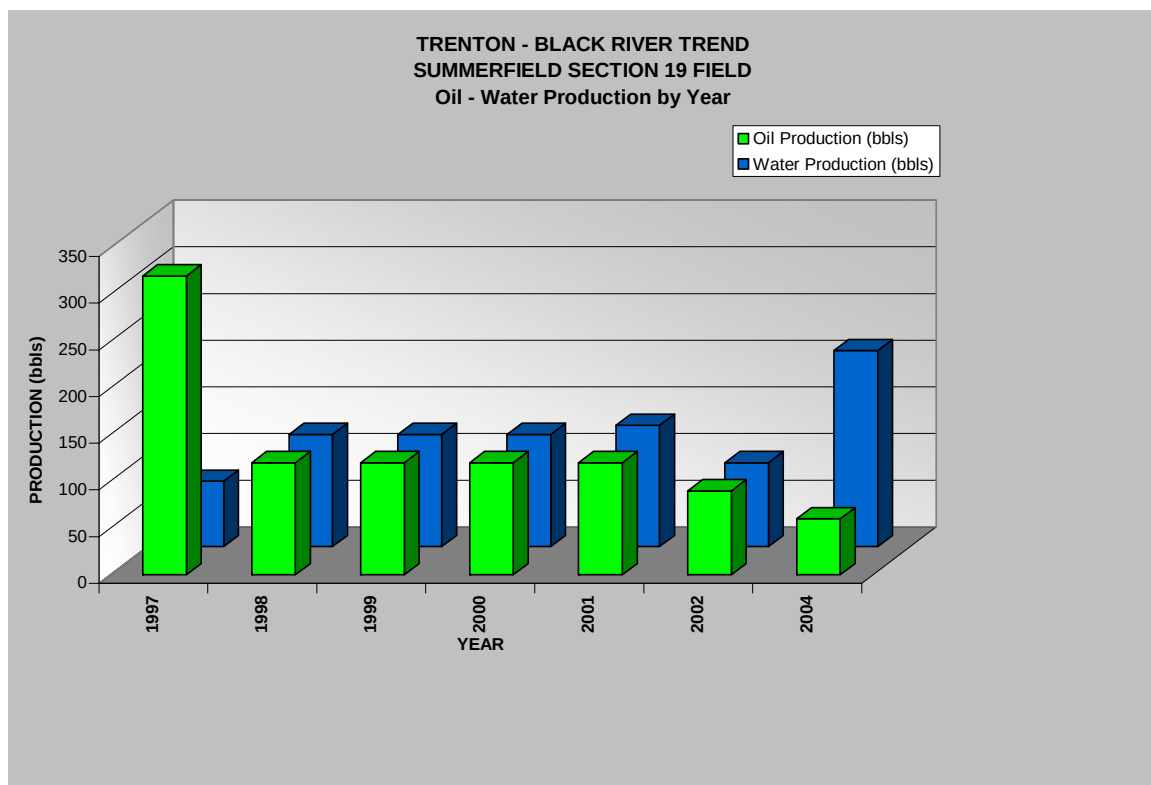
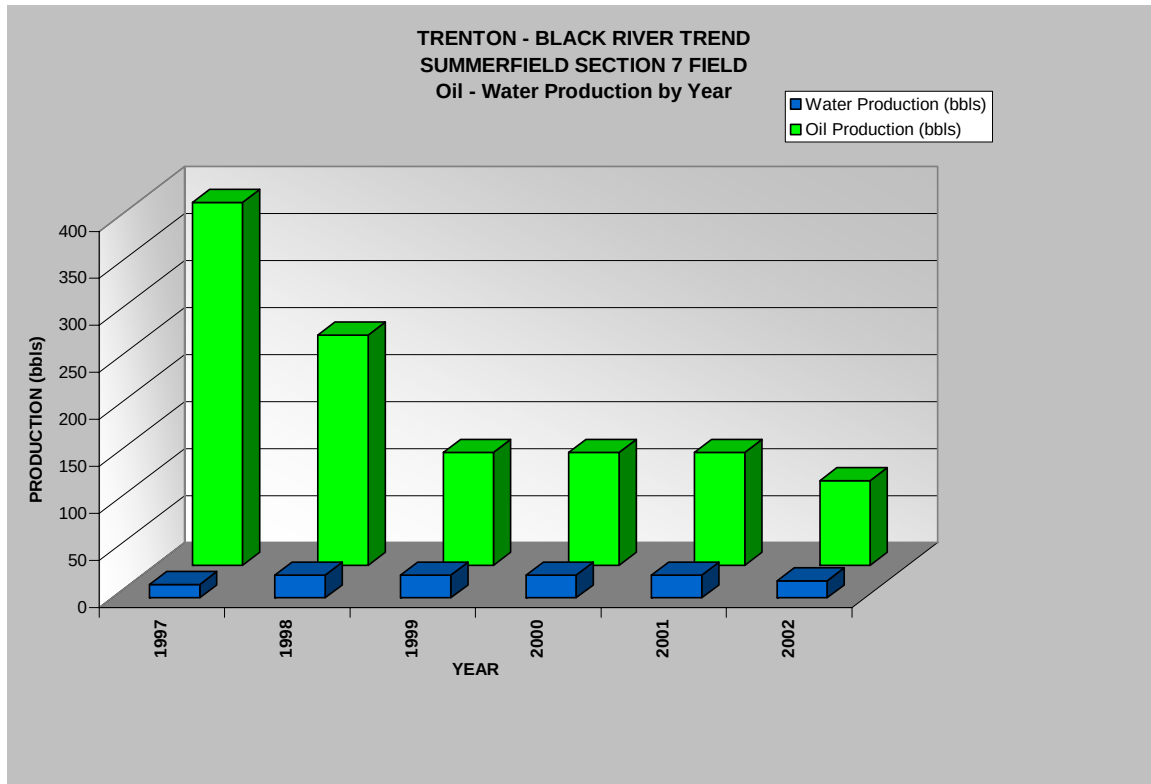


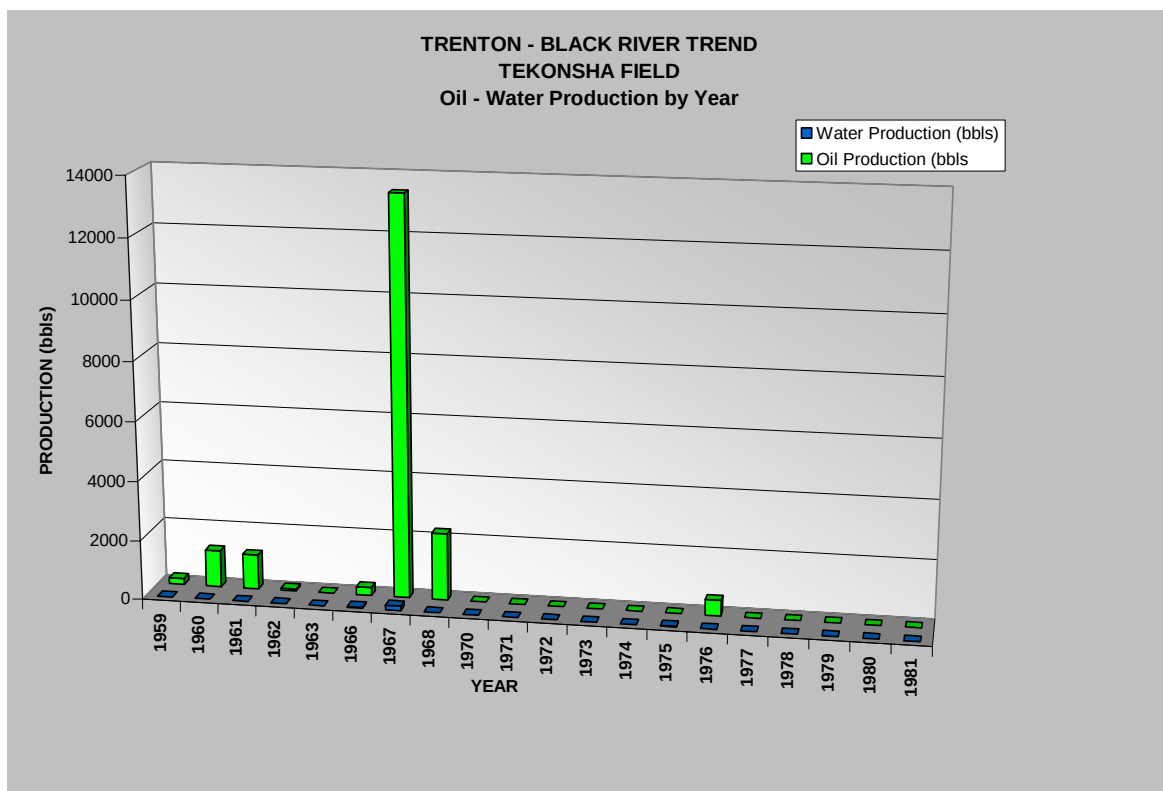
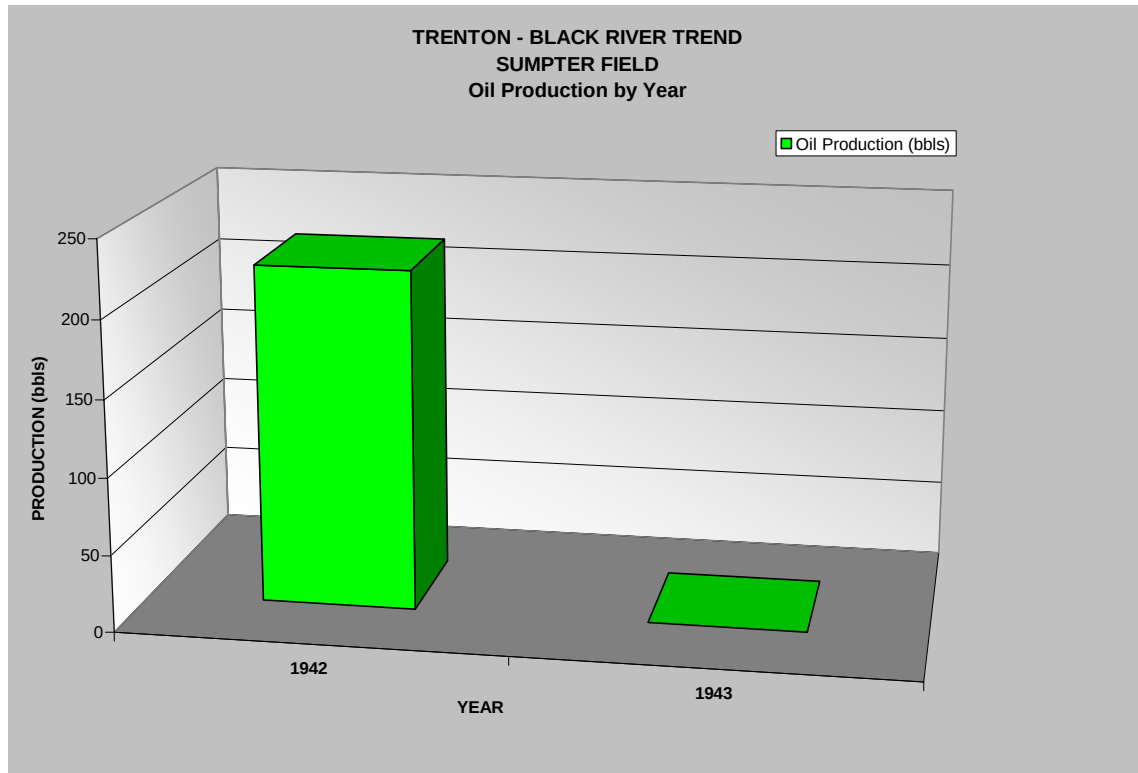
**TRENTON - BLACK RIVER TREND  
STONE POINT FIELD  
Oil - Gas - Water Production by Year**

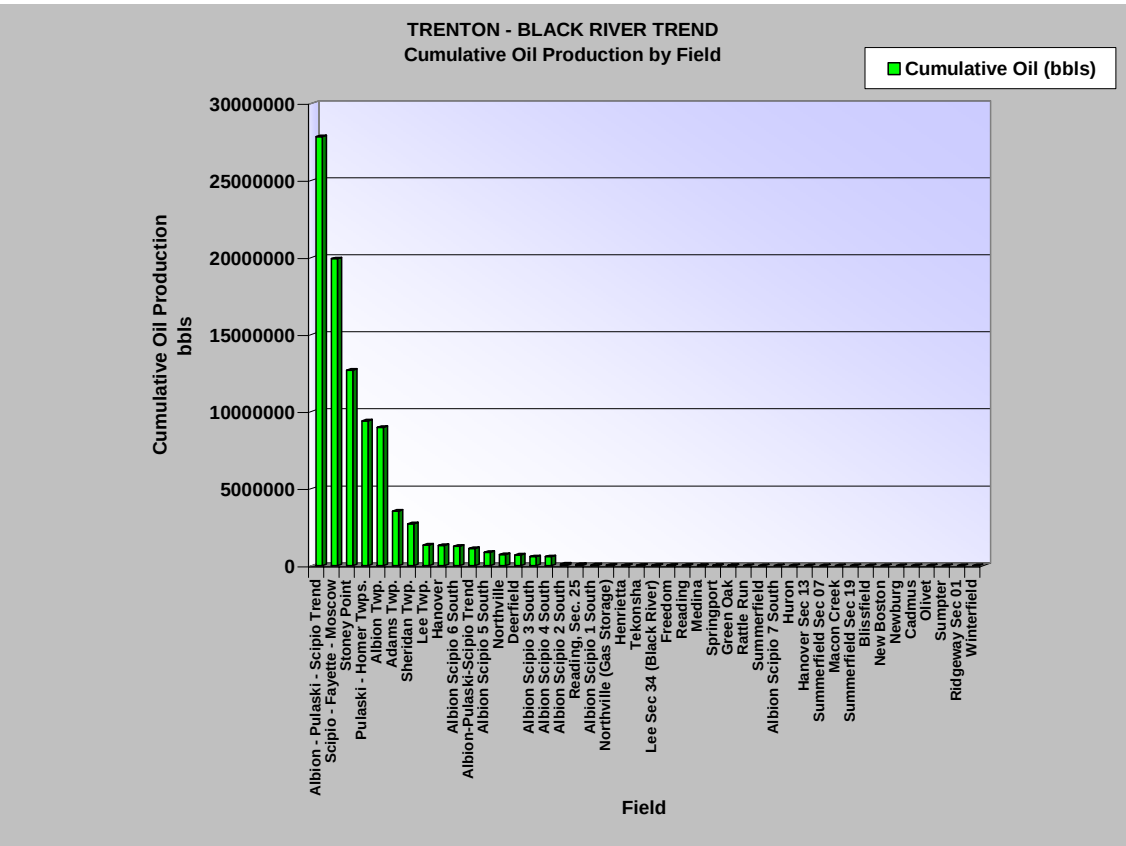
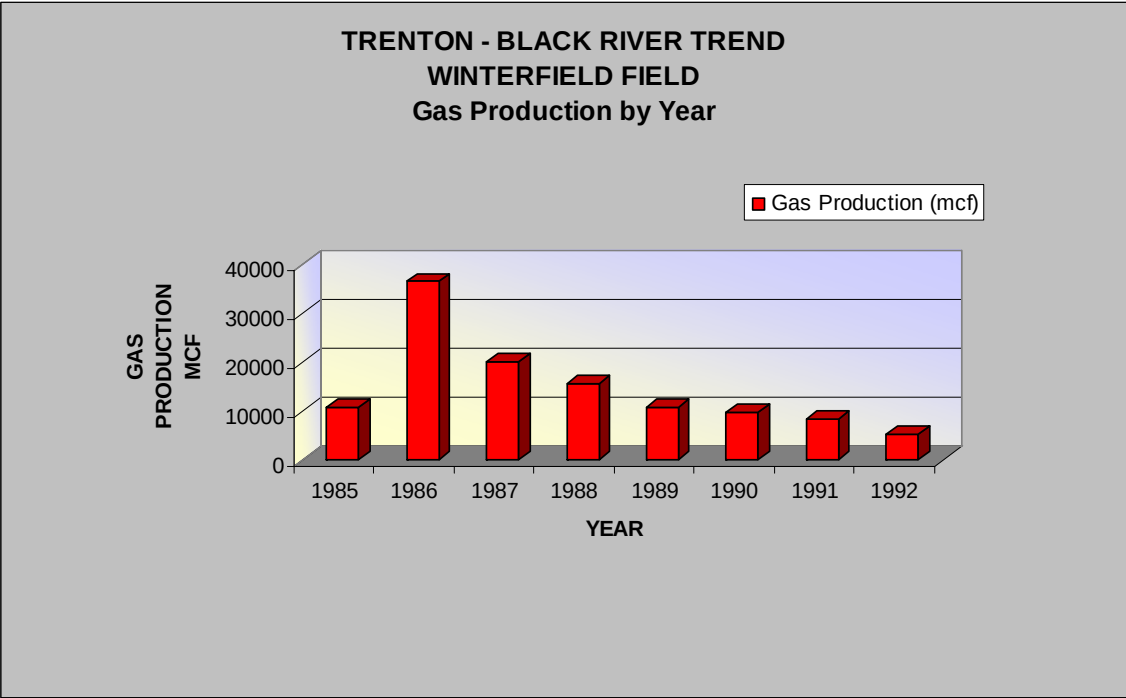


**TRENTON - BLACK RIVER TREND  
SUMMERFIELD FIELD  
Oil - Water Production by Year**

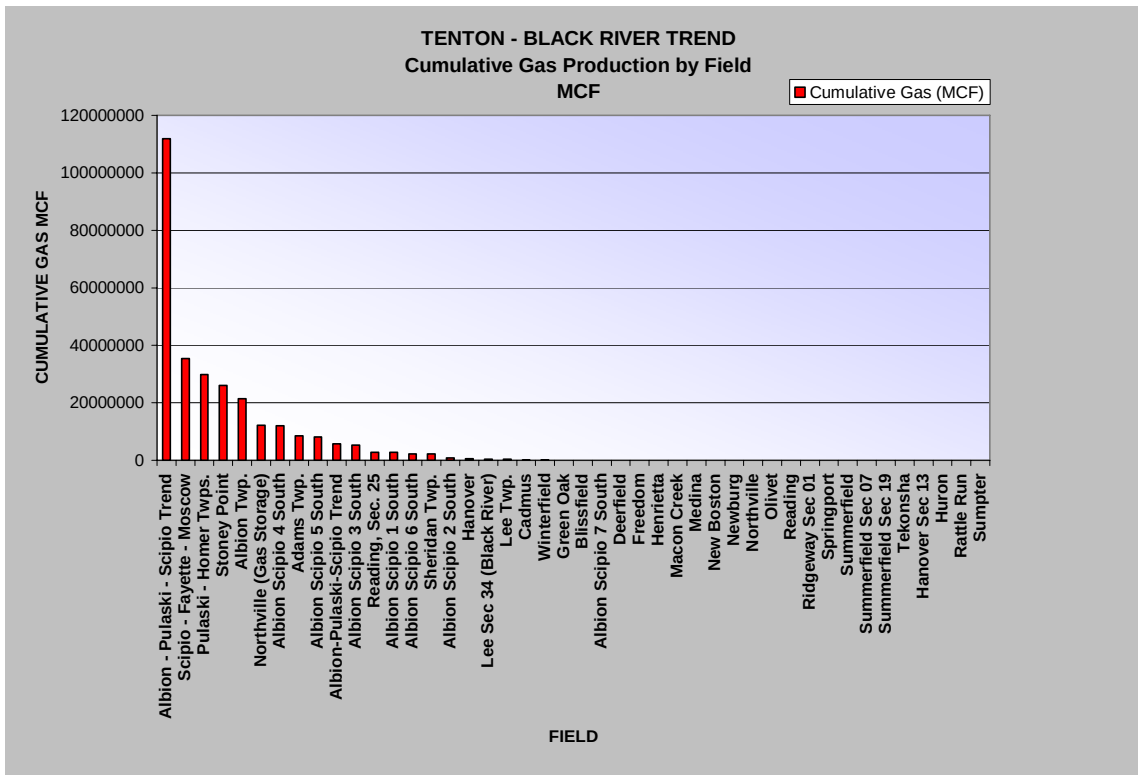
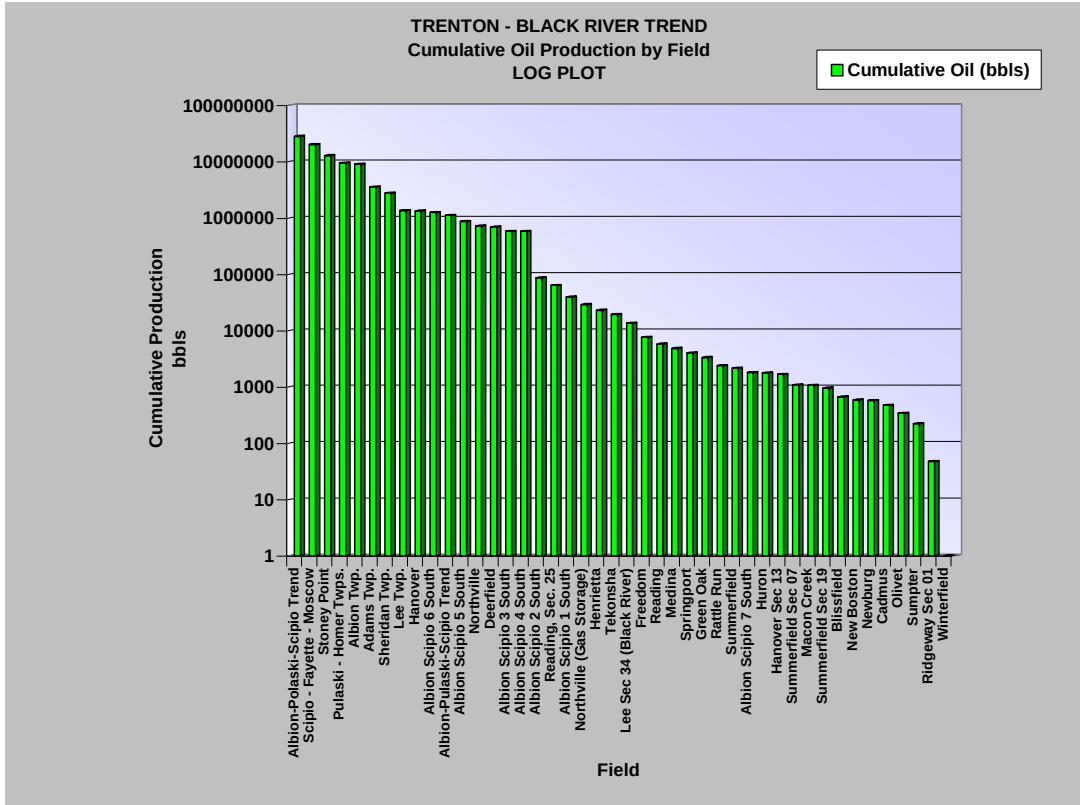


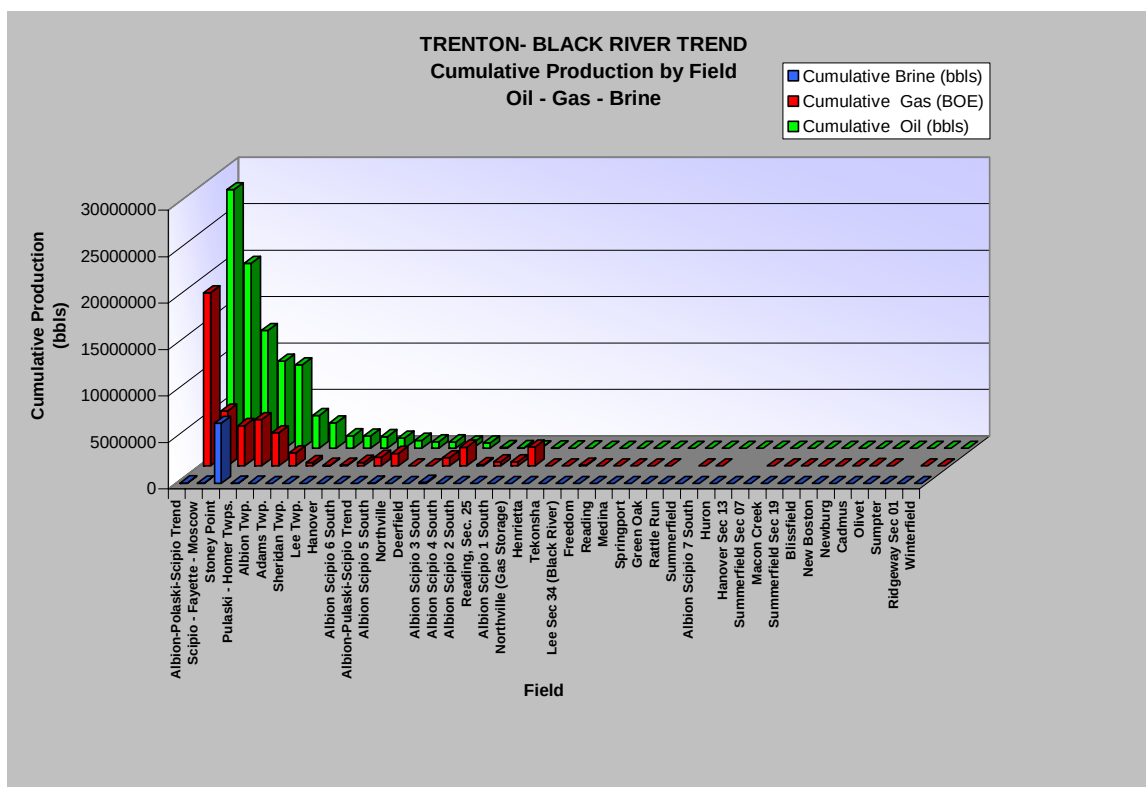
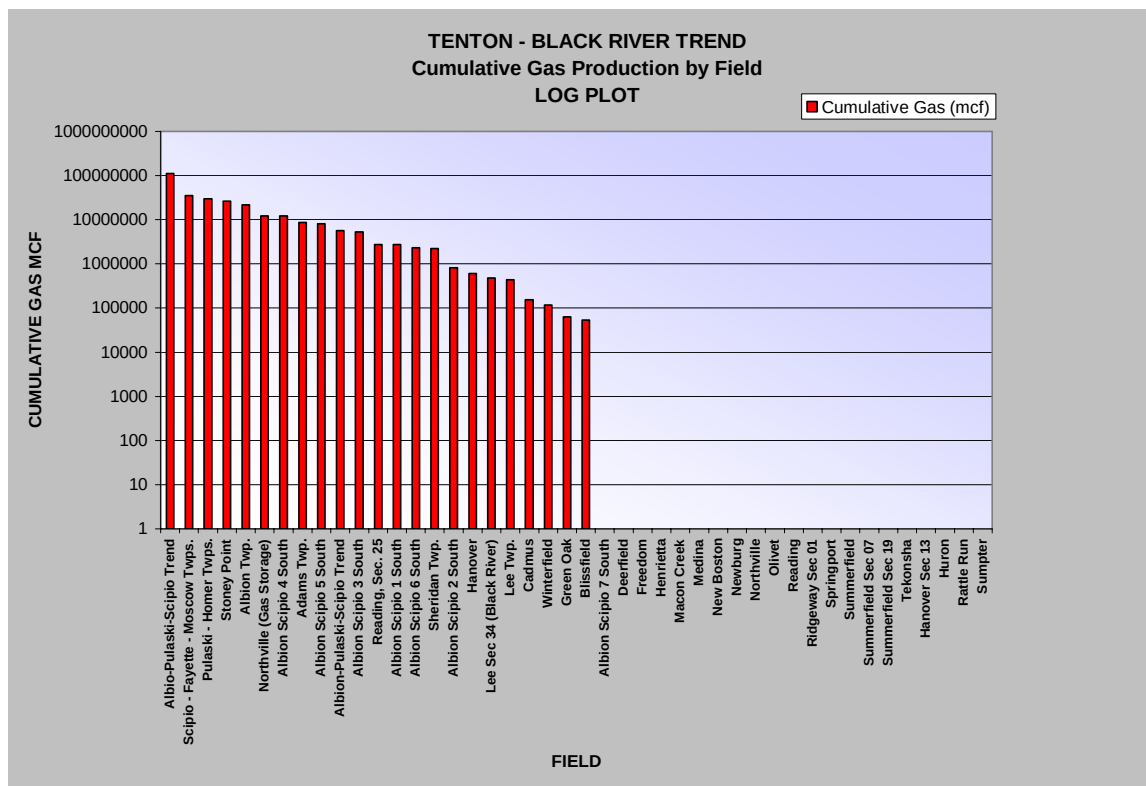


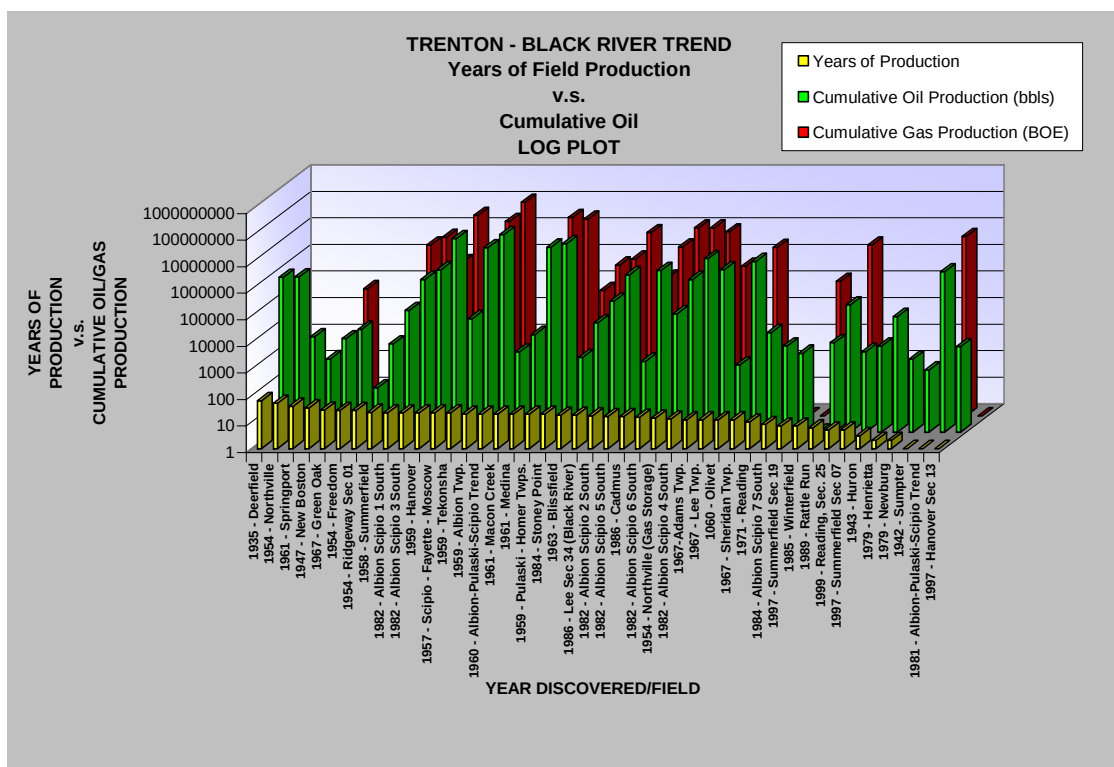
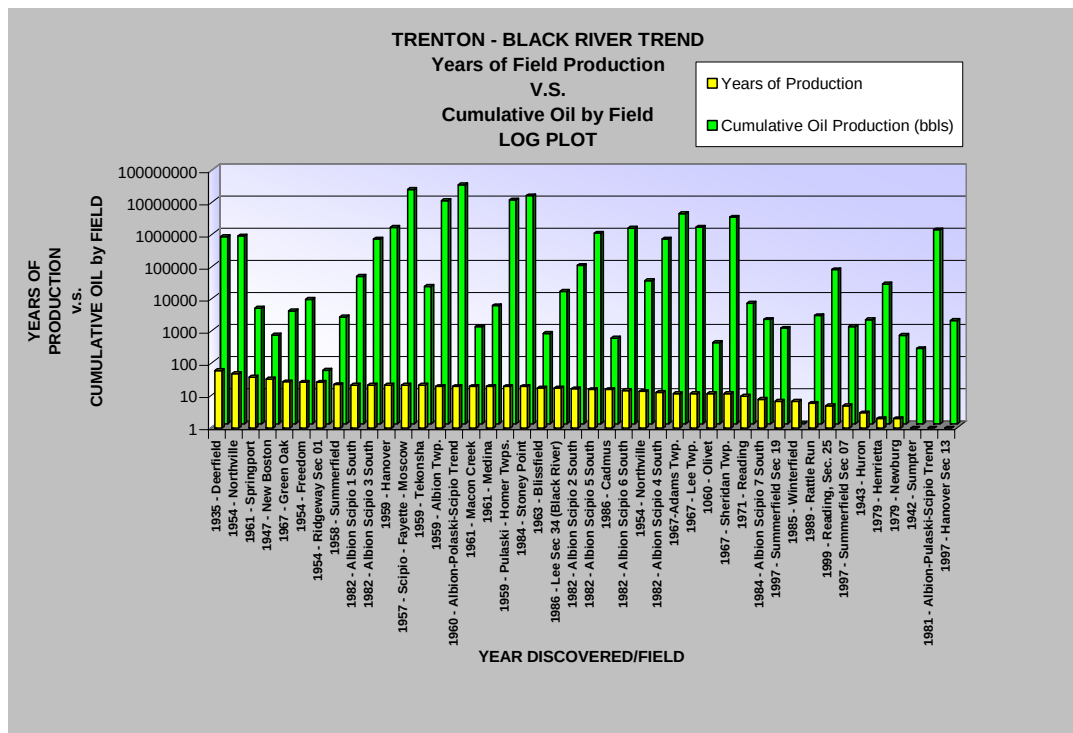












## **NIAGARAN TREND PRODUCTION ANALYSIS**

### **General Observations**

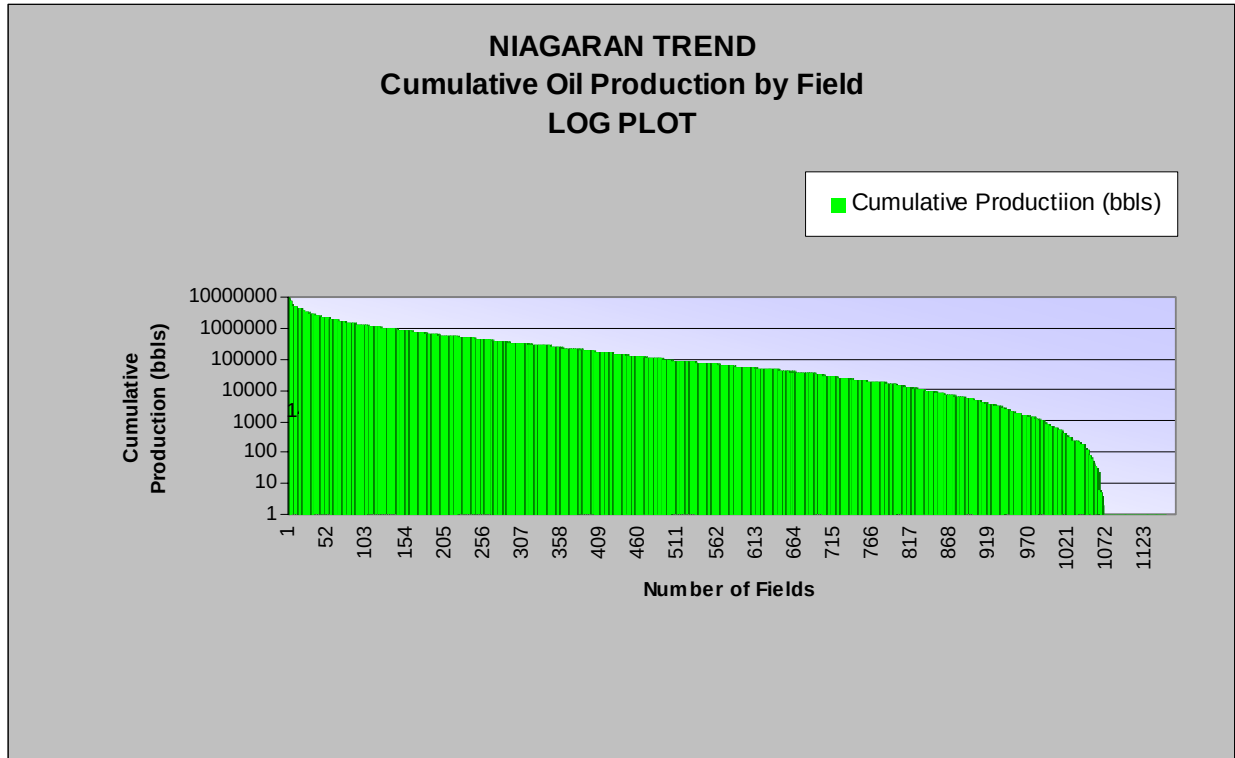
- 1.) Production data for the Niagaran Trend is generally good. The play began in the early 1950's and hit its peak during the 1970's-1980's. Digital data bases developed by the state beginning in 1981 include a large portion of the data for this play.
- 2.) The log plot of the data displays a curve typical of that for a mature play. Nearly all field sizes are represented and no "gaps" in field size occur. The slope of the curve is shallow indicating full representation of each field size. Future potential is probably resource limited for this particular exploration model; however, new technology, combined with a new/expanded exploration model could potentially re-set the curve to a higher level.
- 3.) There are 1,162 fields in this play. There are 1,063 fields producing oil. This volume of data makes it difficult to plot trends including individual field names. Rather, data can best be examined as categories based upon field size. "Cumulative Oil Production" can be broken down into 5 basic categories:
  - 1.) Fields 1-10 million barrels cumulative oil production, 2.) fields 100,000 – 1 million barrels cumulative oil production, 3.) fields 10,000 – 100,000 barrels cumulative oil production, 4.) fields 1,000 – 10,000 barrels oil cumulative production and 5.) fields less than 1,000 barrels cumulative oil production.
- 4.) Fields making less than 1,000 barrels oil cumulative production are probably not economic based upon oil production alone. The sharp drop-off in fields of this size is probably due to the fact that no one purposely looks for this sized field. However, a few disappointing fields of this size do occur and are produced to recover at least some of the cost of exploration and development. These fields, in most cases, are associated with gas production that makes the venture economic.
- 5.) Gas is produced in 991 fields compared to oil being produced in 1,063 fields. Gas production volumes remain somewhat level in relationship to oil production volume (1 million BOE).
- 6.) Brine is produced in 664 fields. Production of brine is roughly related to oil production. The larger oil fields all produce brine whereas the smaller the oil field, the less likely it is to produce brine. Only 8 fields produce only gas and brine. Brine volumes are roughly related to oil volumes. Only 28 fields produce more brine than oil. (refer to Cumulative Oil-Gas-Brine Production by field Graph)
- 7.) The State of Michigan imposes a 200 barrel-per-day maximum allowable on production which often distorts the true capabilities/performance of the affected wells.

- 8.) The graph of “Discovery Size (Cumulative Oil) by Year of Discovery” displays a wide variety of field performance for each year. Although originally kicked-off in 1950, Niagaran fields did not hit peak oil productivity until 1971 when drilling boomed with the discovery of 32 new fields that year. The 1970’s represent the “best times” for Niagaran discoveries, with a sharp decline after 1981. This data set does not include the onset of horizontal drilling during the 1990’s.
- 9.) There are 1,162 fields in the Niagaran Trend. The oldest field in the trend was discovered in 1950. Only 9 fields in the Niagaran Trend have produced more than 35 years. Nearly one half of the fields have produced for 15 – 30 years (531 fields). Only 181 fields have produced for 5 years or less. Seventy three fields were either produced for less than one year or not produced at all.
- 10.) “Cumulative Oil Production” varies substantially when plotted against “Years of Production.” However, the best producers in each age bracket show impressive results. Nearly 10,000,000 barrels of cumulative oil have been produced by fields in the 30 to 50 year age bracket. Fields in production from 22 years to 30 years have top producers in the 1-5 million barrel range. Top producing fields in the 5 – 22 year bracket still hit the 1 million barrel mark other than for year 9. Even fields in production for only 1 year have obtained the 100,000 barrel mark.

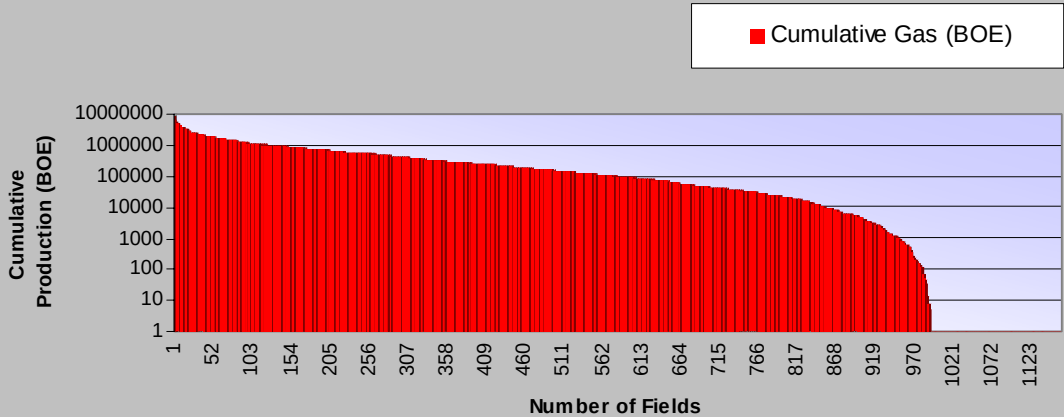
#### **CURRENT ACTIVITY**

- 1.) Fields from each of the 5 basic categories defined above will be correlated to the newly developed index covering data quantity, quality and availability for each field. Fields in each category ranking high in data coverage will be selected for detailed study.

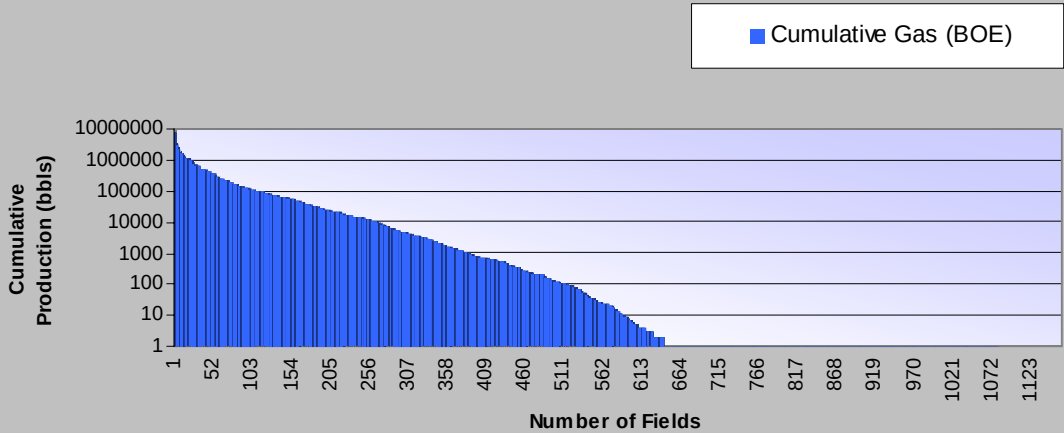
# Silurian Niagaran Trend Production Analysis Graphs



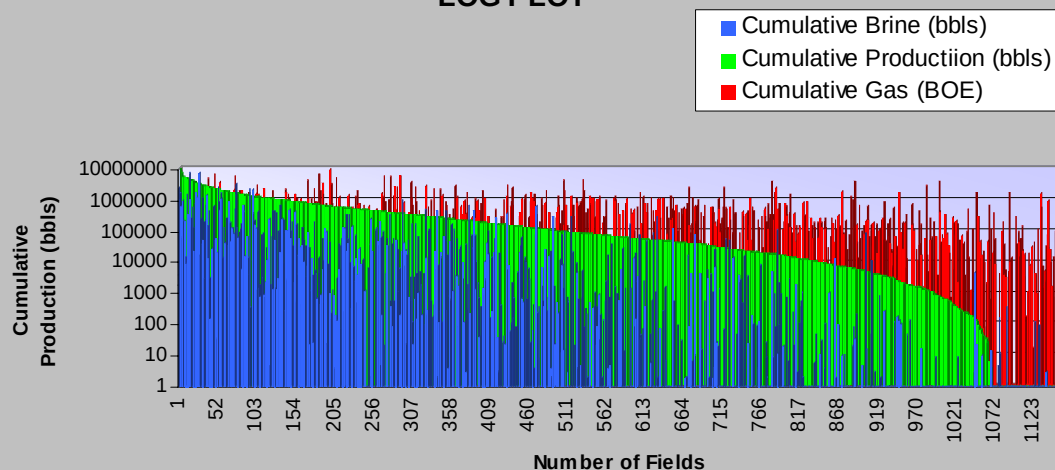
**NIAGARAN TREND**  
**Cumulative Gas Production by Field**  
**LOG PLOT**



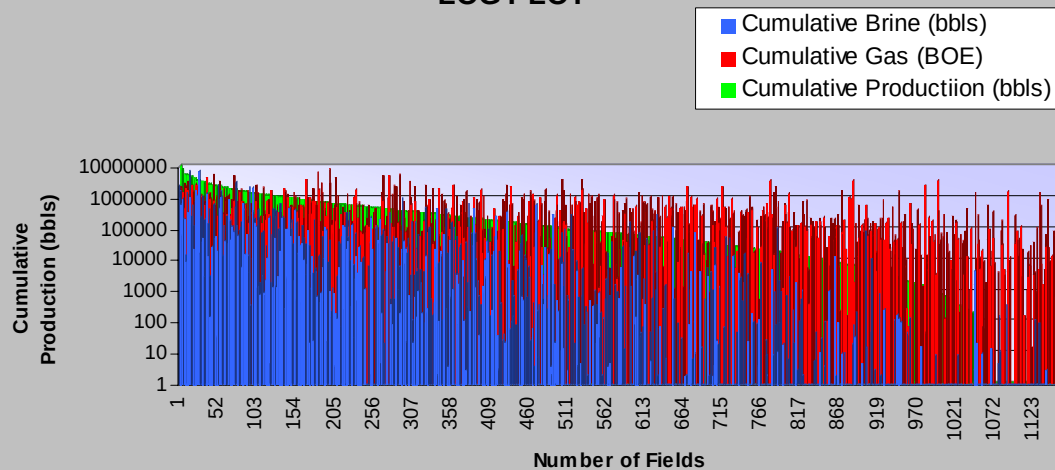
**NIAGARAN TREND**  
**Cumulative BRINE Production by Field**  
**LOG PLOT**



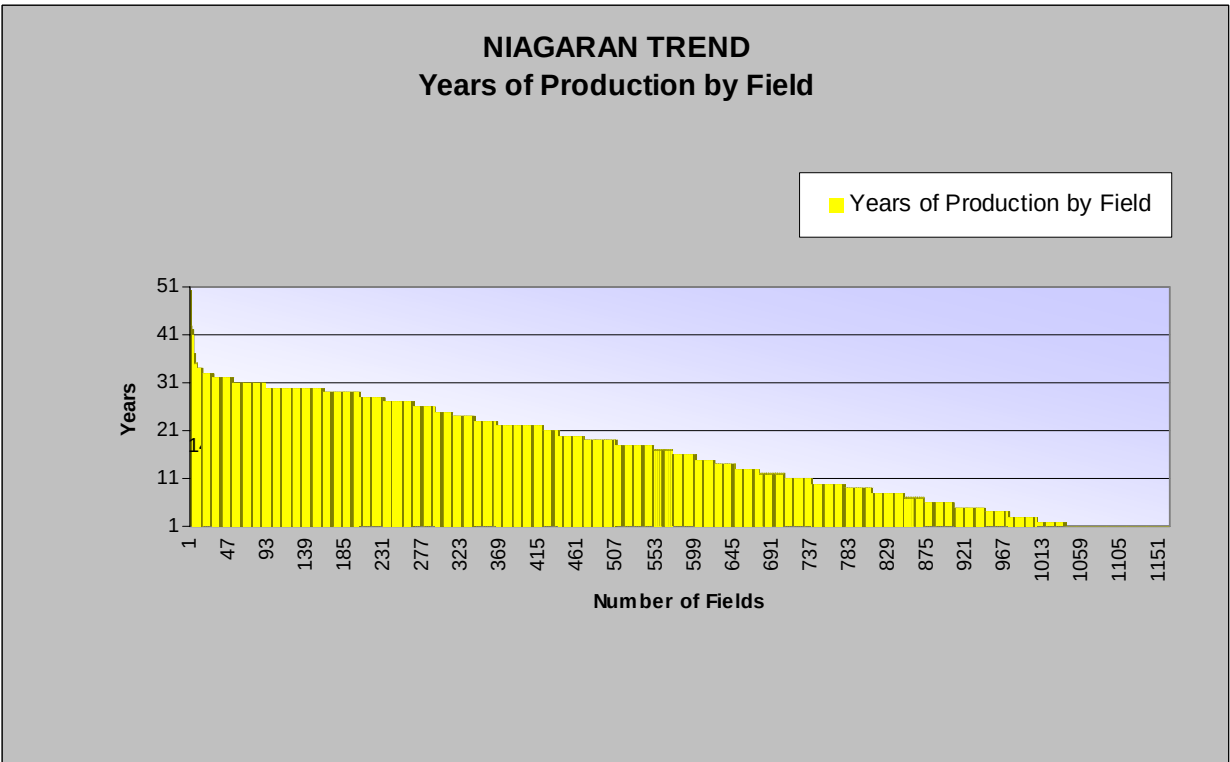
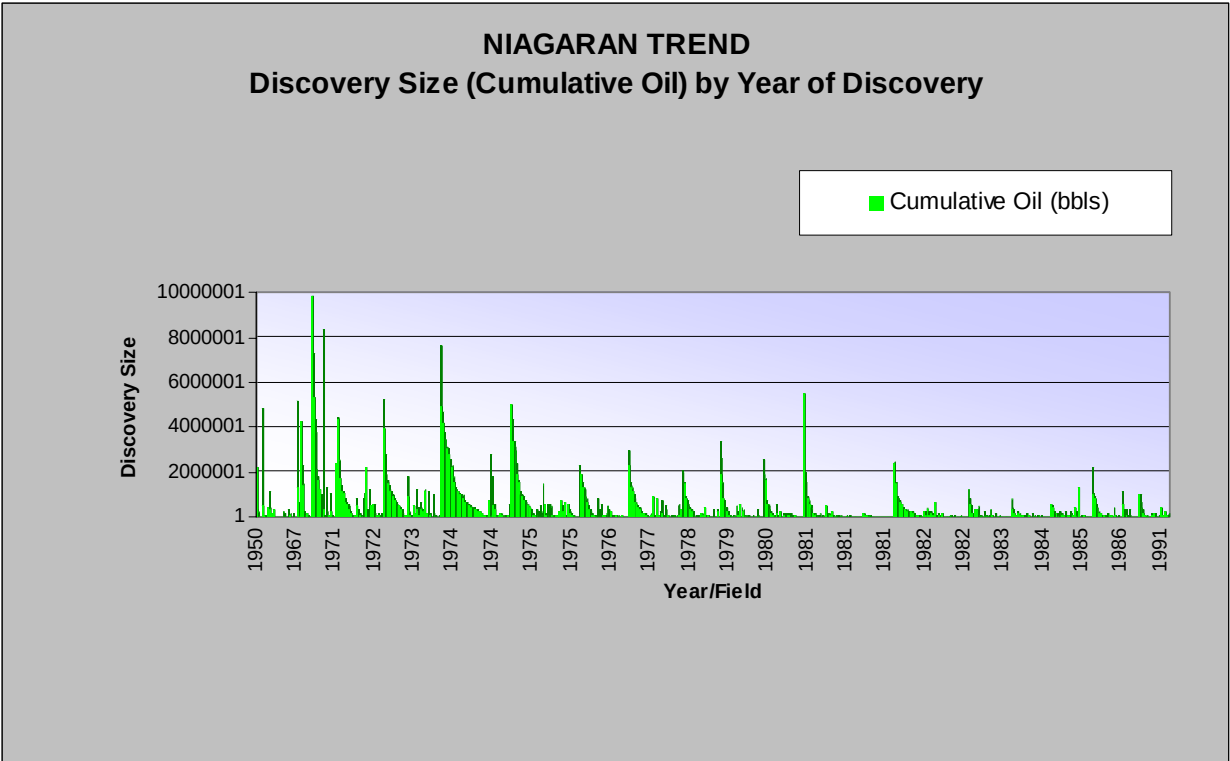
# **NIAGARAN TREND** **Cumulative Brine - Oil - Gas Production by Field** **LOG PLOT**



# **NIAGARAN TREND** **Cumulative Brine - Gas - Oil Production by Field** **LOG PLOT**

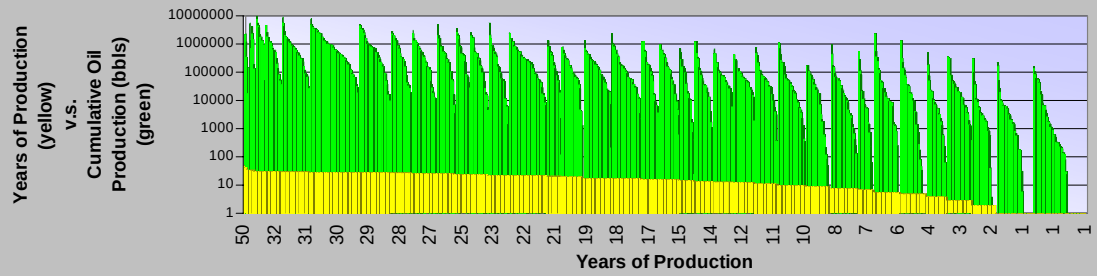






# NIAGARAN TREND Years of Field Production v.s. Cumulative Oil LOG PLOT

■ Years of Production by Field  
■ Cumulative Oil (bbls)



## **DUNDEE TREND PRODUCTION ANALYSIS**

### **General Observations**

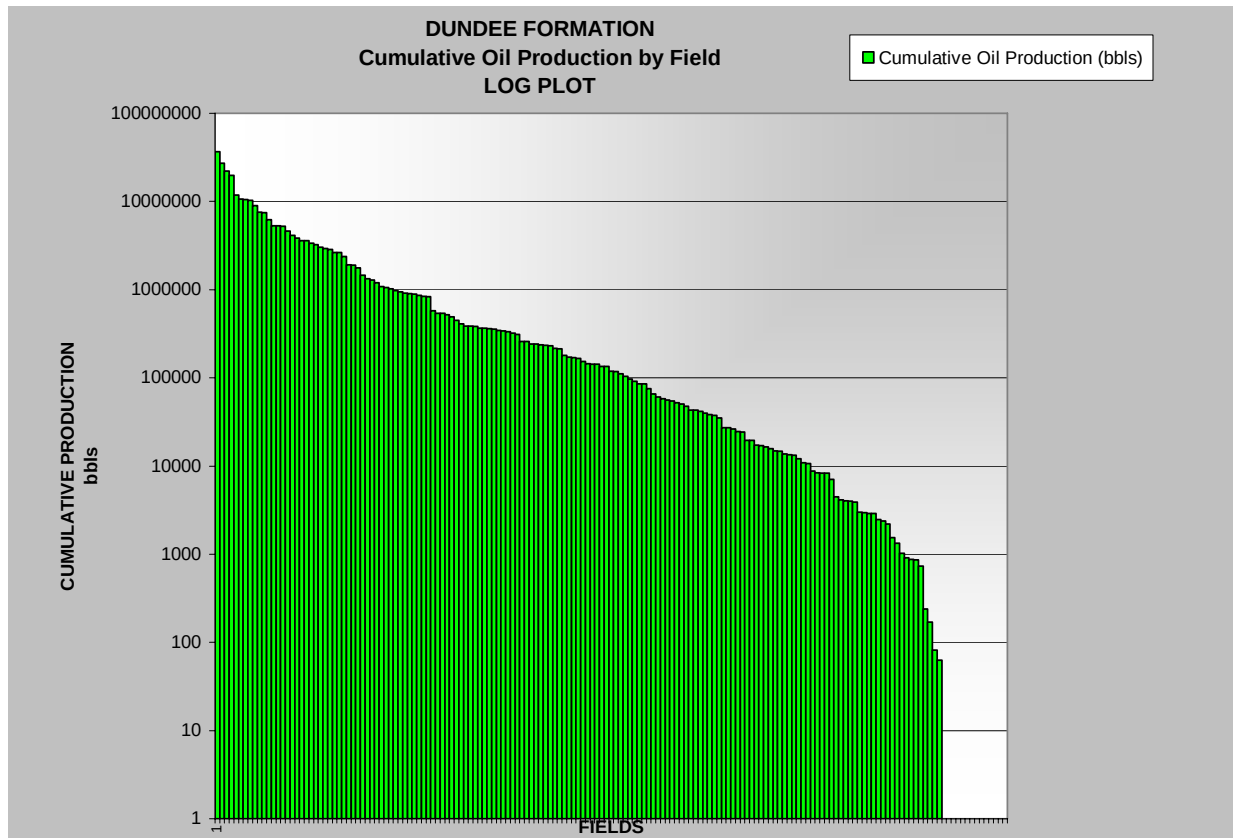
- 2.) Production data for the Dundee Trend is generally good. Dundee production goes back to 1934 and has remained a stalwart of the Michigan Basin ever since. Its production ranks second only to that of the Niagaran Trend; however, the Niagaran Trend contains 1,162 fields v.s. only 178 fields in the Dundee Trend.
- 2.) The log plot of the data displays a curve typical of that for a mature play. Nearly all field sizes are represented and no “gaps” in field size occur. The slope of the curve is shallow indicating full representation of each field size. Future potential is probably resource limited for this particular exploration model; however, new technology, combined with a new/expanded exploration model could potentially re-set the curve to a higher level.
- 3.) There are 178 fields in this play. There are 155 fields producing oil. This volume of data makes it difficult to plot trends including individual field names; therefore, data has been examined as categories based upon field size. “Cumulative Oil Production” can be broken down into 7 basic categories:
  - 1.) 8 Fields making 10-50 million barrels cumulative oil production,
  - 2.) 30 fields 1 – 10 million barrels cumulative oil production,
  - 3.) 50 fields making 100,000 – 1 million barrels cumulative oil production,
  - 4.) 39 fields making 10,000 – 100,000 barrels oil cumulative production and
  - 5.) 20 fields making 1,000 – 10,000 barrels cumulative oil production,
  - 6.) 8 fields making 0 – 1,000 barrels cumulative oil production, and
  - 7.) 14 fields making 0 oil production.
- 4.) Fields making less than 1,000 barrels oil cumulative production (9 fields) are probably not economic based upon oil production alone. The sharp drop-off in fields of this size is probably due to the fact that no one purposely looks for this sized field. However, a few disappointing fields of this size do occur and are produced to recover at least some of the cost of exploration and development.
- 5.) Gas is produced in 41 fields compared to oil being produced in 155 fields
- 6.) Brine is produced in 141 fields. Only 13 oil fields do not produce brine. Only 4 gas fields do not produce brine.
- 7.) The State of Michigan imposes a 200 barrel-per-day maximum allowable on production which often distorts the true capabilities/performance of the affected wells.

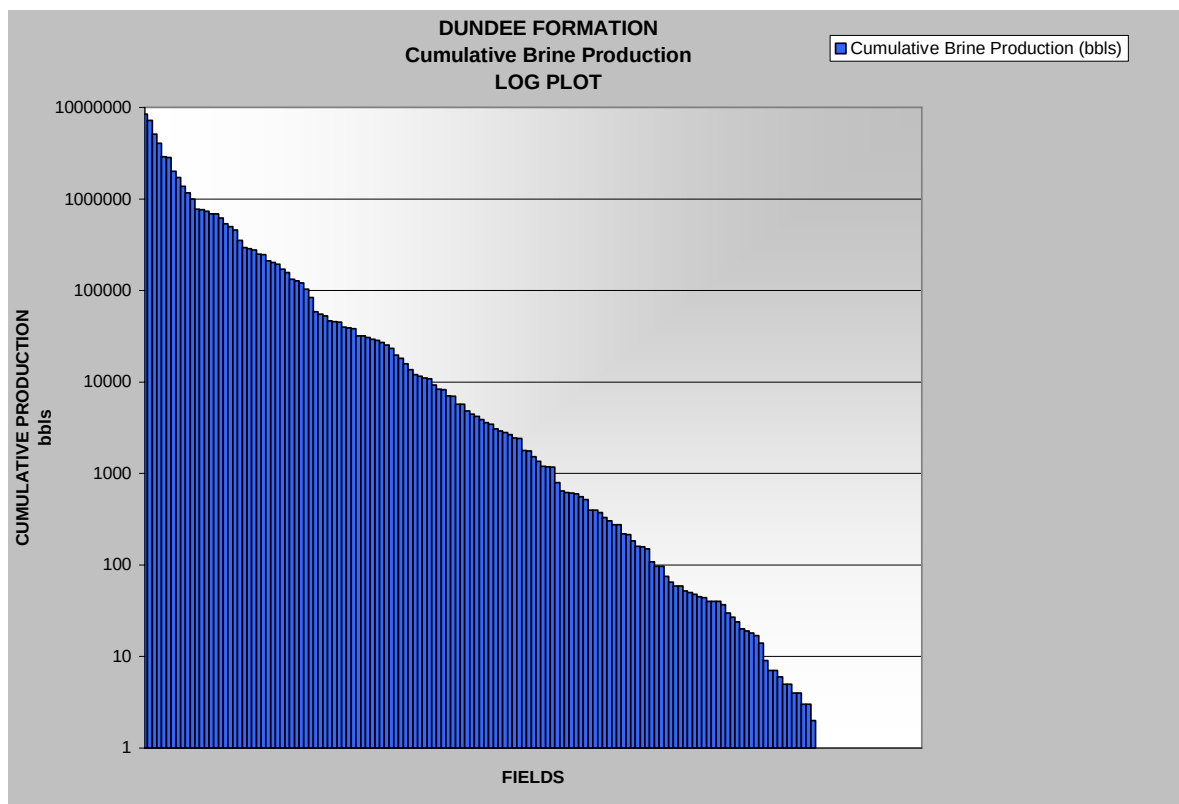
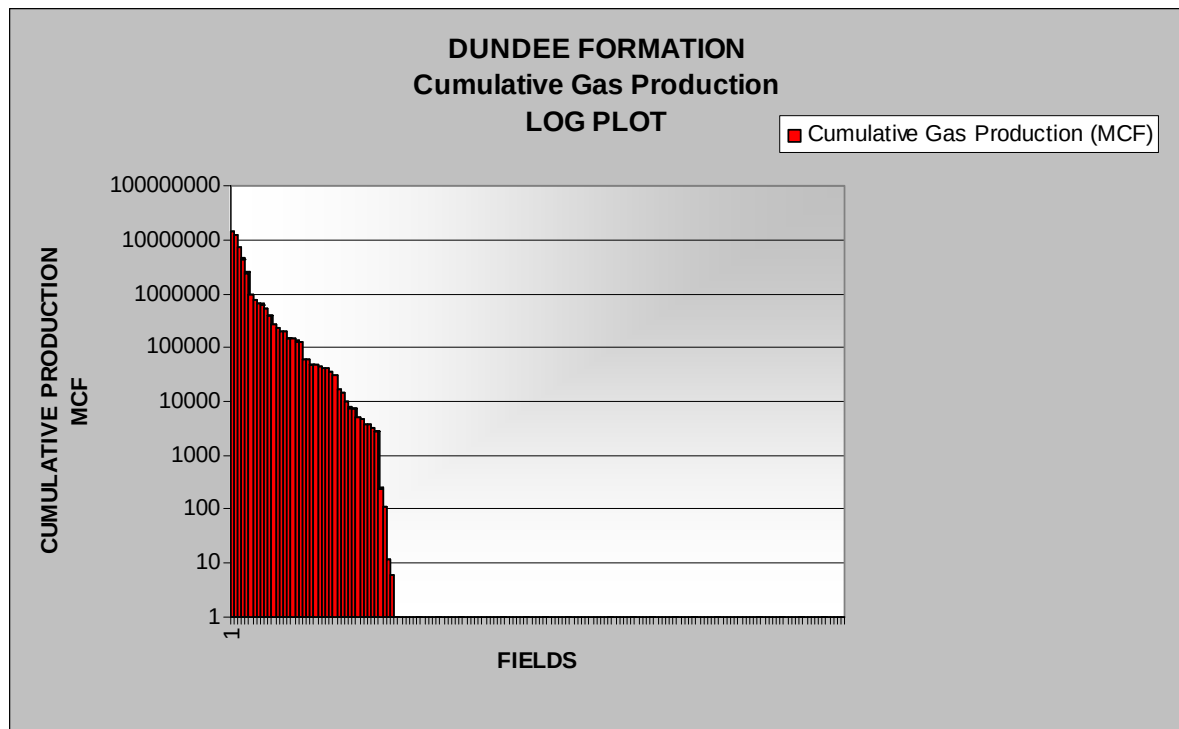
### **CURRENT ACTIVITY**

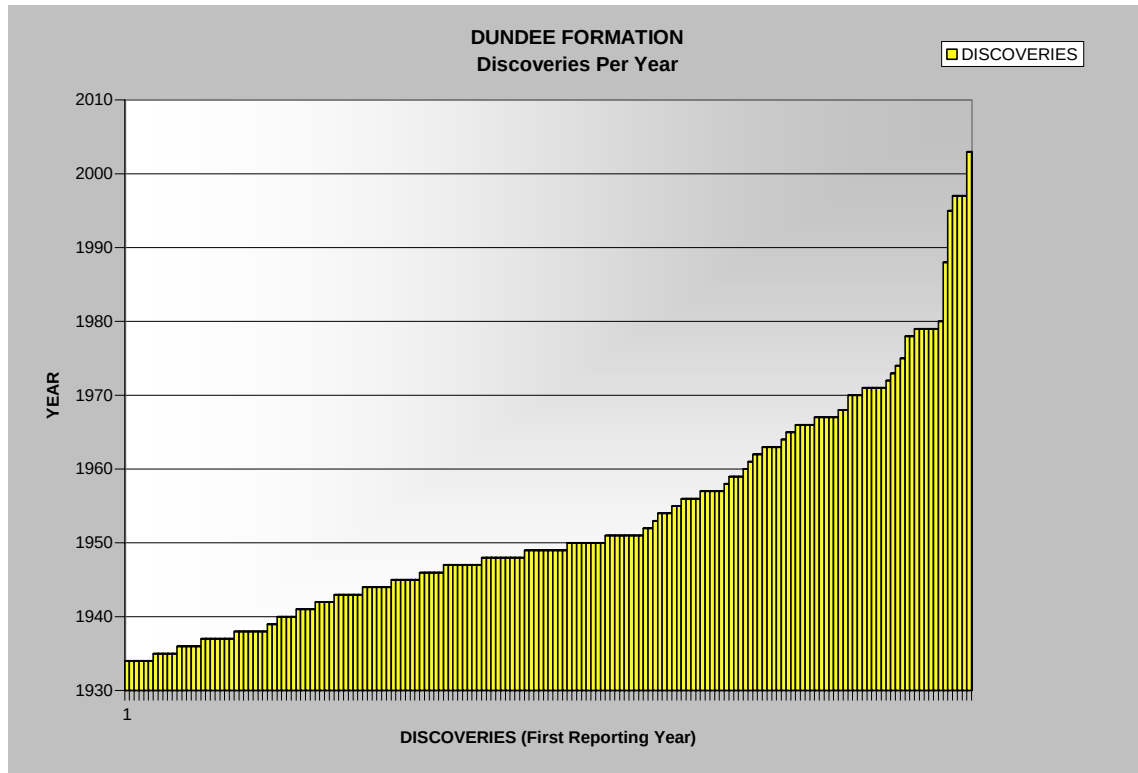
- 1.) Work is currently underway to further develop data covering Reed City v.s. overall Dundee Formations.

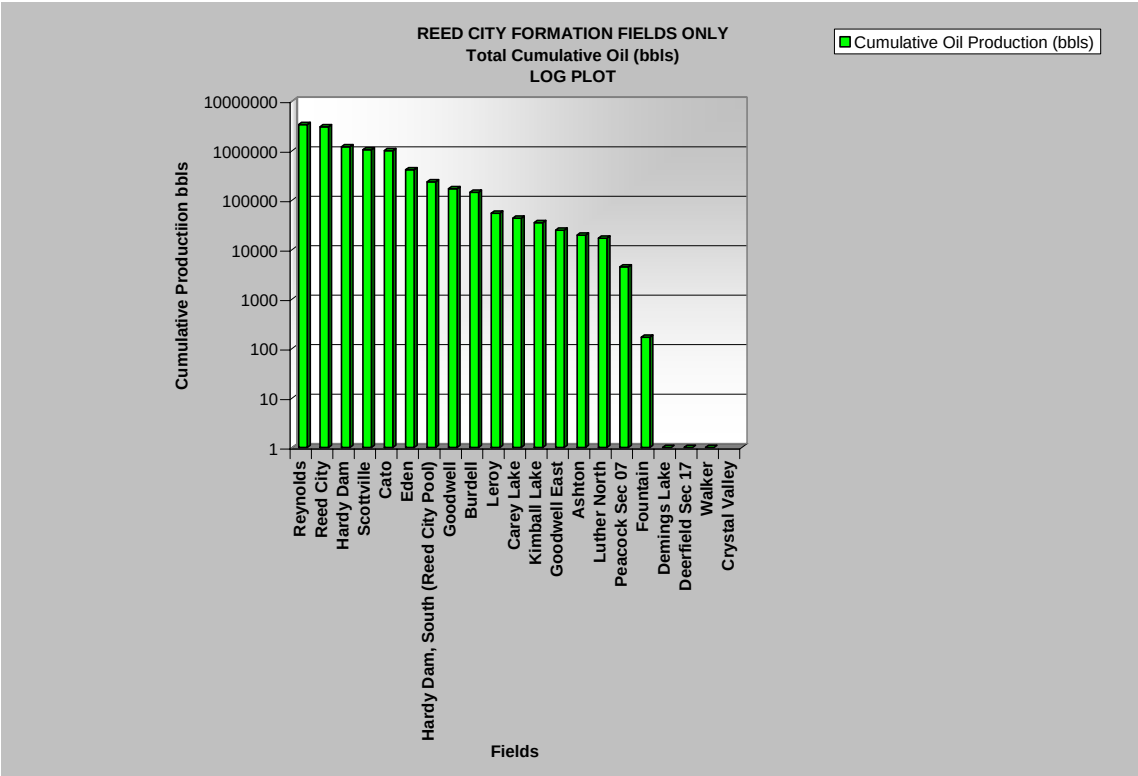
- 2.) Dundee Cumulative production v.s. Year Discovered data is currently being edited for analysis.
- 3.) Fields from each of the 7 basic categories defined above will be correlated to the newly developed index covering data quantity, quality and availability for each field. Fields in each category ranking high in data coverage will be selected for detailed study.

## Devonian Dundee Trend Production Analysis Graphs

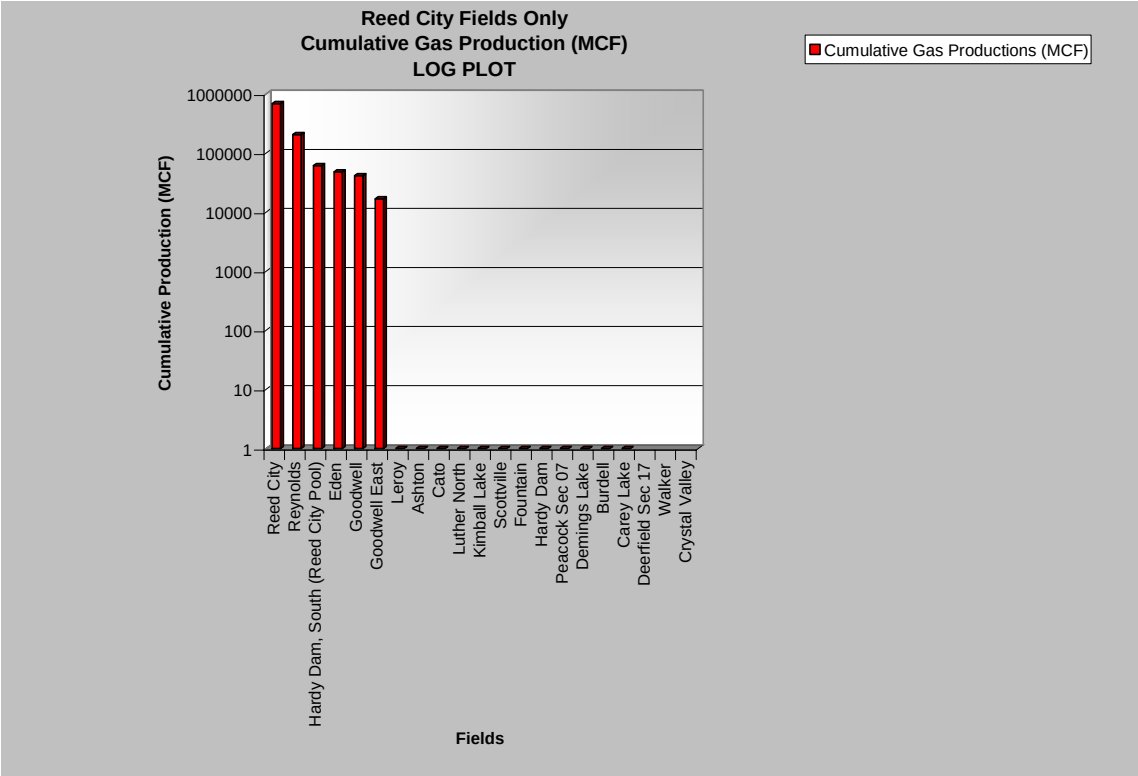












### **Appendix 3: Representative Project Presentations at Professional Meetings**

WMU Project Staff activity at Eastern Section AAPG Annual Meeting in Buffalo, NY  
October 8-11, 2006

Session Chair - Oral Technical Session: New Approaches to Carbonate  
Reservoirs of Eastern America, Michael Grammer

Session Chair - Oral Technical Session: Geological Carbon Sequestration in the  
Eastern U.S., William Harrison,

#### **Papers presented:**

- New Insight into the Reservoir Architecture of Silurian (Niagaran) Pinnacle Reefs in the Michigan Basin - G. Michael Grammer, W.B. Harrison, III, D.A. Barnes, and R. Gillespie, Western Michigan University, A.E. Sandomierski, Exxon Mobil Production Company
- Albion/Scipio Field, Michigan: What does a detailed look at cores tell us about the reservoir? - Robb Gillespie, David A. Barnes, G. Michael Grammer, and William Harrison, III, Western Michigan University
- Potential for Geological Carbon Sequestration in the Michigan Basin - William B. Harrison III, David A. Barnes, G. Michael Grammer, and Amanda Wahr, Western Michigan University
- Combining CO<sub>2</sub> sequestration with EOR activities – a synergistic approach for the future: An example from the Michigan Basin - G. Michael Grammer, David A. Barnes, William B. Harrison III, Western Michigan University and Robert G. Mannes, CORE Energy
- Geological Carbon Sequestration Potential in Devonian Saline Aquifers of the Michigan Basin, USA - David A. Barnes, Amanda Wahr, William Harrison, III, G. Michael Grammer, Western Michigan University and Neeraj Gupta, Battelle Memorial Institute

#### **Posters Presented:**

- Hydrothermal Dolomite: Occurrence and Mechanisms, Michigan Basin, USA David A. Barnes, G. Michael Grammer, William Harrison, III, and Robb Gillespie, Western Michigan University
- Subsurface Stratigraphy of the Devonian Dundee Formation, Michigan Basin, USA – A Log Based Approach - Joshua P. Kirschner, and David A. Barnes, Western Michigan University

#### **Posters Presented:**

- Four Student Job Quest posters presented by Jessica Crisp, Josh Kirshner, Amy Noack and Amanda Wahr

***Hydrothermal Dolomite Reservoirs (HTDR) in a Mature Petroleum Province, Michigan Basin, USA***

**David A. Barnes**, Department of Geosciences and Michigan Basin Core Research Laboratory, Western Michigan University, 1903 W. Michigan Ave, Kalamazoo, MI 49009, phone: (269) 387-8633, [barnes@wmich.edu](mailto:barnes@wmich.edu), **G. Michael Grammer**, Department of Geosciences, Western Michigan University, Kalamazoo, MI 49008, **William Harrison, III**, Western Michigan University, Kalamazoo, MI 49008, and **Robb Gillespie**, Michigan Basin Core Research Laboratory, Department of Geosciences, Western Michigan University, Kalamazoo, MI 49008.

Carbonate reservoirs with a strong overprint of fracture related hydrothermal dolomite (HTDR) have unique spatial distribution, internal geometry, and hydrocarbon production characteristics. Recognition of HTDR in mature but under-studied basins has important commercial implication. Improved reservoir characterization and enhanced recovery operations and support for untested exploration concepts can result from identification of HTDR. One of the first well-documented examples of HTDR in a giant oil field is the Trenton/Black River (T/BR), Albion-Scipio field in the Michigan basin, USA. Wrench faulting and Riedel shear related features, including dilational fractures, and primary facies controlled fluid flow conduits are considered fundamental to the origin of HTDR relative to regional limestone in Albion-Scipio.

Sedimentologic and petrologic analysis of several producing formations in core including T/BR, Ordovician St. Peter Sandstone (aka “PdC”), and Devonian Dundee Formation throughout the Michigan basin indicates a pervasive overprint of hydrothermal dolomite. Hydrothermal mineralization is also observed in units in the basin as young as Mississippian/Pennsylvanian age. Structural mapping and log analysis in the T/BR and Dundee suggest close spatial relationship among gross dolomite distribution and interpreted, wrench fault-related NW-SE and NE-SW structural trends. Hydrothermal origin of much dolomite in several stratigraphic intervals, from Ordovician through Mississippian/Pennsylvanian age and persistent association of this dolomite in reservoirs coincident with wrench fault-related features is strong evidence in support of HTDR in multiple producing intervals in the Michigan basin. Recognition of HTDR in these and other reservoir formations should result in revitalized and improved exploration/exploitation activity and increased production in Michigan and other mature petroleum provinces.

**Evaluating Controls on the Formation and Reservoir Architecture of Niagaran Pinnacle Reefs (Silurian) in the Michigan Basin: A Sequence Stratigraphic Approach**

SANDOMIERSKI, A.E., GRAMMER, G.M. and HARRISON, W.B., III,  
Western Michigan University, Kalamazoo, MI

Silurian-aged (Niagaran) pinnacle reefs have been productive in the Michigan Basin for 60+ years, but extensive lateral and vertical heterogeneity limits primary production to as little as 25%. Enhanced recovery efforts are generally focused on water and CO<sub>2</sub> floods, or horizontal drilling, but the connectivity of the reefs laterally and vertically is poorly understood and unpredictable, leading to marginal success in many reefs. Niagaran pinnacle reef growth has previously been described as continuous growth during a single relative sea level rise. In this model, the characteristic shoaling upward sequence varies from a microbial mound facies at the base, with a stromatoporoid-dominated reef core capped by algal laminites and anhydrites that form a regional seal for many of the reefs in the Basin.

Detailed core analysis within a sequence stratigraphic framework, however, indicates that the overall shoaling sequence is made up of higher frequency depositional cycles, each bounded by exposure or flooding surfaces. These tens of meters to meter scale cycles support an episodic reef growth model controlled by multiple fluctuations in relative sea level, and provides a means to predict reservoir quality since porosity and permeability is often related to primary facies in these reefs. Because many cycles contain reservoir facies bounded by low permeability units, the result is often significant vertical compartmentalization. This core-based understanding of the episodic nature of pinnacle reef growth, as well as the vertical facies successions and resulting impact on reservoir heterogeneity, should lead to enhanced predictability of reservoir architecture from wireline log signatures alone.

**Albion/Scipio Field, Michigan: What does a detailed look at cores tell us about the reservoir?**

Gillespie, R. ([robb.gillespie@wmich.edu](mailto:robb.gillespie@wmich.edu) 269-387-8633), Barnes, D. A., Grammer, G.M., and Harrison, W.B., Michigan Geological Repository for Research and Education, Western Michigan University, Kalamazoo, MI

Michigan's only giant oil field, the Albion/Scipio Field, has produced over 125 million barrels of oil and is used as an analog for much of the Trenton-Black River exploration in Eastern North America. Current reservoir models, based on published literature suggest extensive fracturing and brecciation followed by pervasive hydrothermal dolomitization created the field's reservoir architecture. The general impression of this reservoir is one of facies-independent and fabric-destructive processes, especially dolomitization that created the reservoir quality.

Detailed examination of numerous cores from the field and a few outside the field, do show some intervals of extensive fracturing and brecciation along with hydrothermal (saddle) dolomite cement. Many other cores show only limited fracturing and rare saddle dolomite cement. Some of the cores, in the heart of the field, show almost no fracturing although much of the cored interval is dolomitized. Several well cores show interbedded dolomite and limestone with primary facies fabrics and textures very well preserved in both lithologies. Depositional environments can easily be interpreted from most of the core material. These cores show a diverse set of shallow shelf and peritidal facies stacked in multiple cycles through the Black River and Trenton intervals.

It appears from this core study that fracturing and brecciation is very laterally restricted to the proximity of major faults within the field. Wells a short distance from these faults may show little or no fracturing. Dolomitization does, however, extend well beyond the fractured zone. Primary sediment texture and porosity may have provided sufficient fluid pathway to transmit the dolomitizing fluids substantial distance from the major faults.

## **Subsurface Stratigraphy of the Devonian Dundee Formation, Michigan Basin, USA – A Log Based Approach**

**JOSHUA P. KIRSCHNER** ([joshua.p.kirschner@wmich.edu](mailto:joshua.p.kirschner@wmich.edu)) and David A. Barnes  
Western Michigan University, Geosciences and MGRRE, Kalamazoo, MI, 49008

A distinct hard ground surface separates two disparate facies tracts in numerous, Middle Devonian, Dundee Formation cores in the Michigan basin subsurface. This sharp stratigraphic contact can be distinguished by scour and/or dissolution of a partially lithified surface, which is commonly bored and/or eroded, and overlain by rip up clasts. This contact is thought to represent both a subaerial or subaqueous exposure surface and a subsequent period of slow sediment accumulation. Supratidal to shallow marine, shoal-water carbonate facies occur below this hard ground surface, basin wide. A lithologically homogeneous, fossiliferous mudstone-wackestone facies overlies the hard ground surface in core and is indicative of transgression to more distal, open marine conditions.

Careful analysis of hundreds of wireline logs throughout the basin reveals a ubiquitous gamma ray marker (grm) that coincides with this hard ground/marine flooding surface in core. Although present across much of the basin, the grm does not always occur apparently due to local variability of carbonate lithofacies, especially in more open marine Dundee successions in the eastern basin. A corresponding decrease in porosity, inferred from lithodensity logs, commonly coincides with the grm and is typically present even when the grm is not.

Formal lithostratigraphy does not subdivide the Dundee Formation in the Michigan basin subsurface. This investigation supports the idea that the Rogers City Limestone formation recognized in outcrop is a laterally extensive unit, which can be differentiated from the underlying Dundee (aka “Reed City equivalent”) Formation throughout the Michigan basin subsurface. Log-based, member scale, stratigraphic subdivision of the Dundee Formation is important in understanding the primary depositional history and the distribution of highly productive secondary dolomite reservoirs in the upper Rogers City Member.

## **New Insight into the Reservoir Architecture of Silurian (Niagaran) Pinnacle Reefs in the Michigan Basin**

**Grammer, G. Michael**<sup>1</sup>, Sandomierski, A.E.<sup>2</sup>, Harrison, W.B., III<sup>1</sup>, Barnes, D.A. and Gillespie, R.<sup>1</sup>

<sup>1</sup>Michigan Geological Repository for Research and Education, Western Michigan University, Kalamazoo, MI 49008

<sup>2</sup>ExxonMobil Production Company, Houston, TX 77002

Silurian-aged (Niagaran) pinnacle reefs have been productive in the Michigan Basin for over 60 years, but extensive lateral and vertical heterogeneity in the reservoirs may limit primary production to as little as 25%. Enhanced recovery efforts have generally been focused upon horizontal or directional drilling and waterfloods, but the internal reservoir architecture is often poorly understood which leads to marginal economic success in many reefs. Recent detailed facies analysis from core suggests that vertical compartmentalization in some pinnacle reefs is the result of complex facies variability, and that the vertical distribution of these facies can be constrained, and therefore predicted, within a sequence stratigraphic framework.

The sequence stratigraphic framework of the Miller Fox 1-11 reef, Oceana Co., MI, is characterized by a tripartite hierarchy of sequences, high frequency sequences, and cycles. Large-scale sequences (90-120 ft) correspond reasonably well to the commonly accepted “pinnacle reef model” in the Basin which describes an overall shoaling from mud mound to coral-stromatoporoid framework reef, to a restricted marine algal/stromatolitic unit which is ultimately capped with supratidal algal mats and evaporites. Smaller scale high frequency sequences (35-50 ft) and cycles (3-10 ft), however, consisting of shoaling upward packages bounded by low permeability facies, result in the potential for vertical permeability baffles or barriers within the overall “pinnacle reef” complex. Because there is a distinct correlation between various facies types and porosity/permeability values within these higher resolution packages, enhanced understanding of how these facies are distributed should result in more effective primary and enhanced production efforts.

#### **Appendix 4: Miscellaneous Project Presentations (titles)**

1. An overview of Hydrothermal Dolomite (HTD) Reservoirs with examples from the Michigan Basin (PTTC, 2007)
2. Reservoir Characterization of Shallow-Shelf Carbonates, Dundee Limestone, Central Michigan Basin (PTTC, 2007)
3. Albion-Scipio Field, Michigan: What does a detailed look at outcrop analogs and cores tell us about the Reservoir? (PTTC, 2007)
4. Hydrothermal Dolomite (HTD): Occurrence and Possible Mechanisms in the Michigan Basin, USA (Eastern Section AAPG, 2007)
5. New Insight into the Reservoir Architecture of Silurian (Niagaran) Pinnacle Reefs in the Michigan Basin (Eastern Section AAPG, 2006)
6. Combining CO<sub>2</sub> Sequestration with EOR activities – a synergistic approach for the future: An example from the Michigan Basin (Eastern Section AAPG, 2006)
7. Carbonate Reservoir Characterization: A new look at a Niagaran Pinnacle Reef (PTTC, 2006)
8. Hydrothermal Dolomite in the Michigan Basin (presentation for DOE-NETL, 2006)
9. Trenton/Black River Oil and Gas Reservoirs in Michigan (Eastern Section AAPG, 2006)
10. Recent advances in Carbonate Sedimentology and Stratigraphy applied to the Silurian Niagara Group, Michigan Basin (PTTC, 2005)
11. Modern Analogs for Michigan Basin Analogs (DOE site meeting and field trip, Tampa, FL 2005)
12. Michigan's Paleozoic Carbonate Formations and their Modern Analogs (PTTC, 2005)