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RESERVOIR GEOLOGY OF THE DUNDEE LIMESTONE, WEST BRANCH FIELD, MICHIGAN

by

Brendan Ciaran Curran

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
Kalamazoo, Michigan
December 1990

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West Branch field is a low-relief, NW-SE-trending anticline near the center of the Michigan basin. Since 1934, the Dundee Limestone (Middle Devonian) has produced over 12 million barrels of oil from this field. From core studies, six depositional facies types were recognized in the Dundee. These are dominated by bioclastic carbonate sand facies deposited in normal-marine shelf settings. Although burial cements have occluded some porosity, carbonate sand facies have retained significant primary interparticle porosity and are the most important reservoir rocks. Micritic facies with restricted faunal assemblages are present at the top of the Dundee. The top 10 to 15 feet were dolomitized before the deposition of the overlying Rogers City Limestone. This dolomite has high porosity but very low permeability. Cross sections from well logs show that facies distribution in the Dundee is largely lenticular. This understanding of distribution of porous and nonporous units will allow design and evaluation of waterflood programs.
ACKNOWLEDGEMENTS

I thank my advisor, Dr. William B. Harrison III (Western Michigan University, Kalamazoo), for his encouragement and support throughout the course of this project. I would also like to thank Neil F. Hurley (Marathon Oil Company, Littleton, Colorado) for the generous contribution of his time and valuable advice.

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Brendan Ciaran Curran
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Curran, Brendan Ciaran, M.S.
Western Michigan University, 1990

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INTRODUCTION

Dundee Limestone (Middle Devonian) reservoirs have produced over 351 million barrels of oil in Michigan. This is more oil production than any other formation in the Michigan basin (Michigan Department of Natural Resources, 1989). Dundee oil fields are generally found in the central region of the basin and are all located on structural highs. On the western side of the basin, the Dundee is commonly dolomitized and contains laminated and nodular anhydrite. Most Dundee fields in the central and eastern side of the basin contain no anhydrite, are much less dolomitic, and produce from primary porosity zones that occur directly below the overlying micritic Rogers City Limestone (Gardner, 1974).

West Branch field has produced hydrocarbons from the Ordovician St. Peter Sandstone and five Middle Devonian formations: Amherstburg, Lucas, Dundee and Rogers City (commonly treated as the "Dundee" reservoir), and Traverse Limestone. The Dundee Limestone has been the main producing unit in West Branch since the field was discovered in 1934, and has produced over 12 million barrels of oil.

Research Objectives

This study is concerned with understanding the stratigraphy,
sedimentology, and diagenesis of the Dundee Limestone and the structural
development of West Branch field. The research objectives are:
1. Describe Dundee depositional facies and the nature of the contact between
the Dundee and the overlying Rogers City Limestone.
2. Characterize the lateral continuity of porous units for evaluation of current
and future waterflood programs.
3. Establish the paragenetic sequence of diagenesis and hydrocarbon
emplacement. Use cathodoluminescence and stable isotope geochemistry to
investigate the origin of calcite cements and dolomites.
4. Document fracture abundance in core. Evaluate a published model
(Prouty, 1989a, 1989b; Ten Have, 1979) for fracture-controlled dolomite in this
reservoir. If they exist, project fracture-controlled dolomite fairways or trends
down to deeper reservoirs.
5. Compare structural timing and sedimentary response in West Branch to
observations of pre-sedimentary folding made in the nearby Buckeye field
(Montgomery, 1986).

Research Contributions

The major contributions of this research are:
1. Detailed descriptions were constructed of cores from the Dundee and
Rogers City Limestones. Six depositional facies types were recognized in the
Dundee; four of these facies occur above the oil-water contact in the reservoir. Two facies were recognized in the Rogers City. The contact between the Dundee and Rogers City is a corroded or bioeroded, pyritized surface. This disconformity represents a sequence boundary between deposition of the Dundee and Rogers City formations. This surface marks the drowning of the shallow water Dundee shelf.

2. Porosity and permeability distribution in both the Rogers City and Dundee were found to be controlled by depositional facies types. The distribution of facies in the Dundee is largely lenticular throughout the field. The Rogers City is dominated by a facies that is generally nonporous. The other facies present in the Rogers City (with marginal porosity and permeability) is correlative throughout the field in two discrete beds.

3. Early diagenesis of the Dundee is characterized by early marine carbonate cements in many facies and the early dolomitization of the top 10 to 15 feet (3 to 5 meters). Burial diagenesis resulted in a limited amount of porosity occlusion by pore-lining calcite, and syntaxial calcite cement, and pore-filling saddle dolomite. Stylolitization occurred throughout much of the burial history of these sediments. Hydrocarbon emplacement occurred before or during the precipitation of the last carbonate cement (saddle dolomite).

4. The presence of throughgoing macrofractures, and small-scale fractures associated with stylolite seams were documented in detailed core descriptions.
Dolomite appears to be facies-controlled rather than fracture-controlled. Therefore, the published model of fracture-controlled dolomite (Prouty, 1989a, 1989b; Ten Have, 1979) in this reservoir is judged to be in error.

5. Correlation of Dundee and Rogers City facies on well logs and comparison of thicknesses of units overlying the Rogers City show no evidence of an existing structural high in the study area during the Middle Devonian.

Previous Work

West Branch field has been the subject of several studies since its discovery in 1934. Newman (1936) discussed the early history and geology of this oil field. Ten Have (1979) studied the structural aspects of the field and mineralogy of the Dundee reservoir. He concluded that late dolomitization enhanced porosity in this field. From maps of dolomite concentrations in well cuttings, he suggested that vertical faults and fractures, inferred from a structure map, controlled the lateral distribution of dolomite in the field. Based on the work of Ten Have (1979), Prouty (1989a, 1989b) cited the West Branch Dundee Limestone as an example of a fracture-controlled dolomite reservoir.

Vugrinovich and Matzkanin (1981) stressed the significance of the development of secondary porosity through dolomitization in West Branch field. They also stated that different productive intervals in wells "seem to
be connected" in the field. Vugrinovich and Matzkanin (1981) considered a waterflood initiated in 1977 in a unitized area of the field to be a success.

Montgomery (1986) studied depositional facies in the Dundee Limestone of Buckeye oil field, about 30 miles southwest of West Branch. His study, based on observations of 12 cores, concluded that depositional facies controlled the distribution of oil producing zones in the Dundee. He also concluded that structural movement occurred before Dundee deposition and carbonate buildsups resulted in approximately 200 feet of thickening in the Dundee over the paleohigh.

Park (1987) addressed the origin and distribution of porosity in the Lucas Formation at West Branch field. The Lucas directly underlies the Dundee. Significant findings by Park (1987), in the context of this paper, include the interpretation that structural movement at West Branch post-dated deposition of the Lucas Formation, and that dolomitization of the Lucas was penecontemporaneous with deposition.

Field History: Dundee Reservoir

The West Branch Dundee oil reservoir was discovered in 1934 with the completion of Pure Oil Company's Fisk #1 well (Sec. 27, T22N-R2E). Top of the Dundee was at 2625 ft and initial production was 21 barrels a day. Field development began on a 10 acre spacing (Newman, 1936).
In 1966, the central area of the field was unitized and a Dundee waterflood program was initiated by Marathon Oil Company. The waterflood utilized a five-spot well pattern (Vugrinovich and Matzkanin, 1981). In 1989, 95 injection wells were operating in this unitized area. A smaller area of the field was unitized by Muskegon Development Company in 1978 and a waterflood began in 1981 with 4 injection wells (Lintemuth, 1989).

Before initiation of waterflood programs, the production ratio of water to oil (on a field-wide basis) was 1:15. After the Marathon waterflood began, water production steadily increased every year, and exceeded oil production in 1970. By 1980, annual water production was approximately six times as great as oil production (Vugrinovich and Matzkanin, 1981).

In 1986, 206 oil wells were active from this reservoir and 99 water injection wells were operating. Vugrinovich and Matzkanin (1981) calculate that the Dundee at West Branch has 1870 reservoir acres. Historically, an average value of -1785 ft (subsea depth) has been used for the oil-water contact in this reservoir.

Methods

This project is based on observations and test results from 11 conventional cores (average length about 100 feet) taken from West Branch field by Marathon Oil Company. The cores generally cover the majority of
the producing section of the Dundee and often include part of the overlying Rogers City Limestone. All cores were subject to whole-core or core-plug porosity and permeability analyses prior to the initiation of this study.

Slabbed core was examined using a low-power binocular microscope during preparation of detailed core description sheets. Cores were described using the format of Bebout and Loucks (1984) (Appendix A, Plates I-1 through I-38). In addition, individual well-summary plates for all cored wells were constructed to correlate rock descriptions, log signatures, and core analyses (Plates II-1 through II-11).

Well logs from 58 wells were used to create subsurface cross sections. These cross sections show the distribution and lateral continuity of facies recognized in core throughout the field (Plates III-1 through III-5).

After core descriptions were completed and depositional facies were recognized, 106 thin sections were cut from selected intervals for petrographic studies. One-half of each thin section was stained with Alizarin Red-S and potassium ferricyanide. This staining allowed easy discrimination of calcite from dolomite, and ferroan carbonates from non-ferroan carbonates (Dickson, 1966). These thin sections were used to study depositional and diagenetic fabrics.

To help determine the paragenetic sequence, 45 thin sections were polished and examined under cathodoluminescence (CL) microscopy. This
work was done in preparation for microsampling of unaltered marine sediments and cements. Luminescence microscopy allowed inferences to be drawn regarding the contamination of primary fabrics by later diagenesis and also allowed the recognition of changing trace-element concentrations in cements that commonly looked homogeneous under plane light.

Microsamples with a mass of 0.2 to 0.5 mg were drilled from cements and marine fabrics for carbon and oxygen isotope analysis. The samples were drilled from polished thin section chips using a low-power binocular microscope and a fixed dental drill bit 500 microns in diameter. Forty-eight microsamples were drilled from 35 polished chips. Sixteen of these were analyzed at the University of Miami (Florida), and thirty-two were analyzed at the University of Michigan, Ann Arbor. All results are reported using the per-mil nomenclature with respect to the Peedee Belemnite (PDB) standard.
GEOLOGIC SETTING

Stratigraphy

West Branch field (Figure 1) is located in central Michigan, slightly northwest of the Middle Devonian depocenter of the Michigan basin. Phanerozoic sediments in this basin exceed 16,000 feet in thickness (Fisher, Barratt, Droste, and Shaver, 1988). The Michigan basin is located over a Keweenawan rift sequence related to the mid-continent rift. Known Precambrian sediments in the basin are composed predominantly of siliciclastic sediments (Catacosinos, 1981). The Cambrian through Silurian sedimentary section contains sandstones, shales, dolomites, and evaporites. Fisher et al. (1988), Catacosinos (1973), and Lilienthal (1978) addressed the gross lithologies and stratigraphic relationships of these lower Paleozoic formations.

The reservoir of interest at West Branch field is the Dundee Limestone. The term "Dundee Limestone" was first used by Lane (1895) to describe limestones that crop out in southeast Michigan. Stratigraphically, these rocks lie between dolomites of the Detroit River Group and shales of the Traverse Group. Bassett (1935) described the stratigraphy and paleontology of these same outcrops. Ehlers and Radabaugh (1938) originally defined the overlying Rogers City Limestone from outcrop studies in northeastern Michigan. Cohee and Underwood (1945) used outcrop and subsurface data to address the
Figure 1. Location of West Branch and Other Nearby Middle Devonian Oil Fields.
regional lithology and thickness of the Dundee and Rogers City formations throughout the Michigan basin.


The Dundee is underlain by the Lucas Formation and is overlain by the Rogers City Limestone and Bell Shale. Conodont research from outcrop samples (Bultynck, 1976) indicates that the Dundee Limestone and the Rogers City Limestone are upper Eifelian (Middle Devonian) in age. Bultynck (1976) also concluded that the contact between Eifelian and Givetian sediments is near the base of the Bell Shale. Conodont research done by Orr (1971) agrees that the Dundee is Eifelian and the Bell is lower Givetian. Although it is implied that the Rogers City is upper Eifelian, Orr (1971) does not speculate on the stratigraphic location of the Eifelian-Givetian boundary.

During the Middle Devonian, the Michigan basin was apparently 20 to 30 degrees south of the equator (Scotese, 1984). The climate was arid, as indicated by thick evaporite and sabka dolomites of the Lucas Formation (Park, 1987). Transgressing Middle Devonian seas returned well-circulated normal-marine waters to the Michigan basin to initiate deposition of the Dundee Limestone. According to Gardner (1974), the Dundee is a biostromal shelf carbonate. He does note, however, that on the extreme western margin of the basin, sabka-lagoonal deposits predominate.
Figure 2 is a regional isopach map of the Dundee Limestone. Note that the basin depocenter is only 50 miles southeast of West Branch field.

The overlying Rogers City Limestone is described as a dark-gray, nodular, massive, aphanitic limestone (Cohee and Underwood, 1945; Gardner, 1974; Montgomery, 1986; and Sanford, 1967). This unit is interpreted here to represent deposition in water depths significantly greater than those encountered during Dundee deposition.

Figure 3 is a typical log from West Branch field. This log illustrates thickness and lithology of stratigraphic units from Lower Devonian to surface. At the base of the Lower Devonian lie the cherty limestones of the Bois Blanc Formation. The Bois Blanc is overlain by the Detroit River Group (Lower and Middle Devonian), made up of the Sylvania Sandstone, Amherstburg Formation, and Lucas Formation. The Sylvania Sandstone is generally absent in the West Branch area. The Amherstburg (predominantly limestone) and the Lucas (evaporites and dolomite) are known hydrocarbon reservoirs in the field. The contact between the Lucas Formation and the overlying Dundee Limestone is believed by Sanford (1967) to be a major unconformity. This contact is a problematic pick on well logs and is picked by some workers (e.g., Gardner, 1974) at the first anhydrite below the Dundee. In this study, the top of the Lucas was picked at the top of the pervasive dolomite below the limestone of the Dundee.
Figure 2. Regional Isopach Map of the Dundee Limestone (modified from Cohee and Underwood, 1945).
### Lithology

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glacial Drift</td>
<td>Unconsolidated sand and gravel</td>
</tr>
<tr>
<td>Coldwater</td>
<td>Shale, gray, occasional beds of siltstone, tan to gray, slightly calcareous</td>
</tr>
<tr>
<td>Sunbury</td>
<td>Shale, brown to black</td>
</tr>
<tr>
<td>Bedford-Berea</td>
<td>Shale, gray to greenish gray, trace of sandstone</td>
</tr>
<tr>
<td>Antrim</td>
<td>Shale, gray to black, pyritic</td>
</tr>
<tr>
<td>Traverse FM</td>
<td>Limestone, shaley, light gray, fossiliferous</td>
</tr>
<tr>
<td>Traverse LN</td>
<td>Limestone, light brown to tan, microcrystalline, fossiliferous, some gray shale interbeds</td>
</tr>
<tr>
<td>Bell</td>
<td>Shale, medium gray, calcareous</td>
</tr>
<tr>
<td>Rogers City</td>
<td>Limestone, dark gray, microcrystalline</td>
</tr>
<tr>
<td>Dundee LN</td>
<td>Limestone, light brown to tan, fossiliferous</td>
</tr>
<tr>
<td>Lucas</td>
<td>Dolomite, tan to medium brown, interbedded with anhydrite, limestone, and salt</td>
</tr>
<tr>
<td>Amherstburg</td>
<td>Limestone, light to medium brown, slightly fossiliferous, dolomitic</td>
</tr>
<tr>
<td>Bois Blanc</td>
<td>Limestone, light to medium brown, abundant chert</td>
</tr>
</tbody>
</table>

**Figure 3.** Typical Log Signature and Stratigraphic Units, West Branch Area.
The Dundee Limestone is generally represented by light brown to tan limestone with some preserved primary porosity in the central and eastern parts of Michigan and by dolomites in the western side of the state (Gardner, 1974). Sanford (1967) believes the contact between the Dundee Limestone and the overlying Rogers City Limestone to be conformable. The micrite-rich, nodular Rogers City Limestone is identified by its dark color.

Although outcrop and early subsurface studies treated the Dundee and Rogers City separately (Cohee and Underwood, 1945; Knapp, 1947), many recent workers have informally grouped these two formations together under the name Dundee Limestone (e.g., Gardner, 1974; Lilienthal, 1978; Ten Have, 1979). In this paper these formations are treated separately.

An abrupt contact exists between the Rogers City, which has a very low gamma ray signature on well logs, and the overlying Bell Shale, which has a very high gamma ray signature. This provides one of the most easily identified contacts in the subsurface of Michigan. Although this contact is an unconformity in basin-margin outcrops, it is believed to be conformable in the deeper subsurface (Gardner, 1974). The Bell Shale is the basal member of a sequence of shales and limestones in the Traverse Group. The Traverse Limestone of this group produced minor oil and gas in the early development of the West Branch field.
Above the Traverse Group is a thick package of mainly Upper Devonian and Mississippian shales. The Mississippian Coldwater Shale is the thickest formation in this package and subcrops beneath glacial till on the crest of the West Branch structure.

Regional Structure

Structural trends observed in Paleozoic rocks in Michigan probably represent the interaction of extrabasinal stresses and preexisting lines of weakness in the Precambrian basement rocks of the region (Hinze, Kellogg, and O'Hara, 1975). From a limited number of drill holes and geophysical techniques, Hinze et al. (1975) constructed a basement province map of the Michigan basin (Figure 4). The Precambrian provinces present are: (1) the Penokean province in the central and northern areas of the basin, (2) Central province in the southwest, (3) Grenville province in the southeast, and (4) Keweenawan rift zone which cuts across the basin trending roughly northwest-southeast. Each province is believed to have its own lines of weakness that developed during its long tectonic history.

West Branch is located over the Penokean province which is associated with predominantly northwest-southeast structural trends (Hinze et al., 1975). The West Branch anticline and other local structures reflect this trend. Clayton field, about 8 miles to the southeast of West Branch is a smaller, yet
Figure 4. Basement Province Map of Michigan (from Hinze et al., 1975).
similar structure, aligned with West Branch (Figure 1). These two structures are probably related to the same basement feature. Approximately 9 miles to the north of West Branch is the Rose City field (Figure 1). This structure is a low-relief, gentle anticline with the same orientation as the West Branch and Clayton structures.

Figure 5 is a structure contour map on top of the Rogers City Limestone in West Branch. Several features of this structure map are notable. The structure here is asymmetric, dipping about 350 feet per mile on the northeastern side and about 250 feet per mile on the southwestern side. The Clayton anticline exhibits a similar asymmetry (Versical, 1989, 1990). This provides further evidence of a close genetic relationship between these two structures. West Branch anticline also appears somewhat irregular in shape. Ten Have (1979) separated the structure into six principle folds based on the orientation of structural highs and saddle areas observed on his structure map. The crest of the West Branch fold migrates to the northeast with depth, indicated by the recent drilling activity about 2 miles north of the Rogers City/Dundee structural crest in wells targeting the gas-producing St. Peter Sandstone.
Figure 5. Structure Contour Map of the Top of the Rogers City Limestone.

Contour interval = 40 feet. Circled dots = cored wells of this study. Adapted from maps by M. Fahy, R. Dow, and W. Cheek. All contours are based on well-log tops. Off-structure contours are based on seismic and log tops.
SEDIMENTOLOGY OF THE DUNDEE LIMESTONE

From study of core and thin sections, six facies types were identified. These are: (1) crinoid grainstones, (2) skeletal-peloidal grainstones and packstones, (3) skeletal wackestones, (4) restricted mudstones and wackestones, (5) stromatoporoid-coral floatstones, and (6) fenestral-cryptalgal laminites. Various subfacies have been defined within these groups. All facies generally represent shallow-water, marine-shelf depositional environments. This section describes the depositional facies characteristics and cyclicity observed in core. Table 1 summarizes the characteristics of each facies type recognized. For each facies type, major diagenetic effects are briefly described in this section. These are discussed more thoroughly in a later section. Appendix A (Plates I-1 through I-38) contains detailed core-description sheets of each core. Plates II-1 through II-11 summarize core-analysis, well-log, and core-description data for each cored well. Field wide cross sections (Plates III-1 through III-5) show the lateral continuity of facies groups.
Table 1

Facies Characteristics, Dundee Limestone

<table>
<thead>
<tr>
<th>Facies types</th>
<th>Carbonate Grain Types</th>
<th>Internal Structures and Cyclicly</th>
<th>Porosity and Permeability</th>
<th>Depositional Setting</th>
<th>Distribution in Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crinoid Grainstone</td>
<td>Coarse-grained crinoid ossicles. Also brachiopod, bryozoan, coral-line algae, and trilobite parts</td>
<td>Limited amount of parallel bedding</td>
<td>5 to 15%</td>
<td>Quiet water crinoid meadow</td>
<td>Low in section, present in NW one half of field. 13 to 15 feet thick in cored wells, thickens to NW on cross section</td>
</tr>
<tr>
<td>Skeletal-Peloidal Sand Facies</td>
<td>Medium-grained crinoid &amp; brachiopod parts, and fine-grained peloids. Also other normal marine fossils</td>
<td>Coarsening upward hemicycles. Burrows. Rare of parallel bedding.</td>
<td>1 to 12%</td>
<td>Extensive shallow water shoal</td>
<td>Present throughout field, 60 to 80 feet thick, main lithofacies within oil producing interval</td>
</tr>
<tr>
<td>Skeletal Wackestone</td>
<td>Crinoid ossicles, brachiopods (commonly articulated), corals, and other normal marine fossils</td>
<td>Horizontal burrows</td>
<td>nil</td>
<td>Quiet subtidal environment</td>
<td>Present in different parts of section, correlative laterally for miles. Less than 10 ft thick, most common in SE end of field</td>
</tr>
</tbody>
</table>

### Porosity and Permeability

- **Crinoid Grainstone**: 5 to 15% porosity, 5 to 10 md permeability
- **Skeletal-Peloidal Sand Facies**: 1 to 12% porosity, 0.1 to 8 md permeability
- **Skeletal Wackestone**: nil porosity, nil permeability

### Depositional Setting

- **Quiet water crinoid meadow**
- **Extensive shallow water shoal**
- **Quiet subtidal environment**

### Distribution in Field

- **Crinoid Grainstone**: Low in section, present in NW one half of field. 13 to 15 feet thick in cored wells, thickens to NW on cross section
- **Skeletal-Peloidal Sand Facies**: Present throughout field, 60 to 80 feet thick, main lithofacies within oil producing interval
- **Skeletal Wackestone**: Present in different parts of section, correlative laterally for miles. Less than 10 ft thick, most common in SE end of field

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<table>
<thead>
<tr>
<th>Facies types</th>
<th>Restricted Micritic Facies</th>
<th>Stromatoporoid-Coral Floatstone</th>
<th>Fenestral-Cryptalgal Laminites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbonate Grain Types</td>
<td>Ostracods, forams, gastropods, tentaculitids, and peloids</td>
<td>Hemispherical and encrusting stromatoporoids and corals. Matrix of bioclastic sand dominated by crinoid ossicles</td>
<td>Very few fossils in laminated muds. Storm lags contain a wide diversity of fossil types</td>
</tr>
<tr>
<td>Internal Structures and Cyclicity</td>
<td>Horizontal burrows and some parallel laminations</td>
<td>None recognized</td>
<td>Cryptalgal laminations</td>
</tr>
<tr>
<td>Porosity and Permeability</td>
<td>1 to 15% (highest where dolomitized)</td>
<td>6 to 10%</td>
<td>5 to 10%</td>
</tr>
<tr>
<td></td>
<td>0 to 2 md (highest where dolomitized)</td>
<td>0.2 to 10 md</td>
<td>1 to 90 md</td>
</tr>
<tr>
<td>Depositional Setting</td>
<td>Restricted lagoon</td>
<td>Shallow subtidal</td>
<td>Supratidal environment</td>
</tr>
<tr>
<td>Distribution in Field</td>
<td>Top 10 to 30 ft of Dundee (largely dolomitized). Also present low in the section in two cores (undolomitized)</td>
<td>Low in section (below oil-water contact in cored wells), present in two cores, not correlative on log cross sections</td>
<td>Low in section (below oil-water contact), present in two cores, not correlative on log cross sections</td>
</tr>
</tbody>
</table>

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Facies Types

Crinoid Grainstone

This facies was cored in the Heintz #9 and the Cox #2 wells (Figure 5). The zone is 13 to 15 feet thick in these wells and is correlative in the northwest one-half of the field (Plates III-1 and III-2). Although low in the reservoir (approximately 80 feet below the Rogers City-Dundee contact), this facies appears to be productive in the Heintz #9 and Cox #2 wells.

Composition

This moderately-sorted, medium-grained sand is made up largely of pelmatozoan parts. Other common constituents include brachiopod, bryozoan, calcareous algal, and trilobite skeletal material (Figure 6). Neither micrite nor non-skeletal grains were observed. Two microfacies with subtle differences are present in this lithotype. The first is a moderate to well-sorted grainstone that contains 80-95% coarse-grained crinoid ossicles. The other microfacies is a moderately sorted grainstone that contains an admixture of other skeletal grain types. These two microfacies are represented in about equal proportions in this facies and are irregularly interbedded on scales ranging from less than about 2 cm to more than 30 cm (Figure 6). Bedding is most commonly horizontal. In some areas however, contacts between these microfacies appear
Figure 6. Characteristics of Carbonate Sand Facies, Dundee Limestone.

(A) Crinoid grainstone with some interparticle porosity. Brachiopod valves ("B") appear to have been articulated before physical compaction, suggesting a low energy setting. Plane light, scale = 1 mm. Heintz #9, 2862.6'.

(B) Crinoid grainstone. Bedding of two microfacies are highlighted by oil stain in the dominantly crinoidal microfacies. Scale = 3 cm. Heintz #9, 2862.5'.

(C) Peloidal-skeletal packstone. Labeled are: brachiopod ("B"), crinoid ("C"), and peloids ("P"). Crossed polars, scale = 0.5 mm. Cox #2, 2756.7'.

(D) Skeletal-peloidal grainstone with interparticle porosity. Crinoid stems ("C") are the main allochem. Brachiopod grains ("B") are rounded fragments of original skeleton. Peloids ("P") are common. Plane light, scale = 0.25 mm. Estey E-8, 2721.0'.
to be churned or disturbed, probably due to bioturbation. Brachiopod shells show no preferred orientation in either of these microfacies, and some brachiopods are articulated. This suggests that bedding is non-current induced.

**Common Diagenetic Effects**

The grains in this facies show no signs of early marine cementation. They appear to have experienced significant early compaction. Delicate grains (e.g., brachiopod, bryozoan, and trilobite parts) were commonly broken between crinoid ossicles as the sediment was compacted.

Pressure solution has also occurred in this facies, mainly through the suturing of grain contacts. Stylolite solution seams are rare in this lithotype. The mixed skeletal microfacies experienced more pressure solution than the dominantly crinoidal microfacies.

Little burial cement is present in this facies. Crinoid ossicles are covered with thin syntaxial overgrowths. Other skeletal grains generally have no cements on their surfaces. Saddle dolomite (discussed in more detail later in this paper) occurs in trace amounts in intergranular pores of this facies.
Permeability and Porosity

Porosity and permeability are both relatively high; porosity ranges from 5-11%, and permeability is 1 to 50 md (Plates II-1 and II-3). The nature of the porosity is interparticle, and it is the result of preservation of primary porosity. Diagenesis has reduced porosity through compaction (physical and chemical) and, to a lesser extent, precipitation of syntaxial cements.

Depositional Environment

The depositional environment of this facies is interpreted to be a quiet-water crinoid meadow below wave base. The interpretation is based on: (1) the lack of abrasion or rounding of skeletal grains, (2) no preferred orientation of easily hydrodynamically influenced grains (i.e., brachiopods and bryozoans), (3) the presence of some articulated brachiopods, (4) lack of early marine cements, and (5) the absence of cyclicity in this facies.

This environment was probably areally extensive; on cross section A-A″ (Plates III-1 and III-2) this facies is correlated for approximately 6 miles. It thickens considerably to the northwest. To the southeast, this facies thins and grades laterally into finer-grained, higher-energy skeletal-peloidal carbonate sand that contains coarsening upward hemicycles.
Skeletal-Peloidal Grainstones and Packstones

This facies is represented in all cores examined and is the most common lithotype observed in the Dundee Limestone. This facies is about 60 to 70 feet thick throughout the field and is present higher in the section in the northwest end of the field. This facies group consists of two subfacies that represent deposition in different energy conditions: (1) a lower-energy peloidal-skeletal packstone, and (2) a higher-energy skeletal-peloidal grainstone. These two subfacies are interbedded throughout the field. Skeletal-peloidal grainstones are typically less than five feet thick, whereas peloidal-skeletal packstones are commonly greater than five feet thick. In generalized core descriptions and field cross sections, thin grainstones are grouped with peloidal-skeletal packstones. Grainstone units are differentiated only where they are thicker than 5 feet.

Composition

The lower-energy end member is a muddy packstone that contains fine-grained peloids and skeletal grains and various amounts of micrite (Figure 6). Peloids range in size from about 0.08 to 0.2 mm in diameter. The most common skeletal grain types are crinoid, brachiopod, bryozoan, and coral parts. Average grain size of this skeletal material is about 0.25 to 0.35 mm, although many larger fossils are present (e.g., brachiopod valves, rugose corals,
and tabulate corals). Sorting is poor to moderate. Many skeletal grains show signs of abrasion, particularly the finer grained material that makes up the bulk of this facies. Also present in some parts of this subfacies are whole, unabraded, articulated fossils. The texture in these areas is usually micrite-rich.

The only sedimentary structures commonly observed in peloidal-skeletal packstones are burrows. Two major types of burrows have been recognized. One type appears to have been a lined living chamber. These burrows were observed in orientations from horizontal to vertical, and are 4 to 7 mm in diameter. This burrow type is commonly filled with sediment, although some are filled with later diagenetic cements. Also present are burrows with preserved spriten structures. These structures were found only in the micrite-rich areas of this subfacies. Most burrows of this type are near horizontal and 3 to 4 mm in diameter. It appears that much more burrowing occurred without leaving discrete structures. This accounts for the churned appearance of this lithotype.

The other subfacies in this carbonate sand facies is skeletal-peloidal grainstone, deposited in higher-energy conditions than the peloidal-skeletal packstone. The skeletal grains in this subfacies average about 0.2 to 0.35 mm in diameter and are dominated by crinoid stems, although brachiopod parts are also very common (Figure 6). Other bioclastic material present includes
bryozoans, solitary corals, trilobites, tabulate corals, coralline algae, and stromatoporoids. Stromatoporoids in this subfacies most commonly have an encrusting or bulbous morphology. Peloids are common and range in size from 0.10 to 0.15 mm, and appear to have been hardened so that they support other framework grains. Grains in this subfacies are moderately to well-sorted. The smaller size of the peloids results in bimodal sorting.

Evidence for abrasion and rounding of bioclastic grains is abundant in this subfacies. Fossils, especially brachiopods, display a high degree of fragmentation and rounding. Some crinoid grains appeared slightly micritized. Whereas delicate fossils were preserved in some parts of the peloidal-skeletal packstone, none were found in the skeletal-peloidal grainstone.

Many of the multicrystalline skeletal grains (e.g., brachiopods, bryozoans, and trilobite parts) are partly covered by an early marine cement crust. This crust is commonly obscured by later burial cement. This early cement appears to have been a crust of acicular carbonate cement. If the peloids in this subfacies are of biogenic origin, they may have been hardened by early marine cementation.

The only preserved primary sedimentary structure observed in this subfacies is a two foot interval with planar bedding of fine skeletal material observed in the Cox #2 core (Appendix A, Plate I-8). Inclined beds of disarticulated brachiopod valves were occasionally observed in this subfacies.
These may represent the only remaining indication of ripple marks or cross bedding.

**Common Diagenetic Effects**

This carbonate sand facies shows little or no sign of physical compaction. Peloids are not deformed, brachiopod and bryozoan parts do not appear broken by physical compaction, burrows do not appear to be deformed, and many oversized interparticle pores remain open in grainstones. This lack of physical compaction is probably due to the presence of an open framework caused by early marine cements that encrusted many skeletal grains and hardened peloids.

This facies contains abundant stylolites. Although the grainstones are largely unaffected by pressure solution, micrite-poor packstones typically contain numerous sutured-seam stylolites with amplitudes between 1 and 5 cm. Micrite-rich packstones contain both sutured-seam stylolites and microstylolitic swarms. Sutured-seam stylolites in this facies commonly have fracture sets associated with them. These fractures are between 2 and 30 cm long. Many of these are open, especially near the solution seam. These fractures are vertical and, in individual core pieces, have consistent orientations. Such fractures have been documented elsewhere by Nelson (1981) and Watts (1983).

The most common cement in this facies, particularly in grainstones, is
syntaxial crinoid calcite overgrowths. Overgrowths 10 to 15 μm are common around crinoid columns.

As mentioned above, ghosts of acicular cement crusts have been observed on multicrostalline skeletal remains in this facies. Other calcite cements present in this facies are scalenohedral pore-lining cement and equant, blocky pore-filling cements. These two cement types are most common in relatively large pores (e.g., inside articulated brachiopods, gastropod molds, or open fractures).

Pore-filling euhedral saddle dolomite is present in trace amounts in this facies. This cement was found scattered in all pore types.

Porosity and Permeability

The primary pore type is interparticle with a limited amount of intraparticle porosity. This porosity is what remains of the primary pore space after limited early compaction, neomorphism of micrite, and occlusion of porosity by burial cements. Porosity is highest in the skeletal-peloidal grainstone subfacies. Core-analysis porosity and permeability from this facies range from 4-12% and 0.2 to 20 md, respectively. Peloidal-skeletal packstones have core analysis porosity generally ranging from 2-8% and permeability between zero and 10 md.
Some relatively low-porosity peloidal-skeletal packstones show very high permeabilities in the 100 md range. A comparison of core descriptions and core analyses suggests that these permeability highs are produced by stylolite-related fracture sets. The Cox #2 core between 2730 and 2756 is the best example of this relationship (Plate II-3, and Appendix A, Plates I-7 and I-8).

Isolated coral pieces in this facies group retained much of their original intraparticle porosity, but this is a very minor contributor to overall porosity.

**Depositional Environment**

This facies group represents shallow-water platform sedimentation, often at or above normal wave base. This facies group may be somewhat analogous to the "platform interior sand blanket" described by Ball (1967) from the Great Bahama Bank. Ball's descriptions of allochem types, discrete burrows, lack of primary sedimentary structures, presence of marine cements, and the large areal extent of the environment fit observations from the Dundee cores very closely.

**Skeletal Wackestone**

This lithotype occurs in different parts of the Dundee Limestone section and is generally correlative for miles in cross sections. Although thin, this facies may be of considerable importance for enhanced or secondary recovery
projects at West Branch because of its very low porosity and permeability.

**Composition**

Common skeletal allochems in this facies include crinoid, brachiopod, bryozoan, coral, ostracod, foram, trilobite, and stromatoporoid parts. Fine-grained peloids are also present. These grains show no signs of abrasion. Articulated brachiopods, some with the spiralia well-preserved, are common in this facies. Also present in a few places are colonies of tabulate corals preserved in growth position.

The only sedimentary structures observed within this facies were burrows. The most common type of discrete burrow is generally horizontal, about 4 mm in diameter, with preserved spriten structure. Also present, although rare in this facies, are lined burrows that are nearly vertical, about 5 mm wide, and 5 cm long. These burrows are filled with unstructured sediment similar to that surrounding the burrow.

**Common Diagenetic Effects**

It is difficult to assess the amount of compaction that has occurred in this facies. However, examination of horizontal burrows with preserved spriten and branching tabulate coral colonies suggest that some (<30%) physical compaction did occur.
Pressure solution has taken place in this facies in the form of microstylolites and microstylolitic swarms. Contacts with other facies are usually sharp, especially at the base of this facies. These contacts are commonly sites of thick sutured-seam stylolites.

Few cements were observed in this facies because of the very low volume of porosity available for cementation. Intraparticle porosity associated with corals and stromatoporoids was commonly filled with fine scalenohedral calcite crusts which coarsened outward from the pore wall. Rarely, small rhombs of saddle dolomite were seen in a few of these pores.

**Porosity and Permeability**

This facies is very tight and impermeable. Core analysis porosity is typically 2% or less, and permeability is generally 0.1 md or zero. The only observable porosity in core or in thin section is small amounts of isolated intraparticle porosity in scattered corals and stromatoporoids.

**Depositional Environment**

This facies represents deposition in quiet water, probably below storm wave base. Sharp contacts with other, underlying facies suggests that transgressions happened rapidly and may have occurred (or resulted) in conditions that made continued deposition of the previous facies impossible.
Restricted Mudstones and Wackestones

This facies is present in all cores examined in this study. The top 10 to 15 feet of the Dundee Limestone were invariably found to be of this facies (Plates II-1 through II-11). This facies was also found to be present very low in the section near the base of the Grow #4 core (Plate II-10). This facies group is represented by two end-member subfacies: restricted mudstone subfacies and restricted wackestone subfacies.

The restricted mudstone subfacies contains very few skeletal grains in its predominantly micritic fabric (Figure 7). Fossils include forams, ostracods, and numerous spore cases 100 μm in diameter (Tasmanites). Small, high-spired gastropods are also present, though rare. Ostracods are commonly articulated, indicating that they were deposited under very low energy conditions. Fabric has been nearly completely obliterated by neomorphism and diagenesis. Some fine laminations are present and horizontal burrows are common in some zones. These burrows are 4 to 7 mm in diameter. Rock texture appears mottled in some areas—it is unclear whether this represents burrowing or a diagenetic fabric.

The restricted wackestone subfacies contains a slightly more diverse faunal assemblage that includes forams, ostracods, trilobites, tentaculitids, crinoids, and
Figure 7. Characteristics of Restricted Mudstones and Wackestones, and the Dundee-Rogers City Contact.

(A) Restricted mudstone containing spore case ("SC") and ostracod mold ("O"). Micrite is not pelleted. Plane light, scale = 0.25 cm. Reinhardt #3, 2616.5'.

(B) Restricted wackestone facies with tentaculitid ("T") and brachiopod spine ("B"). Matrix is peloidal in this example. Plane light, scale = 0.25 mm. Grow #9, 2665.7'.

(C) Bioerosional contact at the top of the dolomitized restricted mudstone facies, Dundee Limestone ("DL"). The overlying Rogers City Limestone ("RCL") displays the nodular wackestone texture typical of Rogers City nodular wackestone facies. Scale = 3 cm. Reinhardt #3, 2585.3'.

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brachiopods (Figure 7). Brachiopods are rare in the facies compared to their abundance in the rest of the Dundee. Some horizontal fine laminations are present in this facies, and in these areas the rock fabric may be a fine-grained packstone. This facies occurs as various thicknesses in the cored wells and always forms a gradational contact with the overlying restricted mudstone facies.

The grains in restricted wackestones show no signs of abrasion, but articulated, delicate fossils are very rare. Some crinoid stems in this subfacies have micrite envelopes.

**Common Diagenetic Effects**

In the restricted mudstone facies near the top of the Dundee Limestone, bioeroded, mineralized surfaces that appear to be hardgrounds are common. In the top 30 cm of the Dundee, several cores show as many as three of these distinct surfaces. The uppermost surface is most dramatic. This surface has a pyritized rind a few millimeters thick in most cores, and appears highly bioeroded in the Buckingham #4 core. This surface is overlain by darker, nodular micritic sediments of the Rogers City Limestone (Figure 7).

The restricted mudstone subfacies (and in some cores, the top 3 to 5 feet of the underlying restricted skeletal wackestone subfacies) has been pervasively dolomitized. This is especially true of cores from the southeast end of the
field. Cores taken more to the northwest (i.e., Estey E-8, Cox #2, Donovan #6, Hientz #9) show less pervasive dolomitization of this facies and commonly have thin (less than 30 cm), interbedded streaks of undolomitized mudstone remaining.

Matrix-replacive dolomite occurs in a wide range of crystal sizes, from less than 3 μm to greater than 200 μm. These different crystal sizes occur together to produce a highly tortuous pore network.

The mudstone unit recognized low in the section in the Grow #4 has not been dolomitized and does not contain any recognizable hardgrounds.

In areas where the restricted mudstone has not been replaced by dolomite, it is difficult to tell if these muds were compacted during burial. Fossils appear undeformed but it is possible the unconsolidated carbonate mud could have compacted without deforming more rigid particles (e.g., Shinn and Robbin, 1983). In dolomitized sediments, however, it is apparent that some post-replacement physical compaction has occurred. Skeletal fragments are broken and the spherical spores that are well preserved in unreplaced mudstone are very deformed.

The contact between dolomitized and undolomitized mudstone is commonly sharp. Where a bed of undolomitized mudstone is thin, there commonly are many irregular, high-angle fractures that cut through the unaltered mudstone. Such fractures generally do not continue into the
dolomite.

Some unreplaced mudstones contain microstylolites, and where skeletal grains are locally concentrated, sutured-seam stylolites have developed. A few of the contacts between unaltered mudstone and dolomite have also developed sutured-seam stylolites. Sutured-seam stylolites in this facies typically have an associated set of fractures similar to those discussed in the previous section that concerned the peloidal-skeletal packstone facies. Some fracture sets associated with stylolites in the mudstone facies are, however, much longer; some are over 30 cm in length.

The restricted wackestone subfacies contains a large amount of chert, especially in cores from the southeast end of the field. Much of the chert is clearly nodular, but in some places the entire core is chert for up to six inches. In these areas it is possible that chert is bedded. The chert is most commonly a light buff color, lighter than the surrounding light brown limestone. All but the largest skeletal grains are replaced by chert. Fine textures in the original sediment are very well-preserved, especially burrows that contain spriten. Chert also seems to have preserved trace fossils of other burrowers whose effect on the sediment is not as obvious as other burrows. These burrows are about the same width (5 mm), but they seem to be more random. This gives the sediment a churned appearance. Such subtle textures are not preserved in the adjacent carbonate.
As with the other matrix-supported facies, examination of the limestone fabric of this rock provides few clues for assessing the amount of physical compaction the sediments have experienced. However, many of the chert nodules have numerous vertical fractures, which indicates some physical compaction has taken place. Many of these fractures have been partly filled by carbonate sediment that flowed into the open space.

Stylolitization has also occurred in this facies, creating sutured-seam stylolites, microstylolites and microstylolitic swarms. As in the other facies, sutured-seam stylolites commonly have associated fracture sets. As in the peloidal-skeletal carbonate sand facies, these fractures range in size from 5 to 20 cm long and have consistent orientations in each sample.

Porosity and Permeability

Unreplaced, restricted mudstone interbedded with dolomitized sediment near the top of the Dundee and the restricted mudstone unit deep in the section cored in the Grow #4 have no observable porosity in thin sections, and no core analysis was performed on this part of the core. Near the top of the Dundee in the southeast, where this facies is pervasively dolomitized, core-analysis data indicate that intercrystalline porosity is generally 1-15% and permeability is generally 0.1 md to zero in the top 5 feet, and between 0.1 and 2.0 md below. The low permeability is believed to be the result of the
wide range of crystal sizes present and the tight, random packing of the dolomite rhombs.

The restricted wackestone subfacies has generally very low porosity and permeability as well, although the chert has some microporosity visible when viewed in thin section. In unreplaced limestone fabric, core analysis for this subfacies indicate porosity is 3-6% and permeability of zero to 2.0 md. In the southeast where the top few feet of this subfacies is dolomitized, however, intercrystalline porosity ranges between 1 and 15%, and permeability between zero and 4.0 md (Plates II-5 through II-11).

**Depositional Environment**

This facies group represents deposition in a low-energy subtidal environment. The relatively low diversity faunal assemblage suggests that the seawater present during deposition had limited circulation with normal-marine waters and that environmental stresses in this setting were too high for many normal marine fauna. The gradational contact between the restricted wackestone subfacies and the overlying restricted mudstone subfacies and the decreasing faunal diversity upward indicate that restriction of seawater continued with time. The hardgrounds that cap the Dundee Limestone may be related to further restriction of environmental conditions in this setting.
Stromatoporoid-Coral Floatstone

This facies occurs low in the Dundee section, below the oil-water contact as interpreted from electric logs. This facies is thin (2 to 3 feet) and is present in the cores of two wells, the Estey E-8 and the Grow #4 (Plates II-4 and II-10). This facies is not correlative in cross sections. Although not believed to be a reservoir rock, it is included in this discussion for completeness of discussion of Dundee lithofacies.

Composition

The main constituents of this facies are bulbous hemispherical stromatoporoids (ranging in size from less than 2 cm to over 30 cm in diameter), smaller encrusting stromatoporoids and branching colonial tabulate corals (approximately 1 to 2 cm in diameter). These fossils are typically overturned and they are no longer in growth position. The sediment between these larger fossils is a medium to fine-grained, well-sorted bioclastic sand that contains crinoid ossicles, brachiopod parts, and many unidentified fossil fragments (Figure 8).

Depositional Environment

The well-sorted, mud-free nature of the bioclastic sand and the morphology of the stromatoporoids (encrusting and bulbous forms) indicate
Figure 8. Stromatoporoid-coral Floatstone and Fenestral-cryptalgal Laminitic Facies, Dundee Limestone.

(A) Stromatoporoid-coral floatstone facies. Coral ("C") and stromatoporoid ("S") in a matrix of bioclastic sand. Scale = 3 cm. Estey E-8, 2740.5'. (B) Fenestral-cryptalgal laminitic facies. Top 2 to 3 cm contain cryptalgal laminations. The underlying micritic rock contains some saddle dolomite filled vertical tubes and numerous isolated bubble-shaped voids or fenestrae. Scale = 3 cm. Estey E-8, 2747.5'.
that this facies was deposited in a subtidal environment of moderate to high energy, and was probably above wave-base.

**Fenestral-Cryp talgal Lam inite Facies**

This facies is present in only two cores in this study and it occurs at the base of these cores (Estey E-8 and Grow #4, Plates II-4 and II-10). In both cores, this facies occurs well below the oil-water contact. In all areas, this rock type is light tan to cream colored. The facies is discussed here to document the presence of this lithotype in the Dundee Limestone.

**Composition**

The main fabric present in this facies is a fine-grained carbonate silt or mud that contains many vertical and horizontal fenestral pores (present in both cores). No other structures are visible in this fabric type. Some areas also contain numerous skeletal parts. Fauna represented by these skeletal grains mainly include bryozoans, corals, stromatoporoids, brachiopods, and crinoids. Intraclasts are also common.

The other fabric type is a fine-grained laminated carbonate which contains many fine (100 to 500 μm) fenestral pores. Commonly, these pores are concentrated just below the sharp contacts of these laminations. Most laminations are between 0.25 and 0.5 cm thick (Figure 8). This laminated
fabric type is present only in the Estey E-8 core. This fabric matches algal-laminated sediments described by Shinn (1983).

Also present in both cores are fine-grained (sand to silt size) zones that appear to be disrupted. These zones contain irregular clasts of sediment and some large irregular pores filled with geopetal sediment, sparry calcite, and saddle dolomite. These areas also have vertical disturbances similar to burrows, but they are irregular in size and shape. These areas are interpreted to be soil clast zones (Shinn, 1983).

**Depositional Environment**

The presence of cryptalgal laminations and soil clast zones in this light colored (oxidized?) sediment indicate that the environment of deposition was supratidal (Shinn, 1983). Coarser grained beds of skeletal material probably represent storm deposits.

**Sedimentary Cyclicity**

Coarsening upward hemicycles are present in the skeletal-peloidal carbonate grainstones and packstones. These hemicycles are 2 to 18 feet thick (average thickness about 8 ft) and they were recognized in all cores examined in this study. These coarsening upward hemicycles consist of (in descending order): (1) Skeletal-peloidal grainstone (1 to 8 ft thick), (2)
Peloidal-skeletal packstone (between 2 and 17 ft thick), that contains increasing amounts of micrite downward, and (3) Skeletal wackestone (usually less than 2 ft thick, rare).

Figure 9 summarizes this hemicyclicity and diagrammatically displays the common structures and allochems. Many of the hemicycles identified in core are incomplete. They lack either a well-developed grainstone at the top or a wackestone at the base, or both. Where hemicycles are not complete, the skeletal wackestone is most commonly absent.

In most recognized cycles, the facies changes within a single cycle are gradational. Contacts between hemicycles are typically abrupt. Grainstones near the top of these cycles commonly contain surfaces that appear to have been cemented into a hardground and were either scoured or bored before being covered by more grainstone. Oversized pores are also common; these may indicate early cementation.

Coarsening upward hemicycles are interpreted to represent the shoaling upward of an extensive shallow water environment in response to fluctuations in relative sea level. The evidence of sea floor lithification (hardgrounds) in the grainstones at the top of hemicycles, and abrasion of the skeletal material in this subfacies suggests deposition had slowed considerably. The allochems present in these areas were probably at the sediment-water interface for an extended period of time. The abrupt contact between grainstones and
Figure 9. Idealized Coarsening Upward Hemicycle, Dundee Limestone.
overlying wackestones or packstones suggests a rapid rise in relative sea level before the initiation of deposition in each new cycle. Contributing to the apparent abruptness of these inter-cycle contacts is the effect of lag-time. Lag-time is the period that carbonate environments take to re-establish sediment production after a period of non-productivity (Schlager, 1981).

The change from deposition of packstone to grainstone represents shallowing of the local environment until the sediment surface is in a zone of significant wave energy. Grainstones were deposited first in the shallower areas of the carbonate ramp and spread out laterally as shoaling continued. Shoaling and spreading of this environment continued until the deepening event that started deposition of the next cycle; whether or not these cycles were allo- or autocyclic. Therefore, when a rise in relative sea level occurred, sediments from shallower water areas more commonly had well-developed grainstone caps that created a recognizable coarsening upward hemicycle in the rock record. Sediments deposited in relatively deep water would be expected to contain fewer recognizable coarsening upward hemicycles than sediments deposited in shallow water.

To test this idea, gross interval thicknesses and coarsening upward hemicycles were recorded for each core (Plates II-1 through II-11). These frequencies were normalized to a gross interval of 100 feet so that they could be meaningfully compared. Figure 10 is a plot of the normalized frequency
Figure 10. Plot of Normalized Cycle Frequency vs. Distance From the First Well in Cross Section A-A"".  
Cored wells have been projected into a line that runs N65°W from well A-l on Plate III-1. Note cyclicity increases markedly to the southeast.
of hemicycles in each well versus the distance of that well from the northwestern end of cross section A-A'' (Plate III-1). Cores from the northwestern end of the field have a normalized cyclicity of 12.5 to 15.7 per 100 ft, whereas wells in the southeastern part of the field have between 17.6 and 26.7 cycles per 100 ft. If, as discussed above, shallower water settings are more sensitive to fluctuations in relative sea level, decreasing values of normalized cyclicity to the northwest suggests that the depositional setting of the skeletal-peloidal grainstones and packstones sloped in that general direction. Note that this direction is away from, rather than toward, the depocenter of the Michigan basin during the Middle Devonian (Figure 2).
SEDIMENTOLOGY OF THE ROGERS CITY LIMESTONE

Although the Dundee Limestone is the focus of this study, several cores (Donovan #6, Cox #2, Doran #5, Hart #2, Hart #7, Buckingham #4, and Grow #4) have been described from the Rogers City Limestone. Two main facies types were recognized—nodular wackestones, and skeletal packstones. For completeness, the following section describes these Rogers City facies.

Nodular Wackestone

Composition

Common skeletal allochems in this facies are ostracods, forams, trilobites, tentaculitids, and echinoderms. Megafauna are very rare in this facies and include calcareous sponges, small gastropods, and large crinoid parts. This facies appears dark gray on rough-cut surfaces, but is dark to medium brown when etched with a weak hydrochloric acid solution.

This facies has an obvious nodular texture, with nodules 5 to 8 cm in height and commonly greater than 7 cm wide surrounded by darker limestone. This darker fabric contains numerous wispy laminations and microstylolites that appear compacted around the nodular areas. Horizontal burrows about 5 mm wide are preserved in the nodular areas, but obliterated in the highly compacted limestone surrounding the nodules.

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Common Diagenetic Effects

Nodules are interpreted to represent differential early cementation of the carbonate mud on the sea floor and subsequent burial compaction. No evidence that this nodular texture could be attributed to the actions of burrowing organisms was observed. Some of these nodules have small fractures (less than 2 cm long) around their outer edges that are interpreted to represent burial compaction of early cemented nodules.

Microstylolites are commonly present around the nodules and may have formed along thin organic laminations in these inter-nodular areas.

Cements observed in this facies occur as pore-filling calcite and saddle dolomite, although these cements are uncommon, mainly because visible pore-space is rare in this facies. Most pores are small, wide fractures in nodules or rare skeletal molds.

Permeability and Porosity

Core analysis was rarely performed on rocks from this facies type. Limited plug analysis indicates a porosity range of 1-3% and a permeability range of zero to 1.0 md. The only whole-core analysis performed (Cox #2, Plate II-3) indicates porosity of about 1% with no measurable permeability.
Depositional Environment

This facies is the dominant lithotype of the Rogers City Limestone. The depositional environment is interpreted to be a deeper-water setting than the depositional environments of the Dundee Limestone.

Skeletal Packstone

No thin sections were made from this facies; therefore, all observations are from slabbed and polished core.

Composition

The most common allochems in this facies are crinoid ossicles ranging in size from less than 1 mm to 20 mm in diameter. Some crinoid stems are still largely articulated. Other fossils present are pelecypods, calcareous sponges, and trilobite parts.

Common Diagenetic Effects

This Rogers City facies also appears to have been differentially cemented before significant burial. However, since this facies is a packstone (grain-supported fabric), little or no differential physical compaction has occurred around these cemented areas.

Observations with a low-power binocular microscope indicate that pore-
lining calcite is present in fossil molds. Pore-lining fluorite is also present in some molds. Sutured-seam stylolites are common in this facies.

**Permeability and Porosity**

Core analysis of this facies in the Donovan #6 core indicate porosity as high as 7% and permeability up to 2.0 md. Porosity and permeability values appear to be dependent on the amount of skeletal material present vs. mud and how much of the sediment has been differentially cemented. Porosity is highest where there is little mud or intergranular cement. The main pore type is interparticle with some moldic porosity.

**Depositional Environment**

The poor-sorting of this facies and the presence of articulated crinoid stems and intact calcareous sponges indicate that the depositional environment was a low-energy setting. The differential cementation of this facies appears similar in scale and style to the cementation observed in the Rogers City nodular wackestone facies. The main difference between these facies is the abundance of benthic megafauna hard parts in the skeletal packstone facies that form a grain-supported framework. The depositional environment of this facies is similar to that of the Rogers City nodular wackestone (deeper, quiet water), except something changed to allow the proliferation of benthic
megafauna. The accumulation of the skeletal material of these animals was fast enough relative to micrite deposition to form a packstone with a degree of interparticle porosity.
FIELD-WIDE STRATIGRAPHIC CORRELATIONS

Previous sections have shown that a complex group of facies exists in the Dundee and Rogers City Limestones. These facies are commonly arranged in hemicyclic, shoaling upward sequences. Vertical heterogeneities in facies and reservoir properties are clearly illustrated in Plates II-1 through II-11. Lithologic changes commonly correspond to changes in log signatures. As a measure of lateral heterogeneity, the next logical step is to construct and correlate field-wide cross sections. Features such as pinch-outs, blanket-like permeability barriers, and gradual facies transitions can be detected with such cross sections.

Three field-wide cross sections (Plates III-1 through III-5) have been constructed from well logs. One cross section is parallel, and two are perpendicular to the trend of the field (Figure 11). Each cross section includes well logs from cored wells examined in this study. These sections are hung on the contact between the Bell Shale and the Rogers City Limestone. Units identified in core were correlated in the cross sections in both the Rogers City and Dundee Limestones to examine lateral variations.

Cross section wells were chosen because: (1) they were generally on-trend with the chosen path of the cross section, and (2) they had been logged with "modern" logs in the last 20 years. Preferred wells had gamma ray, neutron
Figure 11. Location of Cross Sections (Plates III-1 through III-5) on Structure Contour Map of the Top of the Rogers City Limestone.

Map adapted from same sources listed in Figure 5. Contour interval 40 feet.
porosity, bulk density, and electrical resistivity logs. Many wells did not have neutron porosity/bulk density logs, so sidewall neutron porosity logs were used instead. It is important to have included resistivity logs in the cross sections. This is because porosity logs alone generally did not have high enough resolution to allow confident correlation of marker beds.

Figures 12 and 13 are simplified versions of the cross sections constructed from well logs (Plates III-1 through III-5). Wells in these figures were projected into straight lines drawn along the trend of the cross sections.

Dundee Limestone Correlations

Thirteen markers in the Dundee were correlated in the cross sections. The markers were picked by comparing distinctive lithologic units in core to the correlative log signatures. Contacts between rock units identified in core commonly appeared as markers on logs because the rock properties of overlying and underlying units contrasted with one another.

Markers D1 and D2 were found to be correlative throughout the entire field. Marker D1 represents the contact between the nodular, micritic limestone of the Rogers City and the underlying dolomitized Dundee. This contact is present in six of the cores examined and is a distinct hardground at the top of the Dundee. Marker D2 is the base of the dolomitized restricted mudstone. In the northwest one-third of the field, the lithotype
Figure 12. Simplified Version of Stratigraphic Cross Section A-A''', Plates III-1 Through III-3.

Datum is the Bell Shale/Rogers City Limestone contact. Core control indicated by texture logs and lithology symbols. Tick marks along the top line are wells used in the cross section and projected into a line N65°W.

Abbreviations of well names in index map: H9 = Heintz #9, D6 = Donovan #6, C2 = Cox #2, EE-8 = Estey E-8, H2 = Hart #2, B4 = Buckingham #4, G4 = Grow #4, and G9 = Grow #9.
Figure 13. Simplified Versions of Stratigraphic Cross Sections B-B' and C-C', Plates III-4 and D atum is Bell Shale/Rogers City Limestone contact. Core control indicated by texture logs and symbols (key for lithology symbols on figure 12). Tick marks along the top line are wells used to orient sections and projected into a line N2°E for cross section B-B', and N80°E for cross section C-C'. Abbreviations of well names in index map: EE-8 = Estey E-8, D5 = Doran #5, H2 = Hart #2, H7 = Hart #7.
Cross Sections B'-B' and C-C', Plates III-4 and III-5.

Core control indicated by texture logs and lithology. Tick marks along the top line are wells used in the cross section B-B', and N80°E for cross section C-C'.

= Estey E-8, D5 = Doran #5, H2 = Hart #2, and H7

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below the dolomitized mudstone is the skeletal-peloidal carbonate sand. In the southeast two-thirds of the field, the restricted skeletal wackestone facies underlies the D2 marker.

The contact between restricted skeletal wackestone and underlying skeletal-peloidal carbonate sand is correlated as marker D3. This marker appears on well logs as a distinctive change from low porosity, high resistivity wackestones to underlying higher porosity, lower resistivity skeletal-peloidal carbonate sands. The D3 marker is correlative in the southeastern two-thirds of the field. The restricted wackestone facies (between D2 and D3) thickens from the southeast end of the field toward the center of the field. The D3 marker and the generally low porosity, high resistivity signature of the restricted wackestone facies gradually disappears between the Estey E-8 and Cox #2 wells (A-18 and A-10, respectively, Plates III-2 and III-1). This suggests a gradational contact between laterally equivalent skeletal-peloidal carbonate sand and the restricted wackestone facies present in these wells below the D2 marker. This lateral facies relationship implies that the depositional environment deepened to the northwest, where marine packstones were deposited, and shallowed to the southeast, where lagoonal wackestones were deposited.

Markers D4 through D9 all occur within the skeletal-peloidal grainstones and packstones. Markers D4, D5, and D8 all mark the tops of coarsening
upward hemicycles that contain unusually thick skeletal-peloidal grainstones. These created interparticle porosity zones that were thick enough to be confidently recognized and correlated on well logs. All three of these markers were correlative for about two miles on the log cross section constructed parallel to the field trend (Figure 12 and cross section A-A", Plates III-1 through III-3). Markers D4 and D5 are present in the northwestern half of the field, and D8 is present lower in the section in the southeastern half of the field.

Markers D6, D7, and D9 all mark the tops of low porosity skeletal wackestone or tight peloidal-skeletal packstone facies. These units create low porosity and very high resistivity responses on well logs and were very correlative for 2 to 3 miles on cross sections (Figures 12 and 13). Marker D7 occurs in the southeast half of the field in a thick section otherwise dominated by peloidal-skeletal packstones (Plates II-4, II-9, II-10, and II-11). Marker D6 is in the northwest half of the field and occurs about 11 ft below marker D5. The unit between D5 and D6 has high porosity and permeability (between 4 and 11%, and 0.1 and 8 md on core analyses, Plates II-2 and II-3) relative to the rock above and below this unit. Markers D8 and D9 bracket a similar high porosity and permeability unit in the southeastern half of the field.
The crinoid grainstone facies is delimited by markers D10 and D11. These markers are present relatively low in the section in the northwestern half of the field. The D10 marker is the contact between the crinoid grainstone facies and the overlying skeletal-peloidal grainstones and packstones. The crinoid grainstone, which has excellent porosity and permeability, overlies a tight skeletal wackestone. This sharp contact is correlated as marker D11. In a traverse from NW to SE (well A-1 through A-19, Plates III-1 and III-2), log signatures of the rocks between D10 and D11 indicate gradually decreasing porosities and increasing resistivities. Interval thickness also decreases in this direction. Examination of this D10 to D11 unit in the Estey E-8 core (Plate II-4, and Appendix A, Plates I-11 and I-12) indicates that the porosity zone in this area is a skeletal-peloidal grainstone that contains two coarsening upward hemicycles. This lateral facies change from crinoid grainstone to skeletal-peloidal grainstone indicates an up-dip change in environment of deposition (shallower, higher-energy environment in the Estey E-8 area than further to the northwest in the Cox #2 and Heintz #9).

Markers D12 and D13 are present low in the section at the extreme southeast end of cross section A-A″ and at the southern end of cross section C-C' (Figures 12 and 13). These markers are the only lines correlated in the cross sections without core control. The area between the markers is a thick correlative unit of low resistivity and high porosity that appears to thicken to
the southeast. Thin gamma-ray peaks of unknown origin occur in this interval.

Marker L1 correlates the inferred contact between the Dundee Limestone and the underlying Lucas Formation. This marker was correlated on well logs at the first large inflection toward higher porosity and higher density associated with Lucas dolomite.

Rogers City Limestone Correlations

Correlated markers in the Rogers City Limestone consist of the very sharp contact with the overlying Bell Shale (labeled R1, Plates III-1 through III-5), and the tops of two relatively high porosity and permeability zones (labeled R2 and R3 in cross sections). Immediately below each of these two markers (R2 and R3) are poorly-sorted, medium-grained skeletal packstones that represent times when benthic megafauna produced enough skeletal material to create packstones with some interparticle porosity. The R2 and R3 log markers were picked at the top of these porosity zones, as indicated by the inflection to lower resistivity on electric logs. The R1 marker is defined by a sharp drop in gamma ray counts from the overlying Bell Shale to the Rogers City Limestone.

Correlation of these markers shows no lateral variation of these units throughout the West Branch field. The correlation lines are virtually parallel to the Bell Shale/Rogers City Limestone datum.
DIAGENESIS

Core and thin section examination has shown the presence of a number of diagenetic phases. These include marine cements, syntaxial overgrowths, scalenohedral and blocky calcite cements, matrix-replacive dolomite, saddle dolomite, and chert. Pressure solution, compaction, and stylolitization are common in some facies. One remarkable feature, important from a reservoir standpoint, is the abundance of primary porosity in these rocks.

This section presents the results of plane light, cathodoluminescent (CL), and ultraviolet fluorescent microscopy of thin sections, and carbon and oxygen stable isotope analysis of microsampled rock fabrics. The purpose of diagenetic work was to unravel the paragenetic sequence, determine a marine isotopic signature from pristine allochems and micrite, and investigate the origin of dolomite. Dolomite origin is important in light of the fracture-controlled dolomite models developed by Prouty (1989a, 1989b) and Ten Have (1979) for the Dundee Limestone in West Branch field.

Figure 14 shows the paragenetic sequence determined in this study. Early marine cementation was followed by chertification and dolomitization of restricted facies. Various calcite cements were deposited and stylolitization occurred upon burial. Saddle dolomite and late non-carbonate cements are the most recent diagenetic phases. The following discussion focuses on the
Figure 14. Paragenetic Sequence Determined for the Dundee Limestone, West Branch Field.
evolution of diagenesis in these rocks.

Early Marine Fabrics

Precipitation of early marine carbonate cement was common in some of the depositional environments of the Dundee Limestone. In the skeletal-peloidal grainstone subfacies, acicular cement crusts grew on some skeletal parts (Figure 15). Peloids in this subfacies are undeformed framework grains and therefore are believed to have been hardened on the sea floor by early marine cementation (Figure 6). Also, rare hardgrounds in this subfacies provide further evidence sea floor cementation.

The preservation of limestone beds in the dolomitized, restricted mudstone facies is attributed to early marine cementation. After cementation, these beds were then impermeable to fluids that later dolomitized the surrounding sediment. The way these beds deformed when physically compacted also supports the conclusion of early lithification (Figure 15).

Certain marine rock components were examined and microsampled for stable isotope analysis to provide an isotopic "starting point" to which the stable isotope composition of cements could be compared. The ideal starting point is the original marine isotopic composition of calcite precipitated from Dundee-age seawater. The effects of neomorphism and precipitation of burial cements, however, make this determination of original marine signature
Figure 15. Early Marine Calcite Cement and Replacive Chert, Dundee Limestone.
(A) Acicular early marine carbonate cement crust ("MC") on a brachiopod substrate ("B"). Dark area ("BC") is blocky calcite cement extinct under crossed polars. Scale = 0.005 mm. Cox #2, 2730.2'. (B) Boudins of a calcite bed ("C") surrounded by dolomite ("D"). Bed is interpreted to have been cemented on the sea-floor and fractured during the early stages of burial compaction. Marine cementation apparently protected this bed from dolomitization by reducing permeability. Scale = 3 cm. Grow #9, 2625.5'. (C) Chert nodule in the restricted wackestone facies. Fractures ("F") in chert and compaction of dark laminations in limestone ("L") around chert nodule ("C") indicate physical compaction. Scale = 3 cm. Estey E-8, 2655.6'.

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difficult, if not impossible. Work done by Popp, Anderson, and Sandberg (1986) on Middle Devonian carbonate rock constituents indicated that brachiopod skeletal material is commonly very stable in the burial environment. It is commonly thought that brachiopod valves are secreted as stable low-magnesium calcite. In their study, Popp et al. (1986) found that brachiopods that appeared pristine when examined using a scanning electron microscopy were non-luminescent under CL microscopy. They determined a $\delta^{18}O$ value of $-3.7 \pm 0.2$°/oo for an original marine signature of Middle Devonian biogenic calcite (Figure 16).

Hurley and Lohmann (1989) sampled Late Devonian brachiopods, marine cement, micrite, and subtidal stromatolites for isotopic analysis. They determined an original marine signature of $-4.5 \delta^{18}O \pm 0.5$°/oo and $+2.0 \delta^{13}C \pm 0.5$°/oo for the Late Devonian of the Canning basin (Figure 16). This compared well with other Late Devonian results from Australia, Canada, and Belgium.

In this study, non-luminescing brachiopods were microsampled in an attempt to obtain an estimate of the original marine isotopic composition of these sediments. Not all brachiopods were non-luminescing. In fact, many brachiopods luminesced dull red to orange, and most were contaminated with cements that precipitated in microfractures that were common in these fossils.
Figure 16. Isotopic Signatures of Early Calcite Fabrics Compared to Published Devonian Marine Signatures.
Rock chips that contained non-luminescent brachiopods were re-examined under CL after isotope microsamples were drilled. Unfortunately, some of the samples were contaminated by diagenetically altered matrix and/or cements within brachiopods. Analyses of contaminated samples ranged from $\delta^{18}$O = -7.39 to -3.40 $^\circ/_{oo}$ and $\delta^{13}$C = 0.12 to 1.86 $^\circ/_{oo}$. Uncontaminated brachiopods had isotopic signatures from $\delta^{18}$O = -4.79 to -3.40 $^\circ/_{oo}$ and $\delta^{13}$O = 1.10 to 1.33 $^\circ/_{oo}$ (Figure 16).

Non-luminescent micrite from the undolomitized restricted mudstone facies (present near the bottom of the Grow #4 core, Plate II-10) was also sampled. This mudstone facies is now very impermeable and non-porous. Carbonate muds typically have high porosities (50-70%, Bathurst, 1975) before lithification. Subsequent lithification and neomorphism is believed to occur early in the burial history of micritic sediments (Bathurst, 1975). If this were the case, then the result was a very impermeable rock, and the calcite in this facies might be protected from further rock-water reactions. If so, the stable isotope signature would reflect conditions of the early burial environment. These samples were taken assuming that if the isotopic signature was preserved from a shallow burial environment, it may be near the original marine signature and may help define the general values for the original marine signature. Two samples of this type were taken and the results ranged from $\delta^{18}$O = -5.53 to -5.38 $^\circ/_{oo}$ and $\delta^{13}$C = 1.10 to 1.13 $^\circ/_{oo}$ (Figure 16).
Chert

Chert nodules occur in the restricted wackestone facies (Figure 15). The presence of chert in this one lithotype strongly suggests that its distribution is facies controlled. The original sediment may have contained relatively large amounts of amorphous silica. However, no sources of silica were observed.

The formation of chert nodules is interpreted as being relatively early (eogenetic) as indicated by the preservation of very delicate sedimentary textures. Further evidence comes from compaction of laminae around chert nodules. Many chert nodules contained trace amounts of scattered dolomite. This dolomite was typically euhedral and averaged about 100 μm in diameter. The dolomite looks like the matrix-replacive dolomite that surrounds some of the chert nodules, and may or may not be related. Replacement of carbonate sediments by chert is interpreted to have occurred during or before dolomitization of the top 10 to 15 feet of the Dundee Limestone.

Matrix-Replacive Dolomite

The top 10 to 15 feet of the Dundee Limestone at West Branch is largely dolomite. This occurrence of dolomite coincides with the presence of the restricted mudstone facies and, in some places, the top few feet of the restricted wackestone facies. The base of this dolomitized zone appears to be gradational with underlying limestones. The upper contact of this dolomite
zone is the top of the Dundee. It is abruptly overlain by the undolomitized Rogers City Limestone.

Dolomitization of this zone is most pervasive in the seven cores from the southeast half of the field (Buckingham #4, Doran #5, Grow #4, Grow #9, Hart #2, Hart #7, and Reinhart #3; Figure 5). The remaining four wells in the central and northwest parts of the field show an increased amount of unaltered limestone in this interval, although the relative proportions of calcite and dolomite have not been quantified.

This dolomite occurs as euhedral rhombs that range in size from 1 to 250 μm. A wide range of crystal sizes is typically visible in each thin section. Dolomite rhombs appeared dull red when examined using CL microscopy and showed none of the zoning observed in all other cement types. Evidence to suggest more than one episode of dolomitization was not found.

Fossils preserved in pervasively dolomitized samples show signs of physical compaction that appear to be post-replacement. Similar fossils observed in the same facies, but in areas not replaced by dolomite show no signs of compaction. Several cores contain beds of unaltered micritic limestone that range from 2 to 15 cm in thickness in otherwise pervasively dolomitized rock. These beds typically show some fracturing. Some are broken into rotated boudins (Figure 15). These observations suggest that the dolomitized sediments experienced the effects of burial compaction, whereas
some streaks of micritic sediment resisted both dolomitization and compaction, probably due to early calcite cementation.

Preservation of primary textures is poor where dolomitization occurred. Horizontal burrows are the only structures still visible. Some areas display textures that may be burrows or diagenetic mottling.

While drilling microsamples for carbon and oxygen isotope analyses, an attempt was made to sample areas that were more coarsely or finely crystalline to see if any separation in stable isotope values would emerge. Samples were considered finely crystalline when the bulk of the dolomite was less than 100 $\mu$m in diameter, and coarsely crystalline when most dolomite was greater than 100 $\mu$m in diameter. The results of carbon and oxygen isotope analyses show practically no separation of these different size fractions. The results group between -9.8 to -7.7 $\delta^{18}$O and 1.1 and 2.5 $\delta^{13}$C with two samples deviating significantly from this range (samples at -5.97 $\delta^{18}$O and 1.69 $\delta^{13}$C, and -12.81 $\delta^{18}$O and -0.45 $\delta^{13}$C, Figure 17).

To summarize, matrix-replacive dolomite appears to be an early diagenetic phase. Some dolomite is encased in chert which is thought to be early. Matrix-replacive dolomite is confined to a thin zone in the upper Dundee.
Figure 17. Isotopic Signature of Replacive Dolomite.
Syntaxial Cement

Syntaxial cements occur as overgrowths on crinoid ossicles. These overgrowths are the most common cement type in the grainy facies (packstones and grainstones) and are responsible for about 2-10% porosity occlusion (visual estimates). Overgrowths in the crinoid grainstone facies are generally thin (<10 μm), whereas overgrowths are commonly much thicker in the skeletal-peloidal grainstone subfacies (>500 μm; Figure 18). These overgrowths, where pore space is available, grow thickest over the flat surfaces of crinoid columns. This direction (perpendicular to the flat surfaces of columns) is parallel to the C-axis in crinoid ossicles (Bathurst, 1975).

Potassium ferricyanide staining revealed thin zones of iron-rich calcite in many crinoid overgrowths. These ferroan calcite zones were even more apparent when examined using CL microscopy. Zones that stained blue with potassium ferricyanide were invariably areas of dark luminescence under CL. Otherwise, the general CL character of this cement is relatively bright orange, especially near the crinoid substrate. These cements commonly contain numerous thin, darker orange bands, especially near the outer edges of crystals.
Figure 18. Calcite Cements, Dundee Limestone.

(A) Syntaxial calcite overgrowth ("OG") on a crinoid stem ("C"). Saddle dolomite rhomb ("SD") is present in interparticle pore. Plane light, scale = 0.25 mm. Reinhardt #3, 2683.0'. (B) Scalenohedral calcite ("S") that has grown on a brachiopod substrate ("B"). Blocky calcite cement ("BC") present as a pore-filling cement. Plane light, scale = 0.25 mm. Grow #4, 2669.9'. (C) Stylolite in a micrite-poor peloidal-skeletal packstone. Local cementation around the stylolite has occluded interparticle porosity. Porous areas in the core appear darker due to oil stain, most visible on the unpolished surface (right side of photo). Note fracture ("F") associated with stylolite. Scale = 3 cm. Hart #2, 2647.5'.

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Two different types of microsamples were drilled in this cement type. The first type of sample was drilled from crinoid overgrowths that were just thick enough to microsample without risk of contamination from original crinoid skeletal material. Where overgrowths in a sample were well-developed and had grown into larger pore spaces, only the outermost edge of the crystal was sampled. Five microsamples of whole overgrowths and three of just the outer edges were taken.

Whole overgrowths plotted in a tight group from -6.4 to -7.5 δ¹⁸O and 1.2 to 1.5 δ¹³C. Results from samples of the outer edges of these crystals had a similar C¹³ range, but they ranged from -7.0 to -9.0 δ¹⁸O (Figure 19).

**Intercrystalline Calcite Microspar**

Several samples of the dolomitized restricted mudstone facies contain a fine-grained calcite cement that occludes intercrystalline porosity. The cement is anhedral and is generally about 4 to 5 microns in diameter.

Three areas rich in this cement type were sampled for stable isotope analyses. Because the intercrystalline pores in the dolomite where this cement is present are far smaller than the diameter of the drill used in microsampling (500 μm), each of sample consisted of a mixture of dolomite and calcite cements. These isotopic analyses were intended to be compared with the isotopic signature of dolomite sampled with no intercrystalline calcite cement.
Figure 19. Isotopic Signatures of Calcite Cements.

**KEY**

- ○ Intercrystalline Calcite (Contaminated With Dolomite)
- ▲ Crinoid Overgrowths (Outermost Growth Zone)
- □ Whole Crinoid Overgrowths
- △ Scalenohedral Calcite

**δ¹⁸O (PDB)**

-14  -12  -10  -8  -6  -4  -2  2  4

**δ¹³C (PDB)**

-6  -4  -2  2  4

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The results of isotopic analyses of these three samples yielded results from -8.2 to -8.6 $\delta^{18}O$, and 1.30 and 1.93 $\delta^{13}C$ (Figure 19).

**Scalenohedral and Blocky Cements**

Two other types of calcite cement were observed during thin section examination: (1) pore-lining scalenohedral calcite, and (2) pore-lining and pore-filling blocky calcite (Figure 18). These cements were found to be most common in pore spaces of samples that contained a significant fraction of micrite, especially peloidal-skeletal packstones. Pore-lining scalenohedral cement was most abundant on brachiopods, and was generally oriented perpendicular to the skeletal substrate. This cement was also present in mollusk molds and stylolite-related fracture sets in micritic packstones. This cement typically coarsens outward into the pore and crystals are commonly 400 $\mu$m long and 150 $\mu$m wide. Staining with potassium ferricyanide revealed the presence of some iron-rich zones in this calcite cement. Some scalenohedral cements displayed "fir-tree" zoning of ferroan calcite (Raven and Dickson, 1989).

In some thin sections it appeared that the scalenohedral cement contained dust rim relics of a thin isopachous, acicular cement near the base of the substrate.
One microsample was drilled from scalenohedral cement for isotopic analysis. The cement was drilled from a large gastropod mold in which the scalenohedral calcite had grown. The isotopic signature of this sample was -8.18 δ¹⁸O and 1.35 δ¹³C (Figure 19).

Blocky calcite cement occurred as both a pore-lining cement and as a pore-filling cement that showed little dependence on pore-wall substrates. Where present as a pore-lining cement, the calcite coarsens rapidly outward away from the substrate. The most common substrate for this cement was pore walls made up of micritic fabric. Commonly, the cement nearest the pore wall appeared to be inclusion-rich. This suggests that some of the substrate had been replaced. In pores that were interpreted to have an early origin (e.g., open burrows, shelter porosity, etc.), ghosts of an earlier, thin isopachous acicular cement appeared to be present in the cement nearest the pore wall. The size of the pore-lining crystals is typically about 50 μm. Cement further out in the pore is commonly coarser than 400 μm.

As with the scalenohedral calcite, some of the blocky cement locally contained crystal zones that stained blue with potassium ferricyanide. No samples of this cement type were taken for isotopic analysis.

These two cements commonly occurred together in the same pore space, especially in pores that had an early origin. In such pores the scalenohedral cement texturally predated the blocky cement.
Cement Associated With Stylolites

During core description, stylolites with associated tight zones on either side of insoluble seams were observed in some places (e.g., Appendix A, Plate I-11, Estey E-8 at 2682.0', 2682.5', and 2684.4'). These tight streaks are typically only a few centimeters thick and are most common in the peloidal-skeletal packstone subfacies where this lithotype is micrite-poor (Figure 18). These zones were not sampled for petrographic study. It is unclear what these zones are; they maybe the result of extensive grain suturing or localized cementation associated with stylolitization.

Saddle Dolomite Cement

Trace amounts of saddle dolomite were observed in pore spaces of every facies type in this study (Figure 18 and 20). Saddle dolomite occurred as pore-filling and pore-lining cement. Saddle dolomite is generally euhedral, and displays the curved crystal facies and undulose extinction pattern diagnostic of this cement type (Radke and Mathis, 1980). Crystal size generally ranged from 4 \( \mu \text{m} \) to 500 \( \mu \text{m} \). When examined in core the dolomite is white to light brown. Thin section examination revealed that this dolomite was inclusion-rich. Staining with potassium ferricyanide indicated the presence of distinct ferroan zones within many saddle dolomite crystals. Many crystals showed five or more distinct (ferroan and non-ferroan dolomite) zones. Ferroan dolomite...
zones lacked the numerous inclusions that most non-ferroan zones contained.

Cathodoluminescence microscopy also revealed numerous distinct zones within saddle dolomite rhombs. Luminescence character of these zones ranged from completely black to bright red. The contact between zones of different CL character is very distinct in this cement type (Figure 20).

Ultraviolet-fluorescence microscopy showed the presence of hydrocarbon-filled fluid inclusions in many saddle dolomite crystals (Figure 20). These inclusions are very small (less than 2 microns) and are concentrated in the nonferroan (unstained), brightly luminescent growth zones of saddle dolomite crystals. Cerccone and Lohmann (1987) observed a similar relationship of hydrocarbon fluid inclusions in brightly luminescent saddle dolomite growth zones in samples from Silurian carbonates in the Michigan basin.

This cement type texturally post-dates all other carbonate cements. Saddle dolomite commonly occurs in fractures associated with stylolites, and also forms resistant pinnacles in stylolite seams. This indicates that pressure solution was an on-going process throughout much of the burial diagenesis of these rocks.

One thin section (from the Doran #5 core at 2660.7 ft) contains saddle dolomite that appears to have replaced pre-existing fine-grained calcite. Coarse-grained skeletal fragments remain unreplaced. Dolomite rhombs here are between 200 and 500 μm in size. Compromise boundaries with other
Figure 20. Pore-filling Saddle Dolomite Cement, Dundee Limestone.

(A) Saddle dolomite rhomb ("SD") and anhydrite cement ("AN") in fracture associated with a stylolite. Note the three distinct growth zones ("1", "2", and "3") in the dolomite rhomb. Zone "3" is darkest because it is the most inclusion-rich, whereas zone "1" is the most inclusion-poor. Crossed polars, scale = 0.25 mm. Doran #5, 2660.7'.

(B) Saddle dolomite cathodoluminescence displaying growth zones with distinct luminescent characteristics. Scale = 0.25 mm. Doran #5, 2660.7'.

(C) Saddle dolomite in a shelter pore (open burrow) as seen in plane light (left), and under an ultraviolet (UV) light source (right). Fluid inclusions fluoresce when examined with UV light due to the presence of hydrocarbons in these inclusions. The inclusions are interpreted to be primary. Scale = 0.25 mm. Grow #4, 2595.9'.

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saddle dolomite crystals are very common. This was the only sample where replacement by this cement type was observed.

Twelve microsamples were drilled from saddle dolomite crystals for stable isotope analysis. Two of these samples were taken from the specimen that contained replacive saddle dolomite. The other ten samples were drilled from pore-filling saddle dolomite. Six of these samples were drilled from the outermost growth zone of crystals as identified using CL microscopy before sampling. Two very large saddle dolomite crystals from different wells were sampled twice; the first samples of each were drilled from a discrete CL zone in the center of the crystal, the second samples were drilled from another CL zone toward the outer edge of each crystal. This was done to see if any isotopic trends from early to late saddle dolomite were apparent.

The stable isotope signatures of eleven saddle dolomite samples ranged from -8.35 to -4.85 $\delta^{18}$O and 1.43 to 2.7 $\delta^{13}$C (Figure 21). One very anomalous signature of -8.75 $\delta^{18}$O and -5.85 $\delta^{13}$C was measured for one of the microsamples taken from the replacive saddle dolomite (Figure 21).

Other Burial Cements

Three other cement types were recognized—anhydrite, fluorite, and pyrite. These cements are very rare and all texturally post-date saddle dolomite.
Figure 21. Isotopic Signature of Saddle Dolomite Cement.

Arrows indicate the relationship between inner (at base of arrow) and outer (at tip of arrow) growth zones from single crystals.
Anhydrite occurs as a pore-filling cement. Crystals occurred as long (usually 3 to 4 mm), thin laths with planar contacts with other anhydrite crystals. In many pores filled with anhydrite, pore walls showed evidence of anhydrite replacement of pre-existing calcite cements and sediments. Saddle dolomite also commonly appeared to be in various stages of replacement by anhydrite where these two cements are adjacent (Figure 20).

Late pyrite was observed in four thin sections as a subhedral pore-filling cement. In one sample a saddle dolomite rhomb appeared completely surrounded by late pyrite.

Fluorite was observed in thin section and in core. This cement occurred as sub- to euhedral crystals in sizes from less than 50 μm to greater than 5 mm across.
STRUCTURAL EVOLUTION: WEST BRANCH FIELD

The purpose of this section is to: (a) describe fractures observed in core, (b) determine the timing of structural development of West Branch relative to deposition of the Dundee Limestone, and (c) consider the style of structural deformation in the West Branch area.

Fractures

Three types of fractures were observed during core examination: (1) Small-scale compactional fractures in chert nodules and restricted mudstone beds surrounded by dolomite (Figure 15); (2) Fracture sets associated with sutured-seam stylolites in the peloidal-skeletal packstone subfacies (Figure 22); (3) High-angle, through-going macrofractures.

Various types of fractures are recorded on core description sheets (Appendix A). It is important to be able to compare fracture intensities from one well to another. One approach is to count the number of fractured feet in a core, then express this as a percentage of the total cored footage. Any foot of core with 1 or more fractures is counted as 1 fractured foot. Table 2 shows the normalized fracture intensities for all Dundee cores examined in this study.
Figure 22. Small-scale Fractures Associated With a Sutured-seam Stylolite.

Sample is peloidal-skeletal packstone (unpolished core slab). Scale = 3 cm. Cox #2, 2743.5'.

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### Table 2
Fracture Intensity From Core, Normalized to 100 Feet

<table>
<thead>
<tr>
<th>Core Well Name</th>
<th>Normalized fracture intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heintz #9</td>
<td>44'</td>
</tr>
<tr>
<td>Donovan #6</td>
<td>29</td>
</tr>
<tr>
<td>Cox #2</td>
<td>71</td>
</tr>
<tr>
<td>Estey E-8</td>
<td>57</td>
</tr>
<tr>
<td>Doran #5</td>
<td>40</td>
</tr>
<tr>
<td>Hart #2</td>
<td>49</td>
</tr>
<tr>
<td>Hart #7</td>
<td>56</td>
</tr>
<tr>
<td>Reinhardt #3</td>
<td>48</td>
</tr>
<tr>
<td>Buckingham #4</td>
<td>44</td>
</tr>
<tr>
<td>Grow #4</td>
<td>83</td>
</tr>
<tr>
<td>Grow #9</td>
<td>58</td>
</tr>
</tbody>
</table>

* Approximately 40% of this core is sealed in paraffin (Appendix A). Therefore, normalized fractured foot count may be unreliable.
Small-Scale Compactional Fractures

The small-scale compactional fractures found in chert and mudstones are believed to be the result of relatively early compaction and are discussed in the sedimentology section. These will not be discussed here further.

Fractures Associated With Stylolites

These fractures occur most abundantly in the peloidal-skeletal packstone subfacies. The fractures are generally between 2 and 30 cm long and are vertical. Fractures in a set associated with the same stylolite have the same relative trend. From the examination of core and thin sections, it is clear that these fractures are extensional, not shear related. These are by far the most common type of fracture observed in this study (Figure 22). Nelson (1981) has reported similar fractures. Watts (1983) suggests that stylolite-related fractures are the major fluid conduits in a North Sea chalk reservoir.

These fractures typically contain some amount of burial cement, although some are completely unfilled. Common cement types in these fractures are pore-lining scalenohedral calcite, pore-filling saddle dolomite, and less commonly, anhydrite. Several fractures that contained no calcite cement were connected to fractures that were lined with calcite cement. This relationship indicates that the unlined fractures formed after the formation and cementation of earlier fractures.
Saddle dolomite is present in fractures with and without calcite cement. Saddle dolomite filled some fractures completely. Several dolomite-filled fractures are now resistant pinnacles along solution seams. This relationship indicates that stylolitization continued after the formation and filling of some fractures with saddle dolomite.

Various cement-fracture relationships indicate that the formation of sutured-seam stylolites and associated fracture sets occurred over an extended period of time. It is not clear if the formation of these structures occurred as separate events or in one continuous process.

Fracture sets indicate the presence of triaxial stress conditions during stylolitization, with the stylolites forming perpendicular to the principal stress direction (overburden) and associated extension fractures forming normal to the horizontal paleo-stress minimum (Nelson, 1981). These fractures may be related to the same stress conditions responsible for the formation of the West Branch anticline.

The presence of these fracture sets has an influence on core analysis results and electric log response. The best example of this effect is in the Cox #2 core. In this core, a large number of sutured-seam stylolites with associated fracture sets are present in the relatively thick unit of peloidal-skeletal packstone present between 2730' and 2756' (Appendix A, Plates I-7 and I-8). This packstone has low interparticle porosity and permeability typical
of this subfacies, but the presence of numerous fracture sets results in very high permeability from core analysis (around 100 md) and low resistivity on well logs (Plate II-3).

The distribution of this fracture type is largely limited to the peloidal-skeletal packstone, the depositional facies that contains most of the sutured-seam stylolites.

**Through-Going Macrofractures**

Macrofractures occur as high-angle (non-conchoidal) fractures. The surfaces of these fractures commonly have many small irregularities and they do not show any component of slip. It is unclear how many true macrofractures exist in the core examined because many areas exist where the core was broken and abraded during coring. Some of these areas may have been sites where macrofractures were present. Only twenty three macrofractures were identified in over 1,000 ft of core examined in this study.

The only evidence for relative timing comes from cement observed in these fractures. Saddle dolomite is the only cement observed in macrofractures. Saddle dolomite was very rare, but unequivocally present, even if only in small amounts. The absence of other cement types may or may not be significant, due to the low number of macrofractures observed and because these fracture surfaces were difficult to sample for thin section.
Core examination does not indicate any localized diagenetic alteration of the surrounding rock fabric in the proximity of these fractures. For example, dolomite haloes are not present to suggest that these fractures served as conduits for dolomitizing fluids.

Macrofractures were observed in all facies types except the crinoid grainstone and skeletal-peloidal grainstone. Although the low number of fractures recognized makes it speculative, this may indicate that these lithotypes avoided fracturing because other types of strain were more easily achieved (e.g., grain rotation, suturing, or calcite twinning).

The orientation of these fractures is unknown, and no mechanism of deformation will be assumed in this study.

Prouty (1989a, 1989b) and Ten Have (1979) state that shear faults exist in the West Branch Dundee Limestone. Fracture types documented from core in this study show no component of shear.

Timing of Deformation

The structural development of the West Branch anticline apparently did not begin before or during deposition of the Dundee Limestone. There is no evidence for development of shallow-water build-ups over the structure similar to those in Buckeye field (Montgomery, 1986). The lateral continuity of facies markers in cross sections (especially those perpendicular to the field
trend) strongly suggests that little or no structural movement occurred prior to deposition (Figures 12 and 13).

Isopach maps were examined to see if any of the overlying formations thinned over the structure. Thinning would indicate that structural development predated deposition of the unit examined. The results were inconclusive due to the low number of off-structure control points. However, thicknesses of Mississippian shales from wells in on-structure areas (e.g., wells in Sec. 28, T22N-R2E) were compared with thicknesses in off-structure wells (e.g., States Petroleum Grezeszak #1-16, Sec. 16, T22N-R2E, and Amoco Rau #1-21 in Sec. 21, T22N-R2E). This comparison showed that shales are on average only about 2-4% thicker in off-structure areas to the north over a distance of about 1.5 miles. This is interpreted to indicate that practically no structurally related paleohigh was present during deposition of the Mississippian shales.

In summary, the only age constraint on structural movement at West Branch is the fact that deformation post-dated the Mississippian Coldwater Shale and Marshall Sandstone and pre-dated Pleistocene glacial tills.

Nature of Movement

The similarity of the West Branch and Clayton structures has been discussed in an earlier section. To review, these structures are en echelon
asymmetrical anticlines that dip more steeply on their northeastern flanks. The crest of the West Branch anticline migrates to the northeast with depth. Also, the top of the West Branch anticline appears to be relatively flat on structure contour maps (Figure 5).

Versical (1989, 1990) relates the development of the West Branch and Clayton structures to strike-slip movement on a fault in the Precambrian Penokean basement. He used seismic data from a line shot perpendicular to the Clayton field. Faults believed to be helical Riedel shears that form a "tulip" structure were observed in Lower Paleozoic sediments below the Salina Formation (Silurian). "Tulip" structures are believed to occur in settings where basement-induced wrench faulting has deformed overburden (Naylor, Mandl, and Sijpesteijn, 1986). In the seismic line across Clayton, Versical (1990) noted that the fault on the north side of the structure has considerably more vertical displacement than the fault on the south side of the structure. This probably caused the asymmetry observed in these fields.
DISCUSSION

Facies Interpretation

The Dundee Limestone consists of a complex facies mosaic of crinoid grainstones, skeletal-peloidal grainstones and packstones, skeletal wackestones, restricted mudstones and wackestones, and rare stromatoporoid-coral floatstones and fenestral-cryptalgal laminites. Hemicyclic, shoaling upward sequences are common. These contribute to vertical heterogeneity. Lateral heterogeneity has been established by comparing core descriptions to log signatures, then correlating logs in a series of field-wide cross sections.

During deposition of the normal marine facies, the northwest end of the study area was apparently in deeper water than the southeast. This interpretation is based on the following evidence:

1. The crinoid grainstone facies is present only in the northwestern one-third of the field (Figure 12). This facies is interpreted to represent deposition in a deeper water, lower energy environment than laterally equivalent facies in the central and southeastern parts of the field (i.e., the skeletal-peloidal grainstones and packstones).

2. Cross sections show the crinoid grainstone facies reaches its maximum thickness in the northwestern part of the field. To the southeast, this facies gradually thins and grades into higher-energy, cyclic skeletal-peloidal
granstones (Figures 12 and 13).

3. The frequency of shoaling upward hemicycles in the skeletal-peloidal packstones and grainstones increases to the southeast (Figure 10). This suggests that shallower depositional environments existed to the southeast.

4. The restricted wackestone facies between markers D2 and D3 (Figure 12 and 13) grades into skeletal-peloidal sands to the northwest. This gradation from restricted to open-marine facies suggest that the seaward direction was to the northwest.

5. Dolomite abundance varies in the zone between markers D1 and D2 at the top of the Dundee. This layer is pervasively dolomitized in the southeast part of the field, and less dolomitized to the northwest. Dolomite is an early, matrix-replacing mineral in this zone. Undolomitized layers appear to be marine cemented. The observed variation in degree of dolomitization may suggest that the seaward, more cement-prone depositional environment was to the northwest.

All lines of evidence suggest that the Dundee shelf or platform sloped to the northwest. This is in direct conflict with the fact that the Dundee depocenter was to the southeast (Figure 2). It is probable that the "depocenter" defined by the thickest isopach is not equivalent to the deepest water areas of the Michigan basin during the deposition of the Dundee Limestone.
Disconformity at the Top of the Dundee Limestone

The top of the Dundee is marked by a mineralized or bioeroded hardground in all cores examined in which this contact was present (Figure 7). This previously undocumented surface indicates a drowning event that terminated deposition on the shallow-water Dundee carbonate ramp. As such, the surface is a sequence boundary between the Dundee and Rogers City Limestones. It is unknown at this point what conditions were responsible for creating this disconformity. The processes and conditions present during this hiatus resulted in the lithification and pyritization of this hardground and also caused early replacement of underlying lime muds with dolomite or a protodolomite precursor.

The lateral extent of this surface is unknown beyond the study area. Considering the fact that the West Branch area is near the depocenter of Middle Devonian sediments (Gardner, 1974), the exceptional conditions responsible for this hiatus probably had recognizable regional effects.

Schlager (1981) stated that drowning events in carbonates that do not involve the introduction of clastics to the depositional setting must be caused by short-term processes. Ecologic stress (to suppress the growth potential of carbonate producing organisms) and rapid rises in relative sea level are the two-short term processes that can accomplish this type of drowning. Either process can accomplish drowning (in the presence of longer term eustacy and
subsidence), but when both occur together, drowning of shallow water carbonate settings is even more likely (Schlager, 1981). Faunal diversity decreases in the uppermost Dundee Limestone, (the restricted micritic facies). This indicates that environmental conditions had become too stressful for normal-marine fauna (i.e., brachiopods, corals, and crinoids).

The Middle Devonian rate of subsidence for the central Michigan basin is calculated to be 70 cm/1000 yrs by Gardner (1974). This high rate of subsidence would have an additive effect on rising eustatic sea level to make drowning a more likely occurrence (Schlager, 1981).

Johnson, Klapper, and Sandberg (1985) published a eustatic "sea-level curve" of Devonian time based on rocks from the western United States, the U.S. Appalachians, and Europe. Correlation of the Dundee drowning event is difficult due to discrepancies of stratigraphic correlation from the study areas of Johnson et al. (1985) to the Michigan basin and the conflicting assignment of Michigan basin strata to different established conodont zones (e.g., Bultynck, 1976 and Rickard, 1984). However, Johnson et al. (1985) suggest a transgressive-regressive cycle began near the end of Eifelian time. The beginning of this cycle, recognized by Johnson et al. (1985) in other areas of North America, may be time equivalent with the drowning of the Dundee depositional setting in the Michigan basin.
In the West Branch locality, a decrease in carbonate productivity due to environmental stress seems to be related to the drowning of the Dundee depositional environment. This drowning is also probably related to a eustatic sea level rise, although correlation to similar transgressive events outside the Michigan basin is limited by contradictory conclusions of recent research that has tried to establish the biostratigraphy of the region.

Diagenesis

Core descriptions, thin-section petrography (plane light, CL, and fluorescence) and carbon/oxygen isotope geochemistry have been used to determine a paragenetic sequence in the Dundee Limestone. Early marine cementation was followed by chert and dolomite replacement of matrix. A series of calcite cements predate and post-date pressure solution/compaction. Open fractures commonly formed as a result of stylolitization. Saddle dolomites and other minor late stage minerals line some pores and fractures. Even though a complex series of diagenetic events has occurred in the Dundee Limestone, primary interparticle porosity is largely preserved in many areas.

Isotopic analyses of early marine fabrics (brachiopods and micrites) yield results that are compatible with published Devonian values. The heaviest brachiopod analyzed in this study (-3.40 $\delta^{18}$O and 1.33 $\delta^{13}$C) is taken to be the Dundee "marine signature." Other samples were more or less contaminated.
by later diagenetic overprints and had lighter oxygen values.

The distribution of replacive dolomite in this field—laterally persistent with a gradational contact to the underlying limestone and a sharp contact with the limestone of the Rogers City—strongly suggests an early replacement of the restricted mudstone facies. Textural evidence from core and thin sections shows no indication of subaerial exposure or evaporative conditions at the top of the Dundee where this dolomite is present. A "mixing zone" environment (Badiozamani, 1973) is probably inappropriate here, although not enough is known about the regional paleotopography.

Isotopic results shed some light on considerations of the origin of matrix-replacive dolomite. The oxygen isotopic signature is very depleted (-8 to -9 $\delta^{18}$O). The carbon signature is slightly enriched in $^{13}$C (about 0.5 $\delta^{13}$C) compared to the inferred marine signature (Figures 12 and 13). The light oxygen is not characteristic of marine or evaporitic dolomite. Both of these would be heavier, not lighter, than the marine signature. Light oxygen occurs when there is either high temperature or significant meteoric water involved in dolomitization. Evidence for meteoric influence has not been observed. The coincidence in isotopic composition between matrix-replacive dolomites, all types of calcite cements, and saddle dolomites (Figures 17, 19, and 21) suggests that some late diagenetic event may have homogenized the isotopic signatures of these fabrics.
Fracture-Controlled Dolomite Hypothesis

Ten Have (1979) studied cuttings from wells drilled in the West Branch field and created subsurface maps based on reported formation tops. He concluded that epigenetic dolomitization, localized in the vicinity of faults, enhanced the porosity of the Dundee Limestone. Based on this work, Prouty (1989a, 1989b) cited the West Branch Dundee Limestone as an example of a fracture-controlled dolomite reservoir.

The results of this study conflict with almost all of the major conclusions of Ten Have (1979). The following is a summary of the major points of disagreement:

1. Ten Have (1979) concluded that matrix-replacive dolomite in the Dundee is structurally related based on distribution of dolomite in well cuttings. In this study, matrix-replacive dolomite is interpreted to have a syngenetic origin, based on textural evidence and observed distribution in core.

2. Ten Have (1979) calculated percent dolomite of well cuttings from different depth intervals below the Bell Shale and used this data to create "dolomite ratio maps" for each depth interval. The depth interval 80 to 110 feet below the base of the Bell Shale (the top of the Dundee is approximately 90 feet below the base of the Bell) is the depth interval in which Ten Have (1979) found the highest concentrations of dolomite. This corresponds to the occurrence of replacive dolomite observed in this study. However, Ten Have
(1979) found dolomite percentages to vary greatly (from 2.5-43%) in this interval from well to well. This lateral variability in dolomite distribution was not observed in this study. Three cored wells with similar amounts of replacive dolomite (Hart #2, Hart #7, and Doran #5 cores, Plates II-5, II-6, and II-7) were posted on Ten Have's (1979) dolomite ratio map. Two wells were outside the 5% "isodol," whereas the third well (Hart #2) was between the 25 and 30% "isodols". This suggests that these dolomite percentage maps do not provide an accurate picture of lateral dolomite distribution.

Also, the well log cross sections constructed in this study (Plates III-1 through III-5) do not show rapid lateral variation in log response. Porous zones were found to be laterally persistent on a scale of miles.

3. The depth interval between 80 and 110 feet below the Bell Shale was calculated to contain an average of 20% dolomite by Ten Have (1979). Depth intervals 110 to 140, and 140 to 170 feet below the Bell Shale were calculated to contain an average of about 10% and 5% dolomite, respectively. From the examination of core and thin sections, the percent dolomite estimated by Ten Have (1979) of these two intervals is too high. Perhaps his cuttings were contaminated by cavings. The only dolomite observed in these intervals was trace amounts of saddle dolomite and local, trace amounts of finely-crystalline dolomite associated with stylolite seams. The over-estimation of dolomite from X-ray analysis can be attributed to the inherent error in using well
cuttings and bulk sample analysis for this type of quantitative use.

4). Ten Have (1979) noted that chert was most common in cuttings between 80 and 170 feet below the base of the Bell Shale. This is inconsistent with observations in core, where chert was only observed in the restricted wackestone facies. This facies is less than twenty feet thick in most cores. Estey E-8 is the exception, where the restricted wackestone facies is about 30 feet thick. This facies occurs between 100 and 130 feet below the Bell Shale (about 8 to 38 feet below the top of the Dundee Limestone, Figures 12 and 13). This is further evidence that suggests that cavings contaminated the cuttings used in his study.

5. Ten Have (1979) attributed local thickening in an isopach map made of the Traverse Group (which immediately overlies the Rogers City and includes the Bell Shale) to sags in the Dundee (and Rogers City) Limestone due to dolomitization along fractures. No such sags are apparent on well log cross sections (Plates III-1 through III-5), even at great vertical exaggeration (Figures 12 and 13).

In summary, the interpretation that fracture-related epigenetic dolomite is present in the West Branch field is based on the X-ray analysis of well cuttings. The results of X-ray analyses do not accurately reflect the distribution of dolomite in the subsurface as observed in eleven cores in this field. This illustrates the danger of doing a study restricted to cuttings when
core is available. The fracture-related epigenetic dolomite model for the Dundee Limestone in this field is inaccurate and is not a useful concept for understanding the nature of this reservoir.

Timing of Structural Development

Montgomery (1986) demonstrated that structural development of the Buckeye field occurred before deposition of the Dundee Limestone. The resulting paleo-high was evidenced by rapid on- and off-structure facies changes and over 200 feet of thickening of the Dundee over the structure as compared to off-structure areas. From facies analysis and the construction of well-log cross sections, no similar evidence can be found in the Dundee Limestone at West Branch field. Neither the Roger's City nor the Dundee Limestone show a change in thickness on cross sections perpendicular the trend of the structure (Figure 13). Facies also did not show rapid lateral variation that could be related to structural position.

Comparison of thickness of Mississippian shales in on- and off-structure wells indicated that no paleohigh was present in the study area during the deposition of those shales, as would be expected if structural development had occurred before that time.

Deformation of the Coldwater Shale and Marshall Sandstone, which outcrop and subcrop over and around the crest of the West Branch structure
(Newman, 1936), indicates that development of this structure was probably post-Mississippian and did not affect the deposition of the Dundee Limestone.

Economic Considerations

The Dundee Limestone in West Branch field is currently under waterflood. A number of aspects of this study could have economic implications:

1. Laterally discontinuous porous and permeable zones have been identified. In addition, laterally extensive permeability barriers, such as the skeletal wackestone facies, have been documented. It would be useful to look at completion records and injection profiles in the context of this study to see if improvements could be made in areal sweep efficiency.

2. This study has shown that fine-scale fractures are present in cherts and limestone interbeds in the uppermost Dundee Limestone. Matrix porosities and permeabilities are poor in this zone. If many wells are completed in this interval, and if a lot of fluid is being lost into those perforations, recompletions may be in order.

3. Extensional fractures associated with stylolites are common in skeletal-peloidal packstone facies. These facies have been identified in core studies, and they have been correlated in field-wide cross sections. Stylolite-related fractures may behave as permeable conduits to channel significant volumes of
injected water. If this is known to be the case in certain parts of the
waterflood, gel or cement conformance treatments may be in order.

4. One of the original goals of this project was to see if fairways of fracture-
controlled dolomite existed in the Dundee. If so, it would be useful to project
those down to deeper reservoirs. Unfortunately, the fracture-controlled
dolomite model does not apply to the West Branch Dundee Limestone.
CONCLUSIONS

1. Six depositional facies types were recognized from core studies, four of which are present above the oil-water contact in this field: crinoid grainstone facies, skeletal-peloidal grainstones and packstones, skeletal wackestone facies, and the restricted mudstones and wackestones. The crinoid grainstone and skeletal-peloidal grainstones and packstones contain interparticle porosity. The restricted mudstone is largely replaced by dolomite and contains intercrystalline porosity with very low permeability. The skeletal wackestone is practically nonporous and nonpermeable. The stromatoporoid-coral floatstone facies and the fenestral-cryptagal laminite facies both have high permeability and porosity properties, but they lie below the oil-water contact in this field.

2. The contact between the Dundee and Rogers City Limestones is a disconformity represented by a mineralized hardground that shows bioerosion in some cores. This is interpreted as a sequence boundary that corresponds to the drowning of the Dundee platform.

3. Porous units identified in core and on well logs are related to depositional facies. The zone of high porosity associated with the dolomitized restricted mudstone facies is correlative field wide, whereas porosity zones that are interparticle in nature are more lenticular, and correlate between two and six miles along the field. Two thin, nonporous skeletal wackestone facies were
also found to be correlative in part of the field for several miles. Knowledge of the distribution of porous and nonporous units in this field should prove valuable in the design and evaluation of waterflood programs.

4. Dolomitization of the restricted mudstone facies at the top of the Dundee is believed to have occurred early, before deposition of the Rogers City Limestone. Replacement probably occurred on the sea floor during the hiatus in sedimentation at the end of Dundee deposition. The stable isotope signature of this dolomite is depleted in $^{18}O$ relative to other marine and diagenetic fabrics sampled in this study. This signature is attributed to diagenetic overprinting of the dolomite in the burial environment.

Primary porosity in grainy facies has been partly occluded by calcite cements, mainly crinoid overgrowths. Some porosity destruction has occurred due to pressure solution. Saddle dolomite and other late cements precipitated to occlude minor amounts of porosity.

5. Based on the results of this study, the fracture-related dolomite model for porosity enhancement at West Branch (Ten Have, 1979) is judged to be in error. His study was based on bulk-sample analysis of cuttings. His conclusions are inconsistent with extensive core data available in this reservoir.

6. The anticlinal structure that now defines this field was not present during deposition of the Dundee or Rogers City formations and does not appear to have formed before Early Mississippian time.
Appendix A

Plates I-1 Through I-38, Core Descriptions Sheets
KEY TO CORE DESCRIPTIONS*

<table>
<thead>
<tr>
<th>Pore Type</th>
<th>Mineral Composition</th>
<th>Nature of Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>BP = Interparticle</td>
<td>Logged in percent</td>
<td>ST = Stylolite</td>
</tr>
<tr>
<td>WP = Intraparticle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BC = Intercrystalline</td>
<td></td>
<td>SI = Sharp irregular</td>
</tr>
<tr>
<td>MO = Moldic</td>
<td></td>
<td>G = Gradational</td>
</tr>
<tr>
<td>FE = Fenestral</td>
<td></td>
<td>UK = Unknown</td>
</tr>
<tr>
<td>SH = Shelter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FR = Fracture</td>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Nature of Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>S = Sharp</td>
</tr>
<tr>
<td>SI = Sharp irregular</td>
</tr>
<tr>
<td>ST = Stylolite</td>
</tr>
<tr>
<td>SI = Sharp irregular</td>
</tr>
<tr>
<td>G = Gradational</td>
</tr>
<tr>
<td>UK = Unknown</td>
</tr>
</tbody>
</table>

*Modified from Bebout and Loucks, 1984.*
Key to Core Descriptions—continued

**Carbonate Texture**

- **Left**
  - φ φ φ: Intraclasts
  - b b b: Skeletal grains
  - φ φ φ: Pellets
  - ○ ○ ○: Peloids

- **Right**
  - Micrite

Highly altered. Superimpose over interpreted texture.

**Carbonate Fabrics**

- **M** = Mudstone
- **P** = Packstone
- **W** = Wackestone
- **G** = Grainstone
- **F** = Floatstone

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Key to Core Descriptions—continued

**Structures**

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<tbody>
<tr>
<td>Stylolite</td>
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<tr>
<td>Microstylolites</td>
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</tr>
<tr>
<td>Fracture (filled)</td>
<td>△</td>
</tr>
<tr>
<td>Fracture (partly filled)</td>
<td></td>
</tr>
<tr>
<td>Fracture (open)</td>
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<tr>
<td>Through-going macrofracture</td>
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</tr>
<tr>
<td>Cloudy appearance</td>
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</tr>
<tr>
<td>Scoured surface</td>
<td></td>
</tr>
<tr>
<td>Lamina types—sketch diagram—matically, e.g. irregular laminations</td>
<td></td>
</tr>
</tbody>
</table>

**Size**

This column used to record maximum amplitude of sutured seam stylolites.
Key to Core Descriptions—continued

Color

L = Light
M = Medium
D = Dark
m = Mottled
G = Gray
B = Brown
C = Cream
Bk = Black

Example: MB = Medium Brown

Fossils

Fossil types listed at top of core form. Names often abbreviated, (e.g., Brach = Brachiopod, Pelec = Pelecypod).
Relative fossil abundance logged as shown below.

Not present
Present
Common
Abundant

Cement

Cement observed in large pores.

AN = Anhydrite
F = Fluorite
C = Calcite
P = Pyrite
SD = Saddle dolomite
B = Bitumen

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### WELL  #9

**Stratigraphic Interval:** Dundee

**County:** Ogemaw

**Logged By:** B. Cullen

<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>Structure</th>
<th>Texture</th>
<th>Grain Size (Dolomite</th>
<th>Crystal Rite)</th>
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<td>W</td>
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<tr>
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<td>2810</td>
<td>G</td>
<td>P</td>
<td>MB</td>
<td>SD</td>
</tr>
</tbody>
</table>

**Notes:**
- Dark petrology
- Poor bedding
- Detrital features
- Low angle bedding
- Highly fractured and cemented

*Plate I-1*

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| STRATIGRAPHIC INTERVAL | MINERAL COMPOSITION (PARENTHETICAL) | STRUCTURES | TEXTURE | GRAIN SIZE | COLOR | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | DECAY | 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**Notes:**
- Sample Reused
- Encrusting Strata
- Low K
- High Zoned

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Plate I-9

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Plate I-16

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**Notes:**
- SD reached
- Dashed

Plate I-21

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| Plate 1-22 |

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
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Plate 1-23

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**Notes**

- Darkened Grains

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Plate 1-28

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Plate I-30

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WELL: Snow #1
COUNTY: Ogemaw
STATE: 

Stratigraphic Interval: Rogers City/Dundee Logged by B. Condon

Notes:
- Articulated Brachiopods
- Bridgewood
- Bridgehead
- Rogers City Limestone
- Dundee Limestone
- Bridge reas.
- PO halite and rich in some cases.
- Hinge with thin Bridgewood and rich in some cases.
- Roping (adj)
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|      |     |             |          |         |            |        |        |       |

| Z715 |     |             |          |         |            |        |        |       |
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Plate I-35

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**Notes**
- Some Bioturbation in Well 2
- Many Black Spots in Well 3
- Humidity issues in Well 4
- Some Bedding Issues in Well 5

Plate 1-36

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### Plate I-37

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GENERALIZED CORE DESCRIPTION

DOLOMITIZED MUDSTONE - Fair to poor intercrystalline porosity and permeability. Contains a low diversity of fossil types. Very correlative in all field cross sections (Plates Ill-1 through Ill-5).

PELOIDAL-SKELETAL PACKSTONE - Fair to good interparticle porosity and permeability. Contains many coarsening upward hemicycles. Bases of these hemicycles are usually low porosity, peloid-rich packstones. Finer sorted, coarser grained skeletal packstones and grainstones with good interparticle porosity are common near the top of the hemicycles. A wide range of fossil types are represented, although medium grained crinoid ossicles are the most common grain type. Most skeletal grains show signs of abrasion and many show signs of early marine cementation. This is the most common lithotype observed in the cores examined in this study.

SKELETAL-PELOIDAL GRAINSTONE - These sediments are very similar to those above. The top of this unit is marked by a skeletal-peloidal grainstone about 7 feet thick with good interparticle porosity and permeability. This grainstone is correlative in wells A-4 through A-9 (Cross Section A-A', Plate Ill-1).

CRINOID GRAINSTONE - Very good interparticle porosity and permeability. Coarse-grained crinoid ossicles are the dominant grain type present. Crinoid and other skeletal grains present do not show signs of abrasion or early marine cementation. This unit thickens to the NW and thins to the SE and is correlative in wells A-1 through A-20 (Cross Section A-A', Plates Ill-1 and Ill-2).

SKELETON-WARESTONE TO PACKSTONE - Dark, micrite-rich limestone. Very tight.

KEY

TEXTURE

LITHOLOGY

DOLOMITE

LIMESTONE

CHERTY LIMESTONE

PACKSTONE

UPWARD

HEMICYCLE

UPWARD

HEMICYCLE

RESERVOIR GEOLOGY
OF THE DUNDEE LIMESTONE,
WEST BRANCH FIELD, MICHIGAN

by Brendan C. Curran

Operator: Marathon Oil Company
Well Name: Heintz #9
County: Ogemaw
Location: Sec. 24 T23N R2E

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GENERALIZED CORE DESCRIPTION

DOLOMITIZED MUDSTONE - Fair to poor intercrystalline porosity and permeability. Contains a low diversity of fossil types. Very correlatable in all field cross sections (Plates III-1 through III-3).

PELOIDAL-SKELETAL PACKSTONE - Fair to good interparticle porosity and permeability. Contains many coarsening upward hemicycles. Bases of these hemicycles are usually low porosity, peloid-rich packstones. Better sorted, coarser grained skeletal packstones and grainstones with good interparticle porosity are common near the top of the hemicycles. A wide range of fossil types are represented, although medium grained crinoid ossicles are the most common grain type. Most skeletal grains show signs of abrasion and many show signs of early marine cementation. This is the most common lithotype observed in the cores examined in this study.

SKELETAL-PELOIDAL GRAINSTONE - These sediments are very similar to those above. The top of this unit is marked by a skeletal-peloidal grainstone about 7 feet thick with good interparticle porosity and permeability. This grainstone is correlatable in wells A-4 through A-9 (Cross Section A-A" Plate III-1).

CRINOID GRAINSTONE - Very good interparticle porosity and permeability. Coarse-grained crinoid ossicles are the dominant grain type present. Crinoid and other skeletal grains present do not show signs of abrasion or early marine cementation. This unit thickens to the NW and thins to the SE and is correlatable in wells A-1 through A-20 (Cross Section A-A" Plates III-1 and III-2).

SKELETAL-WACKESTONE TO PACKSTONE - Dark, micrite-rich limestone. Very tight.

KEY

TEXTURE
M.W.P.

LITHOLOGY
DOLOMITE
LIMESTONE
CHERRY LIMESTONE

RESEVOIR GEOLOGY OF THE DUNDEE LIMESTONE, WEST BRANCH FIELD, MICHIGAN

by Brendan C. Curran

Operator: Marathon Oil Company
Well Name: Heintz #9
County: Ogemaw
Location: Sec. 24-T22N-R2E
Permit No.: 38054

Plate II-1
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GENERALIZED CORE DESCRIPTION

ROGERS CITY ZONE 2 - Skeletal-peloidal packstone. Very tight with a thin zone with fair interparticle porosity and permeability. From logs and limited core coverage, the top of this unit appears to have the best reservoir properties in the Rogers City Limestone. Porosity distribution appears irregular in core and may be secondary due to cementation. Skeletal grains are dominated by poorly sorted crinoid ossicles (<10mm to <0.5mm).

DOLOMITIZED MUDSTONE - Fair to poor intercrystalline porosity and permeability. Contains a low diversity of fossil types. This unit marks the top of the Dundee and is very correlatable in all field cross sections (Plates III-1 through III-6).

PELoidal-Skeletal Packstone - Poor to fair interparticle porosity and permeability. These sediments are dominated by pelecypods and generally contain a low amount of skeletal material. A wide diversity of fossil types are represented. The best porosity and permeability occurs at the top of coarsening upward hemicycles where coarser-grained, better sorted skeletal packstones and grainstones are present.

PELoidal-Skeletal Grainstone - Fair to good interparticle porosity and permeability. The tops of hemicycles in this unit are represented by grainstones made up of fine-grained pelecypods and a limited amount of skeletal material. This unit is part of a porosity zone correlatable in wells A-4 to A-9 (Cross Section A-A', Plate III-1).

Skeletal-Peloidal Grainstone - Good interparticle porosity and permeability. Skeletal material is dominated by medium-grained crinoid ossicles and abraded brachiopod fragments. This unit is correlatable in wells A-6 to A-14 (Cross Section A-A", Plate III-1).

KEY

TEXTURE

LITHOLOGY

DECOMITÉ

LIMESTONE

CHERTY

LIMESTONE

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**DOLOMITIZED MUDSTONE** - Fair to poor intercrystalline porosity and permeability. Contains a low diversity of fossil types. This unit marks the top of the Dundee and is very correlative in all field cross sections (Plates II-1 through II-3).

**PELOIDAL-SKELETAL PACKSTONE** - Poor to fair interparticle porosity and permeability. These sediments are dominated by peloids and generally contain a low amount of skeletal material. A wide diversity of fossil types are represented. The best porosity and permeability occurs at the top of coarsening upward hemicycles where coarser-grained, better sorted skeletal packstones and grainstones are present.

**PELOIDAL-SKELETAL GRAINSTONE** - Fair to good interparticle porosity and permeability. The tops of hemicycles in this unit are represented by grainstones made up of fine-grained peloids and a limited amount of skeletal material. This unit is part of a porosity zone correlative in wells A-4 to A-9 (Cross Section A-A", Plate III-1).

**SKELETAL-PELOIDAL GRAINSTONE** - Good interparticle porosity and permeability. Skeletal material is dominated by medium-grained crinoid ossicles and abraded brachiopod fragments. This unit is correlative in wells A-6 to A-14 (Cross Section A-A", Plate III-1).

---

**KEY**

- TEXTURE
  - M.E.P.
  - LITHOLOGY
    - DOLomite
    - LIMESTONE
    - CHERTY LIMESTONE
  - RESERVOIR MATERIAL: SKELETAL, KEeled, HEMICYCLE, RESTORED, UPRIGHT HEMICYCLE

**RESEVOIR GEOLOGY OF THE DUNDEE LIMESTONE, WEST BRANCH FIELD, MICHIGAN**

*by Brendan C. Curran*

**Operator:** Marathon Oil Company

**Well Name:** Donovan #6

**County:** Ogemaw

**Location:** Sec. 19-T22N-R2E

**Permit No.:** 40484

Plate II-2
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GENERALIZED CORE DESCRIPTION

ROGERS CITY ZONE 1 - Dark, nodular micritic limestones. Very tight.

DOLOMITIZED MUDSTONE - Very poor intercrystalline porosity and permeability. Contains a low diversity of fossil types. Capped by a pyritized hardground that marks the top of the Dundee Limestone. This unit is very correlative in all field cross sections (Plates III-1 through III-3).

PELODAD-SKELETAL PACKSTONE - Poor interparticle porosity and permeability. Core permeabilities are very high due to numerous small-scale fracture sets associated with styloclites. Coarsening upward hemicycles are incomplete and are dominated by poorly sorted, peloid and micrite-rich packstones. Many fossil types are present.

SKELETAL-PELODAD GRAINSTONE - A higher energy zone with fair to good interparticle porosity and permeability. Medium-grained crinoid ossicles and abraded brachiopod fragments are the most common skeletal grains. This unit is correlative in wells A-6 to A-14 (Cross Section A-A', Plate III-1).

PELODAD-SKELETAL PACKSTONE - Poor to good interparticle porosity and permeability. Contains a wide range of fauna. Porosity distribution is largely controlled by coarsening upward hemicycles (poor near the base, fair to good near the top). This unit is an example of the most common lithotype observed in the cores examined in this study.

CRINOID GRAINSTONE - Good interparticle porosity and permeability. Well-sorted, coarse-grained crinoid ossicles are the dominant allochthon type. This unit is part of a porosity zone that can be correlated between wells A-1 and A-19 (cross section A-A', Plades III-1 and III-2). Between this well and the Estey E-8 (A-10 and A-18 on the cross section A-A'), this unit becomes finer grained, more cyclic, and less porous and permeable.

RESERVOIR GEOLOGY
OF THE DUNDEE LIMESTONE,
WEST BRANCH FIELD, MICHIGAN

by Brendan C. Curran

Operator: Marathon Oil Company
Well Name: Cox #2
County: Ogemaw
Location: Sec. 20-T22N-R2E
Permit No.: 37325

Plate II-3
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GENERALIZED CORE DESCRIPTION

**DOLOMIZED MUDSTONE** - Fair intercrystalline porosity and poor permeability. Contains a low diversity of fossil types. Streaks of unaltered lime mudstones are interbedd with dolomite. Some small-scale fractures are present, creating local permeability highs. This unit is present at the top of the Dundee and is very correlative in all field cross sections.

**CHERTY SKELETAL WACKESTONE** - Poor interparticle porosity and permeability. Small interstices are present associated with stylolites, creating local permeability highs. Contains the skeletal grains of many fossil types and some fine-grained peloids. Some chalk nodules are also present. This unit is very correlative in the SE and thicken toward the center of the field (correlative in wells A-12 to A-33, B-3 to B-12, and C-1 to C-12, cross sections A-A', B-B', and C-C', Plates III-1 through III-5). This unit grades into loose muddy, more porous peloidal-skeletal packstones to the NW.

**PELOIDAL-SKELETAL PACKSTONE** - Poor to good interparticle porosity and permeability. Porosity distribution is controlled largely by cementing upward hemicycles. Low porosity, peloid and micrite-rich packstones are commonly present at the base of hemicycles. Medium-grained skeletal-peloidal grainstones are common near the top of hemicycles and have good porosity. Crinoid ossicles and brecciated shell fragments are the most common skeletal grains. This unit represents the most common lithotype observed in the cores examined in this study and probably accounts for much of the reservoir porosity in this field. The high interparticle porosity zones created at the top of hemicycles are too thin and laterally variable to be correlated individually.

**SKELETAL-PELOIDAL GRAINSTONE** - Fair to good interparticle porosity and permeability. Contains medium-grained crinoid ossicles, abraded brecciated fragments, and fine-grained peloids. This unit is part of a correlative porosity zone identified in wells A-1 to A-19 and B-1 to B-12 (Cross Sections A-A' and B-B', Plates III-1, III-2, and III-4).

**SKELETAL WACKESTONE** - Tight, micrite-rich limestone. Contains a wide diversity of fossil types.

**CORAL-THROMATOPOROID FLOATSTONE** - Very good intra- and interparticle porosity. Not correlative on cross sections.

**FENESTRAL PACKSTONE** - Good fenestral and interparticle porosity and permeability. Not identified in other cores and not correlative on available logs.

**KEY**

<table>
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<tr>
<th>TEXTURE</th>
<th>LITHOLOGY</th>
<th>M.W.P.</th>
<th>DOLOMITE</th>
<th>LIMESTONE</th>
<th>CHERTY LIMESTONE</th>
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**REZERVOIR GEOLOGY OF THE DUNDEE LIMESTONE, WEST BRANCH FIELD, MICHIGAN**

by Brendan C. Curran

Operator: Marathon Oil Company
Well Name: Estey E-8
County: Ogemaw
Location: Sec. 28-T22N-R2E
Permit No.: 32190
Plate II-4

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GENERALIZED CORE DESCRIPTION

ROGERS CITY ZONE 1 - Dark nodular micritic limestone. Very tight.

DOLOMITIZED MUDSTONE - Fair to good intercrystalline porosity and poor permeability. Contains a low diversity of fossil types. This unit is very correlative in all field cross sections (Plates II-1 through II-5).

CHERTY WACKESTONE - Poor intergranular porosity and permeability. Large chert nodules are common. The top 4 feet of this unit are dolomitized and contain fair to good intercrystalline porosity and permeability. This unit is correlative in the SE and thins toward the center of the field. This unit laterally grades into peloidal-skeletal packstones to the NW. Correlative in wells A-12 to A-34, B-3 to B-12, and C-1 to C-12 (Cross Sections A-A', B-B', and C-C', Plates II-2 through II-5).

SKELETAL-PELoidal PACKSTONE - Fair to good interparticle porosity and permeability. Main skeletal constituents are medium-sized crinoid ossicles and brachiopod shell fragments. Better porosity and permeability zones occur near the tops of coarsening upward hemicycles. This unit is correlative in wells A-22 to A-34 and C-4 to C-12 (Cross Sections A-A" and C-C", Plates II-2, III-3, and III-5).

PELoidal-SKELETAL PACKSTONE - The top 3 feet of this unit are a micrite-rich packstone/wackestone with very poor porosity and permeability. This tight zone is correlative in wells A-22 to A-34, and C-4 to C-12 (Cross Sections A-A" and C-C", Plates II-2, III-3, and III-5).

The rest of this unit is a peloidal-skeletal packstone containing numerous coarsening upward hemicycles with fair to good interparticle porosity and permeability. This zone is largely undifferentiated in field cross sections. This represents the most common lithotype observed in the cores examined in this study.

KEY

- Dolomite
- Limestone
- Cherty Limestone
- Coarsening Upward Hemicycle
- Restricted Upward Hemicycle

RESERVOIR GEOLOGY OF THE DUNDEE LIMESTONE, WEST BRANCH FIELD, MICHIGAN

by Brendan C. Curran

Operator: Marathon Oil Company
Well Name: Doran #5
County: Ogemaw
Location: Sec. 27-T22N-R2E
Permit No.: 32143
Plate II-5

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**GENERALIZED CORE DESCRIPTION**

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<th>ROGERS CITY ZONE 3</th>
<th>Dark nodular wackestone. Very tight, few visible skeletal grains. Highly stylolitized.</th>
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<th>ROGERS CITY ZONE 2</th>
<th>Skeletal wackestone to packstone. The top 6 feet of this unit is a packstone with poor to fair interparticle porosity and permeability (visual estimate). The main skeletal constituents are poorly sorted crinoid olistoles (&gt;30mm to &lt;0.5mm). Porosity distribution is irregular and may be the result of diagenetic leaching. The rest of this unit is a very tight nodular wackestone.</th>
</tr>
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</table>

<table>
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<tr>
<th>ROGERS CITY ZONE 1</th>
<th>Dark nodular micritic limestone. Very tight. The top of this unit is marked by a packstone with very poor porosity that often is recognizable on well logs.</th>
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</table>

<table>
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<tr>
<th>DOLOMITIZED MUDSTONE</th>
<th>Poor to fair intercrystalline porosity and poor permeability. Contains a low diversity of fossil types. Very tight strata due to intercrystalline calcite cement are common. This unit occurs at the top of the Dundee and is very correlational in all field cross sections (Plato III-1 through III-5).</th>
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<table>
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<th>CHERTY SKELETAL WACKESTONE</th>
<th>Poor interparticle porosity and permeability. The top 5 feet of this unit are dolomitized and have fair intercrystalline porosity and permeability. Chert nodules are common. This unit is correlational in wells A-12 to A-34, B-3 to B-12, and C-1 to C-12 (Cross Sections A-A', B-B', and C-C', Plates III-2 through III-5).</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>SKELETAL-PELOIDAL PACKSTONE</th>
<th>Poor to good interparticle porosity and permeability. Main skeletal constituents are medium-grained crinoid olistoles and abraded brachiopod shells. Contains many coarsening upward hemicycles which largely control porosity distribution. Lower porosity occurs near the base and higher porosity occurs near the top of these cycles. This unit is correlational in wells A-22 and A-34 and C-4 to C-12 (Cross Sections A-A' and C-C', Plates III-2, III-3, and III-5).</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>PELOIDAL-SKELETAL PACKSTONE</th>
<th>The top 3 feet of this unit is a micrite-rich packstone with very poor porosity and permeability. This tight zone is correlational in wells A-22 to A-34 and C-4 to C-12 (Cross Sections A-A' and C-C', Plates III-2, III-3, and III-5). The remainder of this unit is dominated by peloidal-skeletal packstones with poor to fair interparticle porosity and permeability. Some thin beds of porous skeletal-peloidal grainstone exist near the top of coarsening upward hemicycles in this unit. This is the most common lithotype recognized in the cores examined in this study.</th>
</tr>
</thead>
</table>

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ROGERS CITY ZONE 1: Dark nodular micrite limestone. Very tight. The top of this unit is marked by a packstone with very poor porosity that often is recognizable on well logs.

DOLOMITIZED MUDSTONE - Poor to fair intercrystalline porosity and poor permeability. Contains a low diversity of fossil types. Very tight streaks due to intercrystalline calcite cement are common. This unit occurs at the top of the Dundee and is very correlative in all field cross sections (Plates II-1 through II-5).

CHERTY SKELETONAL WACKESTONE - Poor interparticle porosity and permeability. The top 3 feet of this unit are dolomitized and have fair intercrystalline porosity and permeability. Chert nodules are common. This unit occurs in wells A-12 to A-34, B-3 to B-12, and C-1 to C-12 (Cross Sections A-A", B-B", and C-C", Plates III-2 through III-5).

SKELETAL-PELOIDAL PACKSTONE - Poor to good interparticle porosity and permeability. Main skeletal constituents are medium-grained crinoid ossicles and abraded brachiopod shells. Contains many coarsening upward hemicycles which largely control porosity distribution. Lower porosity occurs near the base and higher porosity occurs near the top of these cycles. This unit is correlative in wells A-22 and A-34 and C-4 to C-12 (Cross Sections A-A" and C-C", Plates III-2, III-3, and III-5).

PELOIDAL-SKELETONAL PACKSTONE - The top 3 feet of this zone is a micrite-rich packstone with very poor porosity and permeability. This tight zone is correlative in wells A-22 to A-34 and C-4 to C-12 (Cross Sections A-A" and C-C", Plates III-2, III-3, and III-5).

The remainder of this unit is dominated by peloidal-skeletal packstones with poor to fair interparticle porosity and permeability. Some thin beds of porous skeletal-peloidal grainstones exist near the top of coarsening upward hemicycles in this unit. This is the most common lithotype recognized in the cores examined in this study.

KEY

RESERVOIR GEOLOGY OF THE DUNDEE LIMESTONE, WEST BRANCH FIELD, MICHIGAN
by Brendan C. Curran

Operator: Marathon Oil Company
Well Name: Hart #2
County: Ogemaw
Location: Sec. 34-T22N-R2E
Permit No.: 26245
Plate II-6

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**GENERALIZED CORE DESCRIPTION**

**ROGERS CITY ZONE 1** - Dark, nodular micritic limestone. Very tight.

**DOLomitIZED MUDstone** - Good intercrystalline porosity and fair to poor permeability. This unit occurs at the top of the Dundee and is correlative in all field cross sections (Plates III-1 through III-5).

**CHERRY SKELETAL WACKSTONE** - Poor interparticle porosity and permeability. The micritic matrix of the top 4 feet of this unit have been dolomitized and have fair to good intercrystalline porosity and permeability. This unit is correlative in the SE and central area of the field (Cross Sections A-A', B-B', and C-C', Plate III-2 through III-5).

(CORE NOT RECOVERED)

**SKELETAL-PELIDAL PACKSTONE** - Poor to good interparticle porosity and permeability. Skeletal grains dominated by medium-grained crinoid ossicles and echinoderm fragments. This unit is correlative in wells A-22 to A-34 and C-4 to C-12 (Cross Sections A-A' and C-C').

**PELIDAL-SKELETAL PACKSTONE** - The top 6 feet of this unit is a micrite-rich packstone with very poor porosity and permeability. This tight zone is correlative in wells A-22 to A-34 and C-4 to C-12 (Cross Sections A-A' and C-C', Plates III-2, III-3, and III-5).

The rest of this unit is dominated by peloidal-skeletal packstones with poor to fair interparticle porosity and permeability. Some porous, thin beds of skeletal grainstone exist near the top of coarsening upward hemicycles.

**KEY**

- **TEXTURE**: NWFC
- **LITHOLOGY**: Dolomite, Limestone, Cherty Limestone
  - Restricted upward hemicycle
  - Pore-filled upward hemicycle

**RESERVOIR GEOLOGY OF THE DUNDEE LIMESTONE, WEST BRANCH FIELD, MICHIGAN**

*by Brendan C. Curran*

- **Operator**: Marathon Oil Company
- **Well Name**: Hart #7
- **County**: Ogemaw
- **Location**: Sec. 34-T22N-R2E
- **Permit No.**: 32145

Plate II-7

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*University Microfilms International*
### Generalized Core Description

**Dolomitized Mudstone** - Poor to good intercrystalline porosity and poor to fair permeability. Some mudstone streaks remain unreplaced by dolomite. This unit is very correlatable in all field cross sections (Plates III-1 through III-5).

**Cherty Skeletal Packstone** - Poor to fair interparticle porosity and permeability. The top 3 feet of this unit have been dolomitized and have fair intercrystalline porosity and permeability. Large short modules are common. This unit is correlatable in wells A-12 to A-34, B-3 to B-12, and C-1 to C-12 (Cross Sections A-A', B-B', and C-C').

**Skeletal-Peloidal Packstone** - Poor to good interparticle porosity and permeability. Micrite-rich tight zones are common at the base of coarsening upward hemicycles. Medium-grained skeletal-peloidal packstones with fair to good interparticle porosity and permeability are common near the top of the hemicycle. Crinoid and brachiopod parts are the main skeletal grain types and show less abrasion and fragmentation near the base of coarsening upward hemicycles than at the top. This unit is correlatable in wells A-22 to A-34 and C-4 to C-12 (Cross Sections A-A' and C-C', Plates III-2, III-3, and III-5).

**Peloidal-Skeletal Packstone** - The top 3 feet of this unit are micrite-rich packstones with very poor porosity and permeability. This tight unit is correlatable in wells A-22 to A-34 and C-4 to C-12 (Cross Section A-A' and C-C', Plates III-2, III-3, and III-5).

The rest of this unit contains many coarsening upward hemicycles and is dominated by peloidal-skeletal packstones with poor to fair interparticle porosity and permeability. Thin grainstone zones are present at the top of some hemicycles and create thin zones of good interparticle porosity.

**Skeletal-Peloidal Grainstone** - Fair to good interparticle porosity and permeability. The medium to fine-grained skeletal material is made up of crinoid ossicles and abraded brachiopod, bryozoan, and other fossil hard parts. Many grains show evidence of early marine cementation. This unit is correlatable in wells A-25 to A-34 (Cross Section A-A', Plate III-3).

### Key

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<tr>
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<th>Lithology</th>
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<td>Limestone</td>
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<tr>
<td>Cherty</td>
<td>Limestone</td>
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**Reservoir Geology of the Dundee Limestone, West Branch Field, Michigan**

*by Brendan C. Curran*

**Operator:** Marathon Oil Company  
**Well Name:** Reinhardt #3  
**County:** Ogemaw  
**Location:** Sec. 35-T22N-R2E  
**Permit No.:** 32144  

Plate II-8

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GENERALIZED CORE DESCRIPTION

ROGER CITY ZONE 1 - Dark, nodular micrite limestone. Very tight.

DOLOMIZED MUDSTONE - Fair to good intercrystalline porosity and poor permeability. This unit is capped by an extensively bio-eroded hardground and is very correlatable in all field cross-sections.

CHERTY SKELETAL WACKESTONE - Poor interparticle porosity and permeability. The top 5 feet of this unit have been dolomitized and have fair intercrystalline porosity and permeability. Permeability highs in core analyses in this unit are probably related to small scale fractures associated with compaction of chalk nodules or stylolization. This unit is correlatable in the SE and thicken toward the center of the field (Cross Sections A-A’, B-B’, and C-C’, Plates III-2 through III-5).

SKELETAL-PELOIDAL PACKSTONE - Poor to fair interparticle porosity and permeability. The top 6 feet of this unit are micrite-rich packstone with very poor porosity and permeability. This unit contains many coarsening upward hemicycles that largely control porosity distribution. Lower porosity occurs near the base, and higher porosity occurs near the top of hemicycles. Correlatable in wells A-22 to A-34 and C-4 to C-12 (Cross Sections A-A’ and C-C’, Plates III-2, III-3, and III-5).

SKELETAL-PELOIDAL WACKESTONE - Very poor porosity and permeability.

KEY

RESERVOIR GEOLOGY
OF THE DUNDEE LIMESTONE,
WEST BRANCH FIELD, MICHIGAN

by Brendan C. Curran

Operator: Marathon Oil Company
Well Name: Buckingham #4
County: Ogemaw
Location: Sec. 35-T22N-R2E
Permit No.: 29775

Plate II-9
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<th>MICROLATERLOG</th>
<th>CALIPER</th>
<th>SIDEWALL NEUTRON POROSITY</th>
<th>CORE DEPTH</th>
<th>(PLUG) PERM k</th>
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**GENERALIZED CORE DESCRIPTION**

### ROGERS CITY ZONE 1
- Dark, nodular micritic limestone. Very tight.

**Dolomitized Mudstone**
- Fair to good intercrystalline porosity and poor permeability. Capped by a pyritized hardground that marks the top of the Dundee Limestone. This unit is very correlative in all field cross sections (Plates III-1 - III-5).

**Cherty Skeletal Wackestone**
- Poor interparticle porosity and permeability. The top 4 feet of this unit have been dolomitized and have fair intercrystalline porosity and permeability. Large chert nodules are common. A variety of fossil types are also common. This unit is correlative in the SE between wells A-12 and A-34, B-3 and B-12, and C-1 and C-12 (Cross Sections A-A', B-B', and C-C', Plates III-2 through III-5).

**Skeletal-Peloidal Packstone**
- Fair to good interparticle porosity and permeability. Micrite-rich tight zones are common at the base of hemicycles. The main skeletal constituents are medium-grained crinoid ossicles and brachiopod shells (usually fragmented). This unit is correlative in wells A-22 to A-34, and C-4 to C-12 (Cross Sections A-A' and C-C', Plates III-2, III-3, and III-5).

**Peloidal-Skeletal Packstone**
- The top 5 feet of this unit is a micrite-rich packstone with very poor porosity and permeability. This light packstone is correlated in wells A-22 to A-34, and C-4 to C-12 (Cross Section A-A' and C-C', Plates III-2, III-3, and III-5).

The rest of this unit contains many coarsening upward hemicycles with poor to good interparticle porosity and permeability. Low porosity peloidal-skeletal packstones to wackestones are common at the base of the hemicycles, and higher porosity skeletal-peloidal packstones and grainstones are common near the top of the hemicycles. This is the most common lithotype represented in the cores examined in this study and makes up many of the largely undifferentiated areas in the field cross sections.

**Skeletal-Peloidal Grainstone**
- Fair to good interparticle porosity and permeability. Dominant allochems are medium to fine-grained crinoid and brachiopod skeletal parts and fine-grained peloids. Skeletal grains show signs of abrasion and marine cementation. This unit is correlative in wells A-22 to A-34 and C-6 to C-12 (Cross Sections A-A' and C-C', Plates III-2, III-3, and III-5).

**Skeletal Wackestone**
- Tight, dark grey limestone. Contains many fossil types, usually dominated by crinoid ossicles and brachiopod shells. Many brachiopods are still articulated.

**Skeletal Grainstone-Floatstone**
- Very good interparticle and intraparticle porosity and permeability. The top half of this zone is a crinoid grainstone, the lower half is a crinoid-stromatolitic floatstone. Not correlative in cross sections.

**Mudstone to Skeletal Packstone**
- Tight, dark grey limestone. Skeletal grain types are dominated by crinoid ossicles, corals, and stromatoporoids. Some delicate corals appear to be preserved in growth position. This unit was not correlative on cross sections with the well logs available during this study.

**Mudstone**
- Very tight, light brown limestone. Fossils include brachiopods, forams, gastropods, and unidentifiable dark organic spheres (spores?). Many cement-filled vertical tubes are present as well as what appear to be large (>2 cm in diameter) vertical burrows or borings. This unit has not been correlated in cross sections in this study.

---

**KEY**

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<th>Texture</th>
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<td></td>
<td>Cherty</td>
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<td></td>
<td>Limestone</td>
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**RESERVOIR GEOLOGY OF THE DUNDEE LIMESTONE, WEST BRANCH FIELD, MICHIGAN**

by Brendan C. Curran

Operator: Marathon Oil Company
GENERALIZED CORE DESCRIPTION

ROGERS CITY ZONE 1 - Dark, nodular micritic limestone. Very tight.

DOLOMITIZED MUDSTONE - Fair to good intercrystalline porosity and poor permeability. Capped by a pyritized hardground that marks the top of the Dundee Limestone. This unit is very correlatable in all field cross sections (Plates III-1 - III-5).

CHERTY SKELETAL WACKESTONE - Poor interparticle porosity and permeability. The top 4 feet of this unit have been dolomitized and have fair intercrystalline porosity and permeability. Large, scaly nodules are common. A variety of fossil types are also common. This unit is correlatable in the SE between wells A-12 and A-34, B-3 and B-12, and C-1 and C-12 (Cross Sections A-A', B-B', and C-C', Plates III-2 through III-5).

SKELETAL-PELIOIDAL PACKSTONE - Fair to good interparticle porosity and permeability. Micrite-rich tight zones are common at the base of hemicycles. The main skeletal constituents are medium-grained crinoid ossicles and brachio pod shells (usually fragmented). This unit is correlatable in wells A-22 to A-34, and C-4 to C-12 (Cross Sections A-A' and C-C'; Plates III-2, III-3, and III-5).

PELIOIDAL-SKELETAL PACKSTONE - The top 5 feet of this unit is a micrite-rich packstone with very poor porosity and permeability. This tight packstone is correlatable in wells A-22 to A-34, and C-4 to C-12 (Cross Section A-A' and C-C'; Plates III-2, III-3, and III-5).

The rest of this unit contains many coarsening upward hemicycles with poor to good interparticle porosity and permeability. Low porosity peloidal-skeletal packstones to wackestones are common at the base of the hemicycles, and higher porosity skeletal-peloidal packstones and grainstones are common near the top of the hemicycles. This is the most common lithotype represented in the cores examined in this study and makes up many of the largely undifferentiated areas in the field cross sections.

SKELETAL-PELIOIDAL GRAINSTONE - Fair to good interparticle porosity and permeability. Dominant allochems are medium to fine-grained crinoid and brachiopod skeletal parts and fine-grained peloids. Skeletal grains show signs of abrasion and marine cementation. This unit is correlatable in wells A-22 to A-34 and C-6 to C-12 (Cross Sections A-A' and C-C'; Plates III-2, III-3, and III-6).

SKELETAL WACKESTONE - Tight, dark gray limestone. Contains many fossil types, usually dominated by crinoid ossicles and brachio pod shells. Many brachiopods are still articulated.

SKELETAL GRAINSTONE/FLOATSTONE - Very good interparticle and intraparticle porosity and permeability. The top half of this zone is a crinoidal grainstone, the lower half is a coral-stromatoporoid floatstone. Not correlatable in cross sections with the well logs available during this study.

MUDSTONE TO SKELETAL PACKSTONE - Tight, dark gray limestone. Skeletal grain types are dominated by crinoid ossicles, corals, and stromatoporoids. Some delicate corals appear to be preserved in growth position. This unit was not correlatable on cross sections with the well logs available during this study.

MUDSTONE - Very tight, light brown limestone. Fossils include ostracods, foraminifers, gastropods, and unidentified dark organic spheres (spores?). Many cement-filled vertical tubes are present as well as what appear to be large (>2 cm in diameter) vertical burrows or borings. This unit has not been correlated in cross sections in this study.

RESERVOIR GEOLOGY
OF THE DUNDEE LIMESTONE,
WEST BRANCH FIELD, MICHIGAN
by Brendan C. Curran

Operator: Marathon Oil Company

Well Name: Grow #4

County: Ogemaw

Location: Sec. 35-T22N-R2E

Permit No.: 28399

Plate II-10

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Scout tickets & core analyses suggest that core depths are mislabeled. Porosity streaks at 2623-2636ft. and 2739-2742ft. (reported core depth) apparently correlate to porosity streaks at 2670-2684ft. and 2633-2636ft. (log depth), respectively. Also, a 52ft. gap in reported core depth between 2674 and 2726ft. does not exist.
GENERALIZED CORE DESCRIPTION

**DOLOMITIZED MUDSTONE** - Poor to good interparticle porosity and poor to fair permeability. Contains a low diversity of fossil types. Very correlative in all field core sections (Plates II-1 through II-3).

**CHERTY WACKESTONE** - Poor interparticle porosity and permeability. The top 4 feet of this unit have been dolomitized and have poor to fair intercrystalline porosity and permeability. Large short nodules are common throughout this unit. Crinoids, brachiopods, bryozoans, trilobites, and ostracod skeletal parts are common. This unit is correlative in the central and SE areas of the field. This unit grades laterally into laminated peloidal-skeletal packstones to the NW. Correlative in wells A-12 to A-34, B-4 to B-12, and C-1 to C-12 (Cross Sections A-A', B-B', and C-C').

**SKELETAL-PELOIDAL PACKSTONE** - Poor to fair interparticle porosity and permeability. Main skeletal constituents are fine to medium-grained crinoid ossicles and abraded and rounded brachiopod shells. Coarsening upward hemicycles are present but poorly developed. This unit is correlative in the SE in wells A-22 to A-34 and C-4 to C-12 (Cross Sections A-A' and C-C', Plates III-2, III-3, and III-5).

**PELOIDAL-SKELETAL PACKSTONE** - The top 3 feet of this unit is a micro-fossil packstone with very poor porosity and permeability. This tight unit is correlative in wells A-22 to A-34 and C-4 to C-12 (Cross Sections A-A' and C-C', Plates III-2, III-3, and III-5).

The rest of this unit is a peloidal-skeletal packstone that contains many coarsening upward hemicycles with poor to good interparticle porosity and permeability. This zone is largely undifferentiated in field cross sections. This represents the most common lithotype observed in the cores examined in this study.

**PELOIDAL-SKELETAL PACKSTONE** - This is the very top of a unit that occurs as a skeletal-peloidal grainstone in other wells with good interparticle porosity and permeability. Although the core that is present is a low porosity packstone, core analysis suggests that core that is now missing had better porosity and permeability, similar to other cored wells.
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RESERVOIR GEOLOGY OF THE DUNDEE LIMESTONE
WEST BRANCH FIELD, MICHIGAN
PLATE III-1, STRATIGRAPHIC CROSS SECTION A-A'
(Wells A-1 through A-11)
by Brendan C. Curran

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A" A-23
A-24
(CORE)

MARATHON OIL COMPANY
WILCOX #2-13
SEC 34 - 22N - 2E
Permit #39307

MARATHON OIL COMPANY
BUCKINGHAM #4
SEC 35 - 22N - 2E
Permit #29775

R1 DATUM
R2
R3
D1
D2
D3
D7
D9

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RESERVOIR GEOLOGY OF THE DUNDEE LIMESTONE
WEST BRANCH FIELD, MICHIGAN
PLATE III-3, STRATIGRAPHIC CROSS SECTION A'-A''
(Wells A-24 through A-34)
by Brendan C. Curran

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RESERVOIR GEOLOGY OF THE DUNDEE LIMESTONE
WEST BRANCH FIELD, MICHIGAN
PLATE III-4, STRATIGRAPHIC CROSS SECTION B-B'

by Breandan C. Curran

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