

ABSTRACT

A research consortium consisting of members of the Department of Geological Engineering and Sciences at Michigan Technological University, the Department of Geology at Western Michigan University and Terra Energy Inc. (Traverse City, MI) and supported in part by the U. S. Department of Energy, was formed in an effort to help companies recover bypassed oil from the shallow shelf carbonate reservoirs in the Michigan Basin.

Total hydrocarbon production in the Michigan Basin has surpassed 1 billion barrels (Bbbls) and total unrecovered reserves are estimated at 1-2 BBbbls. However, hydrocarbon production in Michigan has fallen from 35 MMbbls/yr in 1979 to about 10 MMbbls/yr in 1996. In an effort to slow this decline, a field demonstration project designed around using a horizontal well to recover bypassed oil was designed and carried out at Crystal Field in Montcalm County, MI . The project had two goals:

1. to test the viability of using horizontal wells to recover bypassed oil from the Dundee Formation, and
2. to characterize additional Dundee reservoirs (29) that are “look alikes” to the Crystal Field,

As much as 85 percent of the oil known to exist in the Dundee Formation in the Michigan Basin remains in the ground as bypassed oil. Early production techniques in the 137 fields were poor, and the Dundee was at risk of being abandoned, leaving millions of barrels of oil behind. Crystal Field in Montcalm

County, Michigan is a good example of a "worn out" field. Crystal Field was once a prolific producer which had been reduced to a handful of wells, the best of which produced only 5 barrels per day.

The demonstration well drilled as a result of this project, however, has brought new life to the Crystal Field. Horizontal drilling is one of the most promising technologies available for oil production. The new well was completed successfully in October of 1995 and has been producing 100 barrels of oil per day, 20 times better than the best conventional well in the field.

Estimated recoverable reserves for the new well are 200,000 barrels of oil. The success of the well has spawned a "miniboom" in drilling in the Dundee Formation. As a direct result of the project, 9 new horizontal wells have been permitted for drilling in Crystal Field, 2 have been drilled and 20 to 30 horizontal wells have been permitted in geologically similar fields in the Dundee Formation.

Further development in Crystal Field is expected to produce an additional 2 million barrels. If other abandoned Dundee fields are redeveloped in a similar manner, the additional oil production will probably be about 80 to 100 million barrels, worth about \$210 million in tax revenues alone. This is oil from existing U.S. fields with proven production, not from riskier new fields in environmentally sensitive regions or those controlled by foreign nations.

TITLE

RECOVERY OF BYPASSED OIL IN THE
DUNDEE FORMATION (DEVONIAN) OF THE
MICHIGAN BASIN USING HORIZONTAL
DRAINS

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I. REPORT OF FIELD DEMONSTRATION PROJECT

INTRODUCTION

In 1993, a research consortium consisting of members of the Department of Geological Engineering, Geology and Geophysics at Michigan Technological University, the Department of Geology at Western Michigan University and Terra Energy Inc. (Traverse City, MI) and supported in part by the U. S. Department of Energy was formed in an effort to help companies recover bypassed oil from the shallow shelf carbonate reservoirs in the Michigan Basin. Total hydrocarbon production in the Michigan Basin (Figure 1) has surpassed 1 billion barrels (Bbbls) and total unrecovered reserves are estimated at 1-2 BBbbls. However, hydrocarbon production in Michigan has fallen from 35 Mbbls/yr in 1979 to about 10 MMbbls/yr in 1996. A field demonstration project designed around using a horizontal well to recover bypassed oil was designed and carried out at Crystal Field in Montcalm County, MI . The project had two goals:

1. to test the viability of using horizontal wells to recover bypassed oil from the Dundee Formation, and
2. to characterize additional Dundee reservoirs (29) that are "look alike" to the Crystal Field.

The intent of looking at additional fields was to provide operators a head start in applying the Crystal Field results to "look alike" fields. This appears to have been a good strategy as a number (12+) additional Dundee fields were drilled or were permitted within 2 years of the demonstration well at Crystal Field. The locations of

Crystal Field and the 29 additional Dundee fields are shown in Figure 2.

FIELD	DATE	DEPTH	FIELD AREA (AC)	PAY THICK	PRODUCERS	ACTIVE WELLS	CUM. OIL (BBLs)
BELLY ACHERS	1/20/44	3475	220	1	7	3	365,225
BROOMFIELD &	0/0/79	3752	540	3	29	23	528,231
CAT CREEK &	1/23/68	3696	300	4	8	6	520,451
CATO	9/9/44	3542	670	3	22	9	1,231,920
CEDAR	2/24/43	3829	420	2	10	5	1,227,448
COLDWATER	8/6/44	3696	3200	25	81	14	22,312,167
CRANBERRY LAKE &	1/0/00	3835	70	2	8	1	2,252,999
CRANBERRY LAKE EAST	10/15/63	3760	160	6	4	4	862,040
CRYSTAL	5/29/35	3186	2000	12	193	7	7,934,350
CURRIE	10/10/36	3918	40	2	2	2	213,202
DOUGLAS	9/14/45	3395	120	2	6	2	261,764
EVART	4/5/42	3774	1100	6	29	0	3,812,127
FORK	9/5/42	3845	2700	8	64	0	7,777,026
FREEMAN-REDDING	10/14/38	3886	2800	19	170	17	19,981,158
GILMORE	2/15/55	3803	360	3	13	4	425,426
HARDY DAM	5/29/66	3351	920	5	23	13	1,231,003
ISABELLA	10/31/48	3783	410	9	21	2	832,395
LAKE GEORGE	6/18/54	3968	100	2	10	0	394,924
LEATON	10/10/29	3657	540	8	45	7	1,877,266
MCBAIN	6/5/59	3969	920	15	24	22	3,506,009
PROSPER &	9/9/42	3837	520	4	13	6	1,916,454
PROSPER SOUTH	10/8/67	3796	280	8	8	7	1,050,521
REYNOLDS	3/20/54	3343	2100	2	53	8	4,869,958
RIVERSIDE (& MCBAIN)	4/18/42	3944	220	3	6	6	235,766
SHERMAN	1/1/34	3634	1020	4	88	5	4,805,774
SKEELS	12/11/50	3840	50	6	5	3	1,012,549
SYLVAN	7/3/48	3930	440	14	11	2	1,220,335
VERNON-ROSEBUSH	5/20/33	3690	2060	6	135	48	8,121,864
WINTERFIELD	0/0/40	3794	2740	15	92	54	5,159,449
WISE	8/9/38	3704	1620	11	82	28	4,087,240

TABLE 1. List of additional Dundee Fields studied in this project with discovery well and permit number.

It has been estimated that as much as 2 MMbbl additional oil might be recovered from Crystal Field through horizontal drilling. With 137 Dundee fields in the trend, it is apparent that the amount of incremental oil recoverable through horizontal drilling could be very significant.

The main producibility problem at Crystal Field, and at many other Dundee Fields, was initially thought to be water coning, e.g. the fields were produced so rapidly during the 1930's and 1940's that the water cuts approached 100% within 1-3 years of pumping. Analysis of old production records suggests that much producible oil was by-passed at Crystal Field as a result and the goal of this project was (1) to determine how much producible oil is still in place and (2) to evaluate, via field trial, how much of this oil can be produced using horizontal wells as drains.

The Dundee reservoir in the Crystal Field study area is a vuggy, coarsely crystalline fractured dolomite that generally occurs at the top of the formation, immediately below the Bell Shale or "cap limestone". Several engineering and geological factors contribute to the poor producibility of the reservoir in the past: the vuggy nature of the pores along with the very high permeability of the fractured portions has caused rapid flow of fluid through parts of the reservoir, while other parts have experienced little or no flow and recovery. Past reservoir management practices have also contributed to poor recovery. Well spacing is generally one well per 40 acres, a density that is inadequate to drain the field given the reservoir heterogeneity. Even the 10-acre spacing at Crystal Field was apparently inadequate to drain the reservoir. Completion and stimulation techniques have been quite variable and some practices have contributed to permanent damage and long term harm to the reservoirs. Water coning, caused by high pumping rates has been mentioned as one adverse practice. Another has been the flaring of natural gas from the wells, causing rapid pressure drops in the reservoir and resulting in premature abandonment of wells.

This study compiled information on past completion and recovery techniques and noted the results achieved for different reservoirs. Because some reservoirs, such as Crystal Field, have active water drives while others are solution or gas drive, the reservoir characterization for one type of field may not be adequate for another. This study evaluated 30 Dundee reservoirs for reservoir characteristics, drilling completion and production practices and developed a protocol for optimal recovery.

The TOW 1-3 HD1 demonstration well demonstrated that significant volumes of producible oil did remain in old fields in the Dundee Formation and that these hydrocarbons could be produced using horizontal drilling technology. Additional project goals were to: (1) develop a “data cube” for the Michigan Basin that would lay the foundation for quantitative studies relating stratigraphic evolution, diagenetic history and timing of hydrocarbon evolution, migration and entrapment in the Michigan Basin, (2), conduct and integrate well-to-well scale reservoir studies into field and basin wide framework for 30 reservoirs producing from shallow shelf carbonates throughout the Michigan Basin.

The TOW 1-3 was drilled at Crystal Field in Montcalm County in October of 1995. This well was the first horizontal well to be successfully completed in the Dundee Formation and was quickly followed by nearly 2 dozen additional horizontal wells. As of December, 1997, the demonstration well had produced over 60,000 barrels of oil in 2 years at a gross value over \$1.02 million dollars (\$17/bbl). The cost of the demonstration well to the federal government was slightly over \$350,000. The amount repaid to state of Michigan in the form of severance taxes and other fees is about \$75,000. The property owners received about \$127,000 in taxable income

while the oil companies paid taxes on the rest. However the biggest benefit was the fact that the TOW 1-3 sparked a “mini-boom” in the Michigan oil patch which still continues. Production at Crystal Field alone is still expected to exceed 1-2 MMbbls, while production from “look alikes” is likely to reach 10-20 MMbbls. Overall, the project has been a distinct benefit to the oil industry in Michigan and has repaid the original federal investment in less than 2 years from just 1 well.

Related projects benefits include:

1. Production of 8-10 students (4 undergraduate and 4 Masters) from Michigan Technological University and Western Michigan University who now have jobs in the gas and oil industry as a result of working on this project,
2. Establishment of Michigan Tech as primary data repositories for subsurface data for the State of Michigan (see below),
3. Helping to reestablish and energize gas and oil programs in the two Michigan Universities involved,
4. Seeding an ongoing technology transfer program with the gas and oil industry

Crystal Field is one of the largest Dundee producers, yielding nearly 8 MBbbls from 1935 to date. At the inception of the project, It was estimated that the 8 Mbbls produced to date represents less than 20% of the OOIP and the project goal was to produce another 1-2 Mbbls from Crystal Field. The demonstration well was designed to produce 100,000 to 200,000 additional bbls of oil over a 1-3 year time period. Follow-up wells were to produce the remaining oil. It is now estimated that full

development of the Crystal Field will require 8-10 additional horizontal wells to produce an additional 3-8 Mbbls.

The producibility problems in the Dundee Formation can be traced to original production practices in the early 1930's and 1940's when many fields were badly mismanaged as operators produced their wells at the maximum possible rates. The result was that much producible oil was bypassed as the wells watered out prematurely.

In addition to the proposed field trial at Crystal Field, 29 other fields with Dundee production in portions of seven counties were selected for study. These reservoirs are located in parts of 88 townships in a 3,170 square mile area of the central Michigan basin. Pertinent characteristics of these fields can be found in Table I. The locations are given in Figure 2. These reservoirs have produced over 110 million barrels of oil, about one-third of the production for the entire Dundee. Discovery dates for these reservoirs range from 1929 to 1979, but most were discovered and produced being during the 1930's and 1940's. A few fields have been abandoned but many have maintained at least a few producing wells. However these are at increased risk of abandonment in the near future. All of these fields have been produced through the primary production phase only; no secondary or enhanced recovery operations have yet been attempted. The technology developed in this project was designed to benefit both smaller independents and larger oil companies.

The reservoir characterization aspect of the project involved several stages of sampling, analysis, interpretation. Samples were selected from cores in public

repositories at the Western Michigan University Core Research Lab, University of Michigan Subsurface Lab, and at other state facilities. Existing core descriptions were used to develop a lithofacies type classification for the Dundee. Samples were collected from several intervals that represent each lithofacies type where the sedimentologic parameters are well understood and detailed core descriptions were completed for each interval. Thin sections made from each sample provided a descriptive analysis of mineral content and general pore form. X-ray diffraction analysis gave quantitative mineral compositions and mercury injection analysis defined pore throat size and pore volume. A portion of the sample from each thin section chip was dissolved leaving a cast of the pore space in the epoxy used for sample preparation. These casts were studied for pore geometry patterns and photographed using the scanning electron microscope. All observations were correlated to standard porosity measurements derived from wireline logs and conventional core analysis.

The wireline log responses for each sampled interval were quantitatively evaluated using the TERRASCIENCES workstation. Oil and gas production history has been recorded for these intervals. By comparing production history, rock and pore properties and log signature, it has been possible to estimate volume of unrecovered oil (Wardlaw and Cassan, 1979) as well as the potential for further development of the reservoir. Field specific as well as regional structural and isopach maps were prepared using standard spatial database management software. These maps allow interpretation of structural occurrence and formation thickness relationships of the productive zones.

REGIONAL SETTING

Stratigraphy and Depositional Framework

The Dundee Formation is composed of open shelf, biohermal, and, locally, sabkha carbonate deposits (Catacosinos, et al., 1991; Harrison, 1992a; Fig. 2).

Stratigraphic nomenclature for the Dundee has been inconsistently applied over the years. The stratigraphic column in Figure 3 is commonly accepted and is sufficient for the purposes of this project. Some of the confusion arose because of regional facies changes associated with the west-to-east shelf-to-basin transition. Because fewer than 50 cores survive from the 137 Dundee fields, and nearly half of these are from a handful of fields that have recently begun enhanced oil recovery operations, regional variations in reservoir lithology are poorly known. However, the following generalities can be made:

In the western Michigan Basin, the Dundee Formation is divided into two members, the Reed City Member, which consists of a dolomite unit overlain by an anhydrite unit and the Rogers City Member (Figure 4), which is usually limestone (Gardner, 1974). In western Michigan, Dundee reservoirs occur in the Reed City Member as porous sucrosic dolomite intervals which underlie the Reed City anhydrite, a sabkha to shallow lagoonal evaporite deposit. The Dundee reservoirs were formed when brines refluxed downward from the Reed City anhydrite and dolomitized underlying carbonates. Reed City Field is the best example of this type of Dundee reservoir (Upp, 1969).

In the eastern Michigan Basin, the Reed City Member is called the Dundee

Limestone. Together, the Dundee Limestone and the Rogers City Limestone are known as the Dundee Formation and are largely undolomitized. Since it is impossible to differentiate the Dundee and Rogers City Limestones in the subsurface without core, the entire section is commonly referred to as the "Dundee reservoir". Throughout much of eastern Michigan, which is near the basin depocenter, the Dundee Limestone exceeds 150 ft in thickness and is composed of thin (2 to 20 ft) coarsening-upward parasequences that grade upward from muddy wackestones to cycle-top skeletal-peloidal grainstones. The grainstone units, which vary from 1 to 8 ft in thickness, are the productive reservoir lithology. West Branch Field provides a good example of this type of reservoir (Curran and Hurley, 1992).

At West Branch Field, the top of the Dundee Limestone is a pyritized, bored hardground, which is underlain by 10 to 15 ft of dolomitized muddy carbonate that is also productive. The overlying, deeper water Rogers City Limestone, which is composed of undolomitized dark nodular wackestone, is unproductive. The Dundee - Rogers City contact has been interpreted as a sequence boundary by Curran and Hurley and undoubtedly correlates with the regressive Reed City anhydrite in western Michigan and possibly with a karst event at the top of the Dundee Limestone in central Michigan. Stromatoporoid - rugose coral patch reefs are widespread in the Dundee Limestone in eastern Michigan, and in some areas production comes from reef core boundstones and reef flank skeletal sands. South Buckeye Field provides an excellent example of Dundee reef production (Harrison, 1992b).

In the central Michigan Basin, where our seven-county study area is located, core coverage is rather limited, but those cores available for examination suggest

depositional environments similar to eastern Michigan. However, in central Michigan, the Dundee Formation has been almost entirely converted to dolomite. Only a thin (<15 ft), tight interval at the top of the Rogers City Limestone, identified in drillers' logs as the "cap limestone", remains undolomitized. IP (Initial Production rates) values in several central Michigan fields group into two categories. Most wells have IP's of several hundred BOPD, while wells concentrated in "sweet spots" have IP's of several thousand BOPD. Lower production rates appear to be associated with the dolomitized equivalents of lithofacies identified in eastern Michigan. Presence of fractures and vugs in cores suggest that higher production rates are associated with zones which contain fracture and solution-enhanced porosity. The productive zone in central Michigan normally occurs immediately beneath the cap limestone in the upper part of the dolomitized Dundee Formation, and is known in this region as the Dundee porosity zone. It is underlain by a thick water leg with an active water drive. Winterfield Field (Chittick, 1995) and Crystal Field provide good examples of central Michigan Dundee production from dolomite reservoirs enhanced by fracturing and solution. It is in this central Michigan productive belt that Crystal Field, and the other 29 Dundee fields being characterized in this project, are located.

FIELD DEMONSTRATION

Site Description

The location of the field demonstration was the Crystal Field in Montcalm County, Michigan. This field is located in the center of the lower Michigan peninsula. It covers parts of Ferris Township (T 11N - R 5W) and Crystal Township (T 10N - R 5W) . Figure 5 shows the structure on the top of the Dundee formation in the vicinity

of Crystal Field while Figure 6 is a more detailed map of the same structure over Crystal Field itself. The TOW 1-3 HD demonstration well was drilled EW in the interwell spacing between 4 earlier wells (Figure 7). A cross section through the Crystal Field at the site of the Tow 1-3 demonstration well (Figure 8) shows that the reservoir has a highly irregular surface topology, even with 10-acre well spacing control on the stratigraphy. Table 2 summarizes the salient characteristics of Crystal Field prior to drilling the TOW 1-3 demonstration well.

Basin Name: Michigan Basin	Field Name: Crystal Field	Target Reservoir: Dundee Fm.
Other Producing Formations: Traverse Ls.	Average Reservoir Depth: 2000- 2500 feet (subsea).	Types of wells: oil, no gas;
4 wells currently producing	>186 abandoned wells	5 disposal wells
12 observation wells (not including 4 drilled as part of this project)	Surface Facilities: gathering lines are in; surface holding tanks are present and adequate	Present Land Use: primarily agriculture
Cummulative production: 7,934,350 bbls oil	Max flow rate: >9000 BOPD	Year of discovery: 1935

Table 2. Salient Characteristics Of Crystal Field

Crystal Field History

Crystal Field was discovered in 1935 and had produced 7,934,350 barrels of oil by the end of 1986. The producing area encompasses approximately 3000 acres and a total of 193 wells have been drilled to date (Figure 9). The field was developed on 10-acre spacing and the average oil recovery per acre drilled is approximately 4,000 bbls/acre. Many of the original wells were capable of flowing oil at very high rates: according to well records, 36 wells originally produced at volumes in excess of 1000 BOPD, with the greatest being 9000 BOPD. In 1993, seven of the original 193 wells were still producing, the best of which was the Robbins #1 operated by Lease Management (5 BOPD and 600 BWPD).

The discovery well at Crystal Field was of the Daily Crude, J. Tow No. 1 well drilled May 29, 1935. The well was drilled on an anticlinal structure (Figures 5 & 6) that had been defined by subsurface mapping using data from nearby wells. Development was rapid. One hundred ninety three producing wells were drilled, most before 1939 (Figure 9). Decline was also rapid. Most wells had a productive life of less than five years (Figure 10). The oil leg in the Dundee reservoir is thin (typically <30 ft) and is underlain by a thick water leg with an active hydrodynamic drive. As a result, wells that were produced at excessive rates coned water and rapidly watered out. By 1940, 95% of Crystal Field's present cumulative production of nearly 8 MMBO had been recovered. By 1995, when this project's demonstration well was drilled, only 7 conventional wells remained on production in the field, the best one producing 5 BOPD with a water cut of 600 BWPD.

Two productive lithologies can be inferred from a contour map of IP values

(Figure 24). Most wells had IP's of several hundred BOPD. However, in several "sweet spots" in the field, IP's of >2000 BOPD were common. Nine wells had IP's > 5000 BOPD, and the maximum IP for the field exceeded 9000 BOPD. Prior to taking the TOW 1-3 core, no core was available for Crystal Field. Dundee core from a wildcat well located 8 miles to the northwest contains fractures and vugs, suggesting that fracture and solution-enhanced porosity may be responsible for the high-IP "sweet spots" in Crystal Field. The core taken from the TOW 1-3 is similar and confirms these findings through the presence of many vugs and fractures.

During development in the 1930's, oil and gas rights were widely divided, with over 45 different operators having producing wells. The wells were pumped at high rates as each operator tried to maximize his share. Significant reservoir damage occurred as a result, in the form of premature water coning. Many of the original wells had a producing life of less than 1 year and 80% of the wells were plugged by 1939. It is clear that significant volumes of oil were left behind that could have been recovered if more conservative production methods had been practiced.

The original development of Crystal Field was over by 1938, i.e. only three years after the discovery well. In the 1950's three operators (Karacher and Slack, McClure Oil Company and Farmers Petroleum) drilled 9 new development wells. Five of these wells were on the margins of the field and were not successful. However, four wells were located in favorable structural positions, and two of these recovered excellent volumes of oil. The Robbins #1 (W1/2, SW1/4, NE1/4 Section 3) and the Rule #1 (E1/2, NE1/4, NW1/4 Section 2) each produced over 60,000 barrels

of oil by 1972. The Robbins #1 averaged over 35 BOPD during its first year of production. And, despite being drilled 20 years later, the Rule #1 produced a larger volume of oil than most of the original wells located within 1/3 mile radius. The Rule #1 is the second best well ever drilled on the NE dome in terms of cumulative oil production. The performances of these two wells were important factors in Terra Energy's decision to select the Crystal Field as the best candidate for enhanced production through horizontal drilling. Production data for all leases at Crystal Field is summarized in Charts 1-3.

Geology Of Crystal Field

Crystal Field ranks 20th on the all time producing list of Michigan oil fields and is the 11th best Dundee producer. Thus Crystal Field is just one field in a class of reservoirs that could be expected to benefit from EOR projects. We now estimate that 1-2 million barrels additional production from Crystal Field is a realistic estimate; it is possible that more than that amount of producible oil remains, but logs and records are still inadequate for a precise determination. Most Dundee Fields are so old (ca. 1930-1940) that it is not possible to adequately characterize them using existing records and logs.

The TOW 1-3 drilling program recovered full core from a vertical well through the complete reservoir interval (50-60 feet). The horizontal well was a sidetrack from this vertical characterization well. The Crystal Field reservoir is partly a structural trap located in the Dundee Formation (Devonian) which lies above the Lucas Dolomite and below the Rogers City/Bell Shale (Figures 3 & 4). Contour maps of the top of the Dundee (Figures 5- 7) define two distinct domes separated by a narrow syncline. At

the top of the Dundee, the larger SW structure has 40 feet of closure while the smaller NE dome has 20 feet of closure. The Crystal Field structure is attributed to flowage and/or dissolution of the underlying Detroit River salts (E. Taylor, personal communication).

The field is also stratigraphic in part because the reservoir is positioned at the updip end of a regional Dundee dolomite trend. The upper third of the Dundee reservoir is a porous dolomite which abuts dense limestone to the south, east and west (Figure 4). The Dundee Fm. is entirely dolomitized over most of the Crystal Field particularly in the northern and eastern sections. These stratigraphic diagenetic features influence oil location in the reservoir. Most of the successful wells were drilled in areas that were completely dolomitized and these generally produce from the very top of the Dundee.

The Smith 1-17 well was logged prior to this project and the closest logged well to Crystal Field, approximately 2 miles away. Similar to the geologists interpretation of the Smith #1-17 log section, a limestone caprock is present over most of the Dundee in Crystal Field (Figure 8). As indicated on the isopach map (Figures 15 & 22) the thickest caprock is located in the southwestern part of the field. The structurally highest wells in the field are also located here and most penetrate between 5 and 12 feet of caprock. A thinner zone, approximately 5 feet, was penetrated in both the vertical and horizontal legs of the demonstration well, the TOW 1-3 HD.

Dundee Development History

The Dundee Formation (Middle Devonian) has yielded more oil than any other

producing interval in Michigan. The Dundee trend, which forms an east-west band across the central Michigan Basin, consists of 137 fields which together have yielded more than 350 MMBO (Figure 11). Most of these fields, including Crystal Field, lie within the gravity high that many investigators conclude defines an early rift basin that dominated the early structural and sedimentologic history of the basin (Figure 13) . The first commercial Dundee production was established at Mt. Pleasant Field in 1928 and most Dundee fields were subsequently discovered and brought on production during the 1930's and 1940's (Champion, 1969). Wells in many of the fields had very high initial production (IP) rates. IP's in excess of 2000 BOPD were common, with values as high as 9000 BOPD reported. Modern reservoir management techniques were unknown at the time. Many fields were produced at excessive rates. As a result, wells watered out early, leaving behind significant volumes of unrecovered oil. Crystal Field in Montcalm County was one of these fields and largely for that reason was selected as the primary focus of the U. S. Department of Energy (DOE) Class 2 Reservoir Demonstration Project.

Production History

Reservoir pressure in Crystal Field is maintained by a strong water drive, which is typical of many Dundee fields. The original oil/water contact (OWC) is projected at -2410 feet subsea. For the structurally highest well in the field (Preston #3) maximum gross pay thickness is 43 feet with an interpreted net pay thickness of 30 feet. Most of the best wells had superior structural position which also resulted in the top of porosity being high relative to the rest of the structure. Based on initial production rates (Figure 12) and cumulative totals it appears that the dolomite

porosity and permeability is best developed in areas where the limestone cap exists and is 12 feet or less in total thickness, as compared to areas where the dolomite directly contacts the overlying Bell Shale. (Detailed locations for these wells is shown in Figure 14 which shows all wells at Crystal Field labeled with the permit numbers.) A gross isopach map of the Dundee Formation at Crystal Field (Figure 15) shows a thickening to the N-NE from approximately 75 feet to more than 125 feet. Wells drilled in the synclinal sections generally penetrated thick limestone at the top of the Dundee, pushing the top of porosity to even lower levels and the tests indicated very poor wells, if they were productive at all.

The best well in Crystal Field is the Flint #1 (NE1/4, NW1/4, NW1/4 of section 11) (Figure 9) which has produced over 400,000 barrels of oil and is still producing at about 2 BOPD. (The operator avoids water production by flowing off the head of oil which separates in the well bore and shutting the well back in before the water surfaces. Five of the seven active wells in the field are produced in this manner.)

The oil production shows dramatic differences in cumulative oil production from one well to the next. The Flint #1 (Figure 14) has produced 400,000 bbls and is flanked by wells to the east (75,000 bbls) and west (300,000) which are also good producers. But an offset well directly north of the Flint #1 encountered a thick limestone caprock and was a dry hole. Similarly, two south offsets produced only 10,000 and 4,000 bbls. Production variances of this magnitude are common throughout the field and indicate extreme heterogeneity in the distribution of oil. Even 10-acre spacing (Figure 14), such as at Crystal Filed, is not adequate to define the heterogeneity completely or to drain the reservoir. The high porosity zones in the

upper Dundee are thought to be lenticular and porosity development varies widely across the field. Despite the 10-acre spacing (, it was considered likely that Crystal Field still contained pockets of oil untapped by the original wells, which was confirmed by the TOW 1-3 HD well.

It should be noted that many wells apparently were damaged due to poor drilling, completion and/or operating procedures: wells were drilled too deep and penetrated the water zone, while others were lost due to mechanical failures during and following drilling. Also, all of the successful wells were probably flowed at excessive rates which resulted in premature water coning.

No wireline surveys or core data exist for any of the wells drilled in the field. The nearest available open hole log is the Smith #1-17 drilled by Jennings Petroleum in 1984. This dry hole is located 2 miles southeast of Crystal Field (SW1/4, SW1/4,SW1/4 of section 17, New Haven Twp., T10N, R4W, Gratiot County). The Schlumberger LDT-CNL-GR logs from this well indicate the Dundee is 177 feet thick. This interval is predominantly dolomite with excellent porosity toward the top. Several dolomite zones have porosity in excess of 18%. These high porosity zones are interbedded with limy dolomite and/or dolomitic limestone of lower porosity. Overlying the dolomite is a 17 foot-thick bed of limestone "cap-rock" with porosity in the range 2-5%. Schlumberger DLL-MLL logs were also run in this hole. The Dundee was structurally low in this well as was water saturated.

The data available for Crystal Field consists of records submitted by the operators, generally formation tops, penetration depths and production data. Based on these records, the reservoir rock was expected to similar to the section penetrated

by the Smith #1-17. As mentioned, this was confirmed by the demonstration well. The oil-bearing rock is expected to be the high porosity dolomites at the top of the Dundee. This dolomite zone is assumed to range in thickness from < 1 foot (very thin) to 15 feet. As in the Smith well, the high porosity dolomitic intervals are expected to be interbedded or alternate with low porosity carbonates. Again, these expectations were confirmed by the TOW 1-3 HD.

Reservoir Characterization

Preliminary examination of the core from the TOW No. 1-3 HD-1 well indicates that depositional facies may exert some control on the location of productive zones, as in Dundee limestone fields in eastern Michigan. Several parasequences are observed in the core. Two of them are topped by thin (1 to 2 ft) grainstone beds with good porosities and permeabilities. However, the most important porosity types in the Crystal Field Dundee reservoir appear to be fractures and vugs. The upper 15 ft of the Dundee is heavily fractured in core and contains centimeter-sized vugs. Most fractures are subvertical with highly variable azimuths, but some fractures are developed at lower angles. Most fractures and vugs are lined with white, sparry dolomite. In the vertical leg of the demonstration well, the top of the Dundee was encountered 8 ft lower than projected and the cap limestone was missing. Together, these observations suggest that a top-down solution process (karst?) may have led to fracturing and collapse of the uppermost Dundee, which enhanced porosity. This concept is still considered a working hypothesis and is currently under active investigation.

A larger goal of our reservoir characterization effort was to develop a Dundee

reservoir model for the central Michigan area that included the results of geological, geophysical, and reservoir engineering investigations. Twenty nine additional central Michigan Dundee fields with similar reservoir lithologies are being characterized so that operators can easily apply the results of our Crystal Field demonstration project to other "look alike" fields. Well data, including drillers' logs and wireline logs for the 8526 wells in a seven-county study area, which includes 4785 wells that penetrate the Dundee, are in our oil and gas well-data set (included on the project CD ROM). About 50 cores of the Dundee Formation from throughout the state of Michigan have been identified and are currently available in public repositories. Cores from the central Michigan area were examined and compared to the Crystal Field core.

Structure contour maps of the top Dundee, the top of the Dundee porosity zone, and the tops of several other formations, as well as contour maps of IP and simple cross sections have been completed for Crystal Field and for all 29 other Dundee fields in the study area. Maps and cross sections have been compiled into electronic notebooks for each field, along with field and reservoir data, field production histories and decline curves, type logs, and core data. These data are on the CD ROM in the "ATLAS" directory in the subdirectory "AutoCad Files". Both the original AutoCad DWG files and Adobe Acrobat PDF files are presented. For each field, 8-10 individual maps were prepared, each denoting a separate field attribute. Each field ususally has the following maps:

- Base map

- Structure contour on top of Dundee Formation

- Isopach map of Dundee formation

Contour map of porosity zone

Initial production map

Cross-section location map

Cross-section(s)

Contour map of net pay

Examples of these maps for the Crystal Field are given in Figures 16-25. The other 25 fields all have similar maps, but these are not included as figures in the final report to save space. They are included on the CD ROM in PDF and DWG files. (Approximately 250 such maps were generated as part of this project.) The Acrobat PDF files contain the full detail originally present in the AutoCad Files, but the details may not be apparent in 8" x 10" figures. However zooming the PDF files or stretching them out will recapture the detail. Also, the PDF files are in color.

Plans are still alive to publish these field summaries combined with an overview and evaluation volume as an "Atlas of Michigan Dundee Reservoirs" through the Michigan Basin Geological Society. As presently envisioned, this Atlas will include a regional overview of Dundee stratigraphy and reservoir variability; development history of the trend, including comparisons between different fields; production history, including a discussion of engineering and completion techniques; and a table of important reservoir parameters for use in characterizing the Dundee reservoir in other old fields for which little data is available. Discussion of the importance of fracturing, fracture density, and irregularity of the dolomitized surface of the Dundee porosity zone should aid in the design of an optimal strategy for horizontal drilling. This Atlas should enhance the capability of the small operators in

the state to independently explore and develop this neglected resource. The Michigan Basin Geological Society has expressed interest in publishing the Atlas, which would be made available to the public as a Geological Society special publication.

This project characterizes Dundee oil and gas reservoirs with pore geometry models, lithologic and sedimentologic parameters and fluid saturation distribution characteristics. Integration of quantitative data with the production history from specific fields will give a credible evaluation of potential future oil and gas resources in the Dundee Formation. Preliminary analyses of many recently acquired cores and modern wireline log suites from producing reservoirs and non-producing intervals shows that porosity results from primary facies-controlled depositional fabrics, diagenetic alteration fabrics, or both. Oil and gas fields developed in open shelf, fenestral limestones and patch reef complexes of the Dundee Formation located atop structural highs are widespread throughout the east-central Michigan basin. Only minor diagenesis has modified these initially porous sediments. Other Dundee fields are localized or linear pods of fractured dolomite within tight open shelf micritic limestone. Dundee fields to the west are porous facies that have been pervasively dolomitized. Each of these field types has produced varying amounts of hydrocarbons, but those in the east-central basin are generally the largest.

DRILLING RESULTS

Crystal Field Demonstration Well

The principal objective of this DOE-sponsored project was to drill a horizontal

demonstration well in order to test the viability of using horizontal wells to recover bypassed oil from the Dundee reservoir in Crystal Field. A secondary objective was to obtain a modern log suite through the entire Dundee Formation and a conventional core through the productive interval, the oil/water contact, and the upper part of the water leg. In order to prevent lost circulation and blowouts in vuggy and fractured dolomites and avoid penetration of the oil/water contact to minimize water coning, it was common practice in central Michigan to drill only a short distance below the cap limestone into the top of the Dundee porosity zone before completing a well. As a result, very limited core and log data is available for the Dundee in this area, and no cores or modern logs are available for any well in Crystal Field. Core and log data from the demonstration well will provide an important anchor point for the regional reservoir characterization study.

The TOW No. 1-3 HD-1 demonstration well was spudded on September 20, 1995. It was sited near the crest of the structure in an area where most wells had high IP's (Figures. 6 and 12). The well was located near the eastern edge of an 80-acre drilling unit containing 8 original wells that had been plugged and abandoned for 20 years or longer. As originally planned, the horizontal leg was to follow a trajectory between 4 well pairs (Figure 7). Because the field has a strong water drive and flow rates for these 8 wells were so high (ave. IP = 2000 BOPD), it was theorized that the wells had coned water, leaving a large volume of bypassed oil between wells. The plan was to drill a horizontal well along the top of the Dundee porosity zone between these abandoned wells to recover this bypassed reserve. Because existing wells are less than 400 ft away from the trajectory of the horizontal well, geologic control was

good.

The drilling program was as follows. A vertical well was drilled to near the projected base of the Bell Shale (Figure 8). A conventional core was taken through the cap limestone, the oil leg, and upper part of the water leg in the (dolomitic) Dundee reservoir. Then, 59.3 ft of core was recovered and the well was then drilled an additional 150 ft below the base of the core to TD at the base of the Dundee Formation (top of the Detroit River anhydrite). The vertical well was then logged from TD (3334 ft) to the base of casing (683 ft). Three log suites were run: 1) a gamma ray and dual laterolog with microresistivity, 2) a lithodensity log (compensated formation density plus photoelectric factor), and 3) a compensated neutron log. Digital copies of these logs as LAS files are presented on the project CD ROM under TOW 1-3 in the "Data" section. This was deemed the most practical way to present these data since the alternative would be to include lengthy printout of the logs themselves.

The top portion of the Dundee displayed good oil staining in the core, confirming that the log suite has good coverage of both the oil leg and the water leg in the reservoir. Later fluid saturation analyses of core samples showed 29 ft of higher residual oil saturations at the top of the Dundee (3190-3219 ft), indicating significant unrecovered oil, seven feet of lower residual oil saturations beneath the oil leg (3219-3226 ft), indicating either a transition zone or a swept zone where the oil-water contact moved up as a result of primary oil production, and a water leg (below 3226 ft) where residual oil saturations are 0%.

After the vertical well was cored and logged, the borehole was plugged back

above the Dundee and a medium-radius lateral was drilled. The lateral leg approached 90° at about 450 ft west of the vertical well, at which point the well was cased. An 1800 ft horizontal leg was planned (Figure 26), but when drilling reached 95 ft beyond casing, the well lost circulation and began flowing oil to the surface. A decision was made to discontinue drilling and the well was brought on stream as a producer, flowing 50 BOPD with no water cut. In January, 1996, new surface facilities were completed and production was raised to 100 BOPD. The water cut remained at 0% and pressure was maintained at 1445 psi by an active water drive. Although higher production rates are feasible, production is being maintained at 100 BOPD to prevent water coning. Estimated reserves for the well are 200,000 BO. The well is expected to continue on production for at least 5 years more years.

CORE

Dundee Core Analysis

Conventional cores have been reported from 37 wells throughout the Dundee study area. Data from these cored wells has been compiled into MS-Excel spreadsheets and is included on the project CD ROM. This includes the core from the Cronus – Tow # 1-3 HD-1 well acquired during drilling of the demonstration well for this project. Eight of the cores were not analyzed. For the analyzed wells the core data includes: sample depth, permeability (may include Maximum horizontal, Horizontal at 90 degrees to Max., and vertical), porosity percent, oil saturation percent and water saturation percent.

Cores are from development wells within fields and from dry hole wildcats outside of known fields. Fields represented by cores are listed in Table 3.

FIELD	PERMIT NUMBER
Crystal Field	50047, 26799 (outside field, nearby), 24011(outside field, nearby)
Cranberry Lake East Field	25198, 25290, 25426, 25475, 19023 (outside field, nearby)
Coldwater Field	10997, 11394, 11525, 26256 (outside field, nearby)
Cat Creek Field	27191, 27264
Cedar Field	36648 (outside field, nearby)
Fork Field	35426, 27122 (outside field, nearby), 27668 (outside field, nearby), 36455 (outside field, nearby)
Hatton Field (not part of study)	39618, 38500 (outside field, nearby)
Isabella Field –	27015
Lake George –	27390
Lincoln 27 Field (not part of study)	30036, 30579
Porter Field (not part of study)	36049
Prosper South	27104
Riverside Field	31448, 26528 (outside field, nearby) 36325 (outside field, nearby)
Sylvan Field	14252
Vernon/Rosebush Field	35607, 35651, 35944, 35987, 36826

Table 3 . List of Michigan Gas and Oil Fields with Dundee core.

TOW#1-3 HD-1 CORE ANALYSES

During the drilling of the TOW 1-3 HD-1 demonstration well for this project, a 59.3 foot core was recovered from the vertical characterization leg of the well at a depth of 3174 to 3233 feet. The core was described at the well site (Figure 27) with lithologic and fluid characteristics being noted. The core was boxed and shipped to Omni Core Analytical Laboratories in Houston, Texas where conventional whole core analysis was performed on a 6-8 inch section from every foot selected. Two intervals of shale (from 3174-3186 and 3192-3195) were not analyzed. A total of 44 foot intervals were analyzed. Data from the core is presented in table and figures in Appendix (see Towcore.xls). After the core was analyzed it was slabbed and a portion was sent to the Geology departments at Western Michigan University and Michigan Technological University. Additional analyses were performed on the slabbed portions.

Lithologic Properties

The upper 12 feet of the core contained Bell Shale, which is mainly a massive to fissile gray clay shale containing thin zones of abundant calcitic fossil fragments, especially crinoids. The Bell Shale is probably a primary seal for many Dundee oil reservoirs. The top of the Dundee at 3187.3 is marked by transition to a burrowed, fine-grained dolomitic limestone with finely disseminated clastic and pyritic grains. This unit is called the “cap limestone” by drillers. It is about four feet thick in this core. In most wells the “cap limestone” is underlain by the porous reservoir rock, however in the Tow #1-3 HD-1 core there is a four foot thick shale bed of Bell Shale lithology. The top and bottom contacts of this shale bed are very irregular, exhibiting as much

as six inches of relief in the four inch diameter core. This anomalous shale is interpreted to be Bell Shale filling of a solution cavity within the upper Dundee. This also suggests karsting has occurred at the top of the Dundee. Cross sections derived from wells in the field support this by showing a very irregular upper surface to the Dundee Formation.

The main reservoir begins at 3194.5 feet in the core. It is composed of several shallowing upward sedimentary cycles. These cycles consist of subtidal mudstones and wackestones that grade upward into shallower water grainstones and packstones. Some cycles are capped by very shallow water, fenestral wackestones and mudstones. Fractured mudstones have good permeability (almost 4000 md), but very low porosity (3-4%). The best reservoir rock is the grainstones with high permeability (up to 800 md) and good porosity (up to 18%). The reservoir is entirely dolomitized and has varying amounts of open and cemented fractures, as well as solution-enhanced vugs.

Fluid Properties

Because the core was not preserved at the well site, the analyses of fluids can only be viewed as minimum values since some fluids were lost through evaporation and drainage during transport. Data from conventional core analysis is only representative of the native state fluid conditions and should not be used to precisely determine reservoir conditions. Relative relationships of measured oil and water saturations suggest some interesting and important trends throughout the cored interval. Oil and water saturations do not total anywhere near 100% for total fluid content due to pre-analysis evaporation and drainage from the core. Oil saturations

do show a trend from 0.0% at the bottom of the core to 21.0% near the top. Oil saturation is zero below 3226, which can be interpreted as the original oil/water contact. The interval from 3219-3226 has oil saturations below 10% and can be interpreted as a swept or unsaturated zone resulting from upward movement of the aquifer water during oil production. There may also be some additional footage above this interval that has also been swept. Based on average field recoveries per acre/foot, approximately 12 vertical feet of the reservoir should have been swept during production prior to drilling this well. The heterogeneity and cyclical nature of the sequences in the reservoir suggest that water encroachment was probably not as a uniform front, but likely followed zones of higher porosity and permeability, producing a coning effect (?).

DIGITIZED LOGS

Several sets of digitized well logs were obtained for this project. A set of digitized logs from 341 wells was obtained for this project from Maness Petroleum Company in Mt. Pleasant, Michigan. These logs consist mainly of Gamma Ray, Neutron Porosity, Density and PEF log tracks. A few Dual Lateralog and Dual Induction resistivity logs were also provided. The digitized interval typically extends from the base of the Antrim Shale to the base of the Richfield Member of the Lucas Formation in the Detroit River Group. This data set is restricted by the license agreement with Maness Petroleum: graphic images of the logs may be distributed, digital data may not be distributed in any form.

The Maness digital log data set represents only a portion of the logs that exist for wells in the Dundee study area. Many additional well logs were observed and

analyzed during this project, and approximately 87 were digitized (Figure 28). This set of digitized well logs are mainly from deep wells and the whole interval was digitized. These logs are included as LAS files on the project CD ROM and are released to the public domain. however only the digitized ones were used for quantitative analyses. Additional well logs are available from wildcat wells not associated with any fields.

Stratigraphic Interpretations

The Dundee Formation in Michigan is a variably thick limestone or dolomite, bounded on top by the Bell Shale and at the bottom by interbedded dolomites and anhydrites of the Lucas Formation, Detroit River Group. The very low Gamma Ray values for the Dundee are easily distinguished from the overlying, much higher, Gamma Ray readings of the Bell Shale. Because of the karsted surface at the top of the Dundee, there are occasional thin beds of Bell Shale appearing interbedded with the uppermost Dundee. This is likely the result of shale infilling of karst solution channels and caverns. However, the top of the Dundee is most often represented by a sharp contact between high and low Gamma Ray values.

Gamma Ray signatures are very similar between the Dundee and underlying Lucas Formation. Both have low readings, however a distinction can be made using Density logs which record the much higher density values for the anhydrites in the Lucas.

Reservoir Interpretations

Wireline logs are extremely useful for various aspects of Dundee Reservoir

interpretation. Accurate, high resolution structural mapping can be done when numerous and closely spaced logs are available. Unfortunately, Most fields in this study do not have many logs.

These logs are also valuable in inferring several reservoir properties, such as, porosity, and fluid saturations. Logs generally correspond reasonably well to core analysis and well testing data, however significant differences may be noticed due to borehole irregularities, type of fluid in the hole and inability to accurately estimate some parameters used for log calculations.

BASIN MODELING

Subsurface Databases

Subsurface mapping and stratigraphic interpretation is greatly facilitated by the use of digital data that can be used to generate graphic displays. Graphic displays of lithologic sample descriptions (LSD) obtained from driller's logs constitute a source of information that can be used to rapidly identify potential inaccuracies in commercially available subsurface databases, subsurface facies changes, and display sequence stratigraphic interpretations. Generation of pseudologs that contain depth vs. lithology information in Log ASCII Standard (LAS) or Log Binary Standard (LBS) format allows use of log analysis software to display information and correlate wells.

Prior to use, LSD data from driller's logs must be converted to digital form. This can be accomplished in-house or through the purchase of a commercial database. For our study a FORTRAN program was written to extract the LSD data from a commercial database and output the data in LAS format. Commercial log

interpretation software was utilized to convert the LAS file to LBS format. A log template was created to graphically display the lithology data. Cross-sections that display lithology data and top subsea picks were then generated.

Examples from the Michigan Basin demonstrate that the display of data in a graphical fashion provides the user with a visual method to compare top subsea picks with log and lithology data. Potentially incorrect top picks can be easily identified using this method, and the database information corrected. Regional cross-sections made using these data define large-scale sediment patterns and permit identification of stratigraphic sequences with a greater degree of confidence. The structure contour and isopach maps along with the standard and lithologic cross-sections were used to create accurate burial histories used in the thermal history modeling described in another section of this report.

The Aangstrom data set, which contains information on 51,359 Michigan wells, was used both in GeoGraphix and in our basin modeling programs. The data set includes well locations, formation tops, lithologies, etc., in a form that can be read directly into our GeoGraphix Exploration System software. After solving numerous formatting problems, we succeeded in loading the data into GeoGraphix and correcting data errors and nomenclature problems. Well location maps have been produced in GeoGraphix which display all wells that intersect each of the deeper formations in the Michigan Basin. A more manageable data set (of 10,000 wells) has been obtained by selecting the deepest well in each section in the state of Michigan. A grid of regional structural cross sections through the basin has been constructed. The cross sections serve two purposes. First, they make it easy to spot and correct

bad picks and bad data. Second, once the errors are corrected and the structural cross section grid is completed, stratigraphic cross sections, hung on key marker horizons, can be constructed. These stratigraphic cross sections will enable visualization of the evolution of 3-D basin geometry through time and permit focussing in on the times and areas of greatest interest for geologic modeling (e.g., areas of rapid and maximum subsidence, where sourcerock maturation and oil generation are favored, should be readily apparent).

This work was being done to prepare the Angstrom data for use in the modeling programs such BasinMod and Akcess.basin. BasinMod will be used for 1-D and 2-D thermal maturation modeling. Access.basin uses a finite-element formulation to examine the effects of thermal processes (conduction, convection, and advection), fluid flow processes (compaction-driven, hydraulic-head driven), sealing mechanisms, and sedimentation/erosion during the development of a sedimentary basin.

The Michigan Department of Natural Resources' bottomhole temperature database has been obtained and formatted for use in modeling programs. Negotiations are still proceeding to acquire a major organic geochemistry study of the Michigan Basin, completed by Brown and Ruth Co., through donation to the project.

Michigan Basin Stratigraphy

A GeoGraphix Exploration System project produced maps showing the locations of all the wells in the Michigan Basin having a top subsea (TSS) pick for a particular formation. These maps were generated for all 105 formations in the basin.

A complete set of TSS structure contour maps covering almost all the formations in the basin was also produced using this project. Structure contour maps were produced using the GeoGraphix' Isomap module.

An arbitrary lower limit of 100 wells was used to create the structure contour maps. That is, if there were fewer than 100 wells with a TSS pick for that formation a structure map was not made. The exception to this being several of the lower Cambrian formations and the Precambrian or basement. For example, the Mt. Simon sandstone (MNSM) structure map was produced from 60 wells. Of the 105 formations, 27 had less than 100 wells with TSS picks. Of these 27, five had sufficient coverage throughout the basin to produce structure maps. Of the remaining 78 formations only ten structure maps were produced using less than 500 wells. The majority of the other structure maps were produced using well over 1000 wells and some were made using 10's of thousands of wells.

We also produced a complete series of isopach maps using the GeoGraphix' Isomap module. All the isopach maps were produced using over 100 wells, except the lowest Trempealeau (TMPL) to basement isopach which used 29 wells. Of the 50 formation by formation isopach maps produced, only eight used less than 500 wells. As with the structure contour maps, the majority of the isopach maps were produced using well over 1000 wells each. Another series of isopach maps was produced using the different formation ages as the criteria. For example, an isopach map was made of the upper Silurian, i.e. the Bass Island formation to the top of the Niagara Group (Figure 29). All together, 78 isopach maps have been produced.

In addition to the structure contour maps and isopach maps, several basin

wide and regional cross-sections were produced. These cross-sections were made using the GeoGraphix' CrossSection module. Many of the cross-sections were made using the LithLog LAS file output described below. These cross sections indicate lithology rather than formation tops.

The Aangstrom Precision Corp. database also contains lithologic sample descriptions (LSD) for the deepest well with the most log information in each section. These LSD data are available for 11,474 wells in the Lower Peninsula. Using GeoGraphix Exploration Systems software, a map was produced showing the location and a color-coded total depth of these LSD wells. These LSD data are listed in the Aangstrom database by depth interval followed by the dominant lithology for that interval. The lithologies are designated by two letter codes, e.g. LS = limestone, AN = anhydrite. A FORTRAN program (LithLog) was written to extract these lithology data directly from the database and output a Log ASCII Standard (LAS) file. The program creates a lithologic well log which is virtually the same as any "standard" well log, e.g. gamma ray or neutron density, but with the dominant lithology per depth step as output. The following is an abbreviated description of the program operation.

The program prompts the user to input a county file name (the Aangstrom database well information is separated into counties) and a permit number. The program opens the selected county file and proceeds to read the well data. When the input permit number is found, the program first extracts the LAS file header information, which includes the well operator, name, number, unique well id (UWI), location, and completion date. These data are included in the header information when the program writes the output file in the standard LAS file format. The program

continues to read the well file until the first line containing LSD data is reached. The lines containing LSD data are designated by a three-digit code. At this point the depth range and dominant lithology is read as a character string. This character string is then read until the “-“ separating the depth range and the dominant lithology code is found. The beginning and ending depths are inputted into a subroutine, which converts them to integer form. The dominant lithology for this depth interval is assigned a value of one while the other possible lithologies are assigned a value of zero. (The program, currently, allows for the ten most common, of the possible 24, lithologies used in the database. The ten most common are: limestone, dolostone, gypsum, anhydrite, halite, sandstone, shale, mudstone, siltstone, and chert.) The program continues to read the well file, storing the beginning and ending depths of each interval in an array as well as assigning a value of one to the dominant lithology and values of zero to the other nine. The depth intervals that are missing the lithology data (designated by an “MI” as the dominant lithology) are saved and written to the output file in the “Parameters Information” section of the LAS file header. When the program reaches the end of the LSD data it begins to write the output file. The LAS header information is written first. Then the depth range array is accessed, and the depth and lithology values are written in one-foot intervals. The following is an example of the output LAS file:

```
PARAMETERS INFORMATION
# Missing lithologic data from:
#   750 to   800
#   813 to   830
# 16050 to 16100
#=====
~A  Depth LS SS DL HA SH AN MU GY SI CH
```

278.0	0	0	0	0	1	0	0	0	0	0
279.0	0	0	0	0	1	0	0	0	0	0
280.0	0	0	0	0	1	0	0	0	0	0
281.0	0	0	0	0	1	0	0	0	0	0

The LAS files output from the LithLog program described above can be converted to a Log Binary Standard (LBS) format using GeoGraphix/Schlumberger's Log Interpretation software package QLA 2. QLA 2 was, also, used to create a well log template, which in conjunction with GeoGraphix' WellBase and CrossSection modules was used to create several basin wide and regional lithologic cross-sections covering much of the basin .

THERMAL MODELING

The thermal modeling study has focused to date on the use of one-dimensional models to determine the thermal history of the Michigan Basin. The Michigan Basin's thermal history is extremely complex and although extensively investigated, no previous study has resulted in a model that satisfies the observed thermal maturity data for the basin. Previous studies have produced two main hypotheses about the basin's thermal history. The two hypotheses are that:

1. elevated basal heat flow affected the basin during its early history, and
2. significant amounts of Pennsylvanian and Permian strata must have at one time been present in the basin.

Results of our study demonstrate that both of the previously proposed hypotheses must be accounted for in any model that produces results consistent with the observed data. Our results also demonstrate that a successful model must incorporate a significant erosional event at approximately the Silurian/Devonian

Systems boundary. The Silurian/Devonian boundary corresponds to the transition from the Tippecanoe II to Kaskaskia Sequence, and an erosional unconformity at that stratigraphic level has been recognized and used for correlation for over thirty years.

Methodology

The first step in the thermal modeling study was to assemble available data that could be used to constrain the thermal history of the basin. These data include tectonic modeling studies that interpret the basin's thermal history based on observed subsidence patterns (e.g., Haxby et al., 1976; Nunn et al., 1984; Nunn, 1994). Organic thermal maturity indicators such as vitrinite reflectance (e.g., Cercone, 1984; Cercone and Pollack, 1991), and conodont and thermal alteration indices (e.g., Hogarth and Sibley, 1985; Bowers, 1989; Cercone and Pollack, 1991) are highly desirable because they can be directly measured and are also readily correlated to stages of hydrocarbon generation. Fission-track data are also available, and these data provide good estimates of the time of maximum burial and subsequent unroofing for the Michigan Basin and surrounding area (e.g., Crowley, 1991; Wang et al., 1994).

The second step was to construct a burial history for a specific site within the basin. The specific site (the Mobil-Jelinek well) was chosen because of an abundance of high-quality organic thermal maturity data for the well. The burial history uses geologic data from the Michigan basin and surrounding areas to determine the time and duration of deposition and erosion events. A heat flow history was also constructed based on the results of previous tectonic models of the

basin's evolution.

The final step in the modeling method was to input the burial history to a numerical model that calculates the temperature of specified stratigraphic levels through time. Calculated temperatures are then used to calculate vitrinite reflectance and TTI (Time Temperature Index) values for the specified stratigraphic levels. This model output can be directly compared to organic thermal maturity data to determine whether the burial history model is effective at predicting the thermal history of the basin.

The Numerical Model

Thermal histories are calculated using a finite-difference solution to the one-dimensional heat conduction equation:

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{a} \frac{\partial T}{\partial t} = -\frac{A}{k}$$

In this equation, T = temperature (oC), z = depth (km), a = thermal diffusivity (m²/s), t = time (m.y.), A = heat production (mW/m³), and k = thermal conductivity (W/mK). The numerical model calculates the temperature distribution in a 30 km thick section lithosphere as a function of time, and is described elsewhere (Furlong and Edman, 1989; Huntoon, 1990; Huntoon and Furlong, 1992; Price et. al., 1996).

The model uses surface temperature and basal heat flow as boundary conditions. Surface temperature is explicitly specified by the user at the start of each model run. The user also specifies a function describing a desired change in surface heat flow through time. Surface heat flow is specified because that value (as opposed to basal heat flow) is commonly measured in sedimentary basins. Heat

flow is varied through time in the modeling because all tectonic studies of the Michigan Basin suggest that heat flow was higher in the past than it is now.

Because heat generated by decay of radioactive elements in crustal rocks contributes to surface heat flow, the basal heat flow boundary condition is calculated to account for cumulative heat production in the upper 30 km of the crust.

$$A_{(z)} = A_o (e^{-\frac{z}{z_o}})$$

In the above equation, A = heat production as a function of depth (mW/m³), A_o = heat production at the surface (mW/m³), z = depth (km), and z_o = depth at which heat production is equal to 1/e of the surface heat production (km), and e is the natural logarithm base.

The model requires that the user specify the timing, duration, and magnitude of depositional and erosional events, as well as the thermal conductivities of deposited sediments and basement materials. Initial, depositional thicknesses of stratigraphic units which are now present in the basin were estimated from measured present-day thicknesses using the lithology-dependent decompaction algorithms of Baldwin and Butler (1985) for sandstone, shale and carbonate lithologies. Units composed dominantly of salt are not decompacted. For decompaction purposes, each stratigraphic unit was classified as a single lithology; mixtures of lithologies were classified as the dominant lithology.

Estimates of thermal conductivity for stratigraphic units are based on lithology using the extensive data set compiled by (Cermak and Rybach, 1984). Where a single stratigraphic unit is composed of several different lithologies, the conductivity

of the entire unit is a weighted mean of the contributing conductivities.

After the surface temperature, heat flow through time, burial history, and thermal conductivity information are input, the numerical model calculates the time-dependent temperature history of a one-dimensional (vertical) profile. Finite difference techniques are used to solve the heat equation at each time step. The results for each simulation include the time-temperature history for every stratigraphic interval that is now present within the basin. From this history, the thermal maturity of the horizons is estimated based on calculated TTI (Waples, 1980) and vitrinite reflectance (% Ro) values. % Ro is calculated using Sweeny and Burnham's (1990) Arrhenius first-order parallel-reaction method. TTI and %Ro are calculated because they are commonly used and are readily correlated with other organic thermal maturity indicators.

Heat Flow Type Models vs. Gradient-Type Models

This modeling method differs significantly from that used in previous studies of the Michigan Basin's thermal history. Previous studies have utilized a gradient method, rather than numerical solution techniques to determine the temperature at specified depths as a function of time. Gradient methods are used appropriately when the basin's heat flow history is simple (e.g., constant heat flow through time), when the deposition and erosion history are straightforward and neither deposition nor erosion proceeds at a rapid rate, and when the modeled sediments have constant thermal conductivities. None of these criteria are satisfied in the Michigan Basin. For example, all previous studies have suggested that the basin experienced elevated heat flow during its early evolution. The large variation in lithology of basin

sediments (e.g., shale, sandstone, limestone, dolomite, and salts) results in large variations in thermal conductivities. In addition, several previous studies have suggested that the basin has experienced episodes of significant and rapid burial and erosion.

Transient thermal effects associated with rapid burial and erosion, or changes in heat flow through time cannot be adequately addressed by gradient-type models. For example, rapid burial has the effect, in reality, of moving the surface boundary condition downward through time, because sediment is added faster than it can reach equilibrium temperatures. A gradient-type model cannot accurately account for this situation. Gradient models are also unable to accurately account for changes in heat flow through time. In the steady-state case described by Fourier's Law,

$$q = -k \frac{dT}{dz}$$

where q = heat flow (mW/m²), k = thermal conductivity (W/mK), and dT/dz = the geothermal gradient (K/km), as heat flow changes so does the geothermal gradient. Gradient models emphasize this linear relation between heat flow and geothermal gradient by suggesting that a change in basal heat flow can be modeled by simply changing the geothermal gradient. In reality, however, the geothermal gradient does not change immediately as the basal heat flow is changed. Instead, it takes some amount of time, as controlled by the thermal diffusivity of the conducting material, for any change in boundary conditions to propagate through the model. In addition, it is geologically unreasonable to expect that basal heat flow might instantaneously change from a high value to a low value. Instead the transition probably occurs over a few to several m.y., although this transition is commonly

modeled as an instantaneous event when gradient-type models are used.

While our results are broadly similar to those of previous studies when we use the same initial conditions, boundary conditions and burial history models, our numerical model allows us to effectively test additional hypotheses about the basin's evolution. The numerical model is a forward modeling simulation, meaning that time in the model progresses forward from the past toward the present day. Thus the initial conditions for the model are the user's estimate of conditions at a particular time in the past. For this study the forward simulation begins at a time corresponding to deposition of the top of the Mount Simon Sandstone. This horizon was chosen for the start of the modeling because the overlying units are the oldest to reflect nearly radially symmetric subsidence within the Michigan Basin. Because forward models are non-unique, the results of this study represent a best-fit solution to both the observed organic maturity data and previous interpretations about the basin's geologic history. An infinite number of successful models can be constructed, however, only a limited number will satisfy both the observed data and tectonic conceptual models.

Mobil-Jelinek Well Thermal Study

In this section the data used to constrain the modeling are first discussed. The burial history and heat flow history that produced the best fit to the observed data when modeled are then described. A complete sensitivity analysis and testing phase was completed prior to obtaining the results presented here, however the details of that portion of the study are not included here. The results of our best-fit model are described at the end of this section.

Data

Vitrinite reflectance data collected from the Mobil-Jelinek well are used to constrain the results of the modeling. %Ro data have been available for this well since release by Mobil and publication by Cercone and Pollack (1991). The Mobil-Jelinek well has been the subject of several previous modeling studies because the %Ro data is abundant for this well, and it covers all of the stratigraphic section. The data also appear to be consistent, in that wide variations in reflectances at particular stratigraphic levels are not reported. This is probably because all of the samples were analyzed at a single time by a single lab.

Figure 30 shows a semi-log plot of the %Ro data vs. depth for the Mobil-Jelinek well. A series of least-squares best-fit lines have been drawn through the data. In the post-Devonian section, a single best-fit line is shown. In the pre-Devonian section, two different lines are shown. One line fits the data near the bottom of the well, while the second fits the data near the top of the pre-Devonian section. In the modeling we attempted to obtain calculated %Ro values that lie along the upper (post-Devonian) best fit line, and lie somewhere between the two lines shown for the pre-Devonian section.

Two important features of the data need to be emphasized as they are important in the thermal modeling study. First, the post-Devonian data lies along a least-squares best-fit line that is significantly offset from the best-fit lines through the pre-Devonian data. This offset suggests that an erosional unconformity is present at the Devonian/Silurian boundary (Waples, 1985). Secondly, the slopes of the pre-Devonian best-fit lines are steeper than the slope of the post-Devonian best-fit line.

This suggests that a different geothermal gradient is recorded by the pre-Devonian section than by the post-Devonian section. Because the thermal conductivities of the pre-Devonian section are generally higher than those of the post-Devonian section, the change in geothermal gradient indicates that higher heat flow effected the basin during pre-Devonian time. The heat flow has been significantly lower since. These two aspects of the data were used in part to guide the modeling effort.

Burial History

A burial history for the Mobil-Jelinek well was produced using information from a wide variety of sources. The Correlation of Stratigraphic Units of North America (COSUNA), Midwestern Basin and Arches Region chart (AAPG, 1985) provided information on the formations in each burial unit as well as age data. This age data provided the times for each burial unit's deposition, along with estimates of the timing of erosion events. The group and/or formation thickness data was collected from three sources. The Aangstrom Precision Corp. Michigan Oil and Gas Well Database provided Top Measured Depth (TMD) values for all but one of the burial units. The depth to the Mt. Simon sandstone (the lowest horizon monitored in this model) was determined from a structure contour map and cross-section produced from Aangstrom Precision data using the GeoGraphix Exploration System software. The thickness values for various formations within the burial units were compiled from cross-sections in the Report of Investigation 19, Stratigraphic Cross-sections of the Michigan Basin (Lilienthal, 1978) and the Aangstrom Precision database.

Initial thicknesses of units that are now partially removed by erosion were first calculated based on the assumption that the sedimentation and erosion rates were

constant and equal to that calculated for the underlying stratigraphic unit. That is, deposition was assumed to have occurred during the first half of the duration of the lacuna, while erosion occurred during the second half. When this first estimate of the amounts of burial and erosion failed to produce reasonable results, other data were considered. For example, the amount of eroded material in the final Triassic (250-200 Ma) erosion event was previously estimated at 1.2-2.0 km (Cercione & Pollack, 1991) and 2.0-5.0 km (Crowley, 1991). A thickness of 2.2 km was used in our final best-fit model and this value is consistent with the ranges suggested by previous studies. In addition, our modeling demonstrated that it is necessary to add 2.2 km at the Silurian-Devonian Systems boundary. This additional burial was necessary to account for the offset in the %Ro data observed in data from the Mobil-Jelinek well. Without this extra burial, maturities in the pre-Devonian section of the well could not be matched by our model results. This amount of excess strata is much greater than previously proposed in the literature, although the Silurian to Devonian transition does represent a major unconformity. It is the location of the transition from the Tippecanoe to Kaskaskia Sequences (Sloss, 1963), and the unconformity at that level is used for interregional correlation of strata.

The thermal conductivity value for each burial unit was calculated using a weighted average based on the lithology and the data presented by Cermak & Rybach (1984). Each unit's lithology was determined from the Lithologic Sample Descriptions (LSD) in the Aangstrom database or from formation descriptions (Lilienthal, 1978; Fisher et. al., 1988). Thermal conductivity values for the eroded units were calculated based on the values determined for the underlying units using

compaction vs. depth curves (Baldwin & Butler, 1985) and the following equation (Robertson, 1988):

$$K_{ci} = C_i (\gamma)^2 K_c$$

where

K_{ci} is the corrected conductivity,

C_i is the thermal impedance correction factor,

γ is the solidity (the fractional grain volume), and

K_c is the calculated conductivity.

The corrected conductivity is found by multiplying the calculated conductivity from the underlying unit by the square of the solidity from Baldwin & Butler (1985) compaction curves and the thermal impedance correction factor from tables in Robertson (1988). The surface temperature is set at 20 C because the basin was near the equator through most of the Paleozoic era.

Heat Flow History

Measured values of the present day terrestrial heat flow in the basin range from 33-58 mW/m² (Combs & Simmons, 1973; Nunn, 1994). Numerous studies (e.g. Nunn et al., 1984; Crowley, 1991) have shown that the present day heat flow values cannot explain the thermal history of the basin. For example, the in situ generation of hydrocarbons in Silurian and Devonian formations would require higher paleotemperatures (Crowley, 1991) than possible if present day heat flow values were assumed to have been effective in the past. Even accounting for thermal effects of significant amounts of burial and subsequent erosion, heat flow values must have been higher in the past (Cercione, 1984).

The heat flow history for this model is based on tectonic models of the basin formation (e.g. Nunn, 1984; Howell & van der Pluijm, 1990). These models predict an elevated heat flow through the Ordovician. Using this heat flow history in our model, the pre-Devonian thermal maturities were underestimated. It was necessary to continue the higher heat flow until the Silurian/Devonian boundary to produce the observed maturities in the pre-Devonian strata.

The initial heat flow used in this model was determined from a plot of the measured vitrinite reflectance (%Ro) values vs. depth for the Mobil-Jelinek well (Figure 30). The graph revealed two groups of %Ro values in the Pre-Devonian strata. A best-fit line was drawn through each of these groups and the slopes were determined. These slopes correspond to heat flows of 114 and 134 mW/m², assuming a constant conductivity of 2.72 W/mK (the average for the pre-Devonian strata). The average, 124 mW/m², was chosen as the initial heat flow for the model. This heat flow is used from the beginning of the model at 510 Ma until the start of the Upper Devonian erosion event at 407 Ma. From this time the heat flow drops until it reaches an equilibrium value of 56 mW/m² at 403 Ma.

Results

The results of the modeling are best displayed in graphical form. Figure 31 is a graphical representation of the burial history used in the preferred model and described above. The tops of the labeled stratigraphic units lie directly above the labels. Other lines represent tops of different depositional units. Figure 32 shows the calculated temperatures for the stratigraphic horizons. Figure 33 shows the calculated TTI for the stratigraphic horizons. Figure 34 shows the calculated %Ro for

the stratigraphic horizons. Figure 30, a semi-log plot of %Ro vs. depth, shows the values obtained by modeling, compared directly to the observed data. Figure 30 in particular demonstrates that the model produces an excellent fit to the observed data.

THE NEW HORIZONTAL WELLS

The field demonstration included drilling 3 horizontal drain wells 3 (Figure 35). The first well, the TOW 1-3, was successful beyond initial expectations. However, the the 2nd and 3rd horizontal wells, the Happy Holidays and Frost 5- were less successful and has taken some of the bloom off the TOW 1-3. The main premise of the project was that significant volumes of unrecovered oil remained at Crystal Field, mainly as a result of poor production practices. It was thought that the original battery of vertical wells were produced so hard that they coned water prematurely and left commercial quantities of hydrocarbons in the inter-well spacings. Following the results of the recent horizontal wells at Crystal, the most question now is “Why are the latest two horizontals wells performing so poorly, especially in the light of the continuing strong performance of the TOW 1-3?”.

By modern standards, reservoir characterization at Crystal Field is poor. While we think we know the structure fairly well, the pay zone is not well defined, the geologic history is uncertain, the producing intervals are not well mapped and the precise locations of the residual oil is unknown. The lack of penetrations past the top of the Dundee greatly hampers characterization efforts. It prevents accurate reserve estimates and the scarcity of well logs precludes any sophisticated analysis. However, we can use the existing data to accurately map the top of the Dundee as

well as the top of the porosity zone. About 278 wells have been drilled to the top of the Dundee at Crystal Field and we have most of these in our database. This density of producing wells permits definition of the top of the Dundee to within 2 feet in most cases. The structure contour map on the top of the Dundee (Figure 6) shows a highly irregular surface suggestive of a mature erosional unconformity, with many attributes of a karstic topography.

INTERPRETATION OF THE TOW 1-3 LOGS

The one modern open-hole log in Crystal field was obtained from the vertical, cored, well at the location of the Tow 1-3, as part of the DOE project. The logs from this well were difficult to interpret for saturation, as pointed out in the last MOFRC newsletter. We now present a tentative interpretation that is consistent with the performance of the three horizontal wells drilled to date.

In the vertical part of the Tow 1-3 well, the Bell shale was encountered to greater depths than anticipated, apparently due to a karst feature, such as a cave collapse filled by shale. On the other hand, there was essentially no "cap" limestone at this location, and the porous dolomite was encountered directly beneath the shale. The logs, therefore, represent saturation as found in the Dundee at depths below 2390 ft subsea. We now interpret the saturation at these depths to represent the produced intervals of the Dundee, rather than some sort of transition zone, and the logs indicate residual oil saturation. The current oil-water contact must be at depths shallower than 2390 ft subsea. The horizontal leg of the Tow 1-3 well intersected the Dundee at a relatively shallow depth, and encountered very little "cap" limestone as it entered porous dolomite, currently producing oil from a horizontal leg that never

reached deeper than 2380 ft subsea. We conclude from these observations that the current oil-water contact is between 2390 and 2380 ft subsea in the vicinity of the Tow 1-3 well; of course, we do not know the upper limit of the porous rock in the area of the horizontal leg, but do note that the surface of the productive interval is highly irregular throughout the region.

The two new horizontal wells were drilled in locations that correspond to predicted depths to the top of the Dundee (the “cap” limestone) of about 2380-2385 ft subsea, and to the top of the porous zones of about 2395 ft subsea. If our current interpretation of the Tow 1-3 well is correct, we can anticipate encountering the current oil-water contact at depths above the porous zone, in the “cap” limestone if it is present at the locations of the new wells. If the new wells did not encounter porous or fractured rock at depths above the current oil-water contact, they should be expected to produce mostly water. Based on these new data and wells, our recommendations for drilling in the depleted Dundee fields are:

- map the upper contact of the “cap” limestone (base of Bell shale) and use that as a guide for drilling;
- try to stay as close as possible to this contact, always drilling downdip and never “porpoising” upward,
- if a fractured, porous interval is encountered above the current oil-water contact, expect to produce good oil,
- on the other hand, if you continue to drill downdip until the current oil-water contact is reached, expect to produce water.

The best exploration prospects now appear to be on the higher structures in

the old Dundee fields, and “attic oil” (i.e. oil remaining above the penetrations of the older production) is the main target.

One further tip is to extend the vertical leg of the horizontal well through the expected production zone, log that vertical well and core it if possible. Then back out, plug off at the appropriate depth and kick off a horizontal well.

A significant volume of this attic oil is likely to be present, due to the highly irregular nature of the Dundee surface. It remains true that the best technique to find and produce this remaining oil is horizontal drilling, which can maintain a trajectory within the uppermost Dundee until a structurally high porous and fractured interval is encountered.

The well log data for the TOW 1-3 HD has been plotted using GeoGrpahix Prizm software (Figures 36-39) All of the figures include a set of logs from the Tow 1-3 well (vertical leg) for comparison. In the logs for the Tow well, we identify the Bell shale and the top of the Dundee; the Dundee at this location also includes a bit of shale filling in an apparent small cavern, giving a high gamma-ray reading below the labelled Dundee top. The porosity logs indicate that the Dundee in the Tow well is entirely dolomite (the cap limestone identified in the core is apparently too thin for resolution on these logs); the resistivity logs do not indicate a strong oil saturation, although the separation between the micro-resistivity (MSFL) and the deeper readings indicate permeability. The logs from other wells were obtained from the Winterfield field study performed as a part of the Project.

TECHNOLOGY TRANSFER

Professional Meetings and Publications

J. Huntoon and W. Pennington presented posters at the SEG Development and Production Forum on "Cooperative Projects to Improve Reservoir Management" in Colorado in June, 1995. Pennington discussed the Michigan Dundee Project and Huntoon presented a poster display on Technology Transfer. The Technology Transfer talk, entitled "Facilitating interaction between universities and industry: mechanisms for personnel and technology transfer", elicited much favorable comment. Huntoon was asked to re-present it as an invited paper at the SEG Annual Meeting. Our representatives at this meeting found it to be very successful in facilitating communication (and Technology Transfer) between various groups carrying out DOE sponsored projects.

A poster titled Subsurface Databases: Graphical Display and Error Detection for Stratigraphic Interpretation in the Michigan Basin was presented at the 1996 GSA Annual meeting in Denver, CO October 28th. The poster focused on the graphical display of information derived from the FORTRAN lithology extraction program (LithLog) described above. The poster included sections on the utility of this type of lithology display for detecting errors in the database as well as its usefulness in correlating sequences in the basin. Further, the lithology log display was combined with more conventional logs, e.g. gamma ray and neutron density, resulting in a vivid graphical display which would prove quite useful as a tool to facilitate the recognition of conventional log responses to different lithologies. At this time a paper is being prepared for publication in the Journal of Geological Education. This paper will

include a copy of the LithLog program.

Other meetings and publications include:

Eastern Section AAPG – East Lansing, MI, 1995

Ontario Petroleum Institute – London, Ontario, 1994

Ontario Petroleum Institute – London, Ontario, 1995

University of Illinois-Chicago - 1996

Western Michigan University – 1996

Michigan Basin Geological Society – 1995

Michigan Basin Geological Society – 1998

Michigan Department of Natural Resources - 1997

IOGCC – Indianapolis, IN – 1996

Professional Papers and Presentations

In October, 1995, W. Harrison presented talks entitled "Improved Oil Recovery from Old Fields in the Dundee Formation, Michigan Basin" to the Geology Department at the University of Illinois-Chicago; "Improved Oil Recovery Using Horizontal Drilling in Oil Fields, Michigan Basin" to the Geology Department at Western Michigan University; and "Improved Recovery Using Horizontal Drilling in the Dundee Formation, Michigan Basin" to the Ontario Petroleum Institute in London, Ontario, Canada.

Also in October, 1995, S. D. Chittick presented a talk entitled "Characterization of the Dundee Formation, Winterfield Field, Clare County, Michigan", co-authored by S. Chittick, C. Salotti, J. Wood, W. Pennington, S. McDowell, J. Huntoon, and W. Harrison, at the AAPG Northeast Section Meeting in

Schenectedy, NY.

In March 1996, two presentations featuring project accomplishments were made at the Michigan Department of Natural Resources' Annual Symposium on "Michigan, Its Geology, Environment, and Resources". W. Harrison was the keynote speaker at the symposium luncheon and S. Chittick presented a poster session. Also in March, Harrison presented a project overview at the Petroleum Technology Transfer Council (PTTC) Regional Meeting in Grayville, IL. In April, Wood, Luo, Chittick, and Suchoski attended the Michigan Oil and Gas Association meeting in Mt. Pleasant, MI, where they informally discussed project results with members of the Michigan oil and gas community.

A paper describing the DOE Michigan Dundee project and the results of the Crystal Field demonstration well is in the final stages of preparation. It is entitled "Recovery of Bypassed Oil Through Horizontal Drilling, Dundee Reservoir, Crystal Field, Michigan" and will be submitted the Oil and Gas Journal.

AAPG Computer Applications in Geology Volume

Wylie and Huntoon are editing a volume entitled "Practical Reservoir Characterization", which is to be published as a volume in the AAPG Computer Applications in Geology series. Wylie is writing the first six chapters, which constitute a "how-to" guide to computerized reservoir characterization. Seven authors have committed to contribute case studies in reservoir characterization. Each of these will be a separate chapter. One of these case studies will be a paper on the Dundee reservoir in Winterfield Field, co-authored by S. Chittick and others.

Michigan Oil Field Research Consortium (MOFRC)

In 1996 a newsletter was established to disseminate information on our project to the original MOFRC members and to other interested parties in the Michigan oil and gas community. Because of the MOFRC Newsletter and press releases, many people who are interested in horizontal drilling and the development of shallow shelf carbonate reservoirs, both within the Michigan Basin and in other areas, have contacted project personnel. During late 1995 and early 1996, J. Huntoon, J. Wood, W. Pennington, and W. Harrison all received at least five phone calls per week about the project. Geologists and managers from KEP Exploration of Traverse City, MI, and Richland Petroleum of Denver, CO, visited Harrison at WMU to review well results and well data. Several project members have been contacted repeatedly by Unocal staff members. (Unocal plans to drill several horizontal wells to the Dundee Formation in Porter Field in 1996). Shell-Western is now seriously interested in the Dundee play.

Companies are starting to tie up Dundee acreage, presumably as a result of the success of our project well. Several contacts were with principal officers of independent oil companies who requested information to help them initiate horizontal drilling programs. Since publication of the first MOFRC Newsletter last summer, our group has received many requests for inclusion on the mailing list.

Workshops

In January, 1996, project members from MTU and WMU held a major two-day workshop at MTU to examine the core from the demonstration well, to discuss project results, and to plan next year's technical program and publication schedule.

Similarly, in September of 1997, a workshop was held in Grand Rapids in conjunction with the September MOGA meeting which summarized the project and made Version 1.0 of the project CD ROM available to the public.

Additional workshops in which the project was the main topic included:

MOGA – Mt. Pleasant, MI - 1996

MOGA – Traverse City, MI - 1997

PTTC – Grayville, Ill – 1996

PTTC – Mt. Pleasant, MI – 1997

Web Site Development

Project WWW (World Wide Web) site were created and maintained at:

Michigan Technological University – <http://www.geo.mtu.edu/svl/michproj/>

Western Michigan University – <ftp://geology.wmich.edu/pub/doi/>

Information transfer to individual companies (Michigan Operators)

Newstar Energy (4 visits)

Dart Oil and Gas (2 visits)

Wolverine Environmental Production (1 visit)

Apollo Exploration (2 visits)

Maness Petroleum (12-15 visits)

Don Yohe Enterprises (2 visits)

KEP Exploration (5 visits)

Lithos Exploration (4 visits)

Summit Petroleum (1 visit)

Muskegon Development (1 visit)

Belco Operating (2-3 visits)

Jennings Petroleum (1 visit)

Enveron (2visits)

CMS – NOMEKO (3 visits)

SUMMARY AND CONCLUSIONS

The play concept tested in this DOE Class 2 Reservoir Demonstration Project, that bypassed or attic oil remained in the Dundee reservoir between wells that had been produced at excessively high flow rates and had coned water during primary production, appears to be correct. The TOW No. 1-3 HD-1 well in Crystal Field is a scientific and economic success and has been influential in encouraging small operators to drill horizontal drain wells in other abandoned fields in Michigan. Although two additional horizontal wells drilled at Crystal Field after the TOW 1-3 HD, they were technical but not economic successes. These wells were important in pointing out limitations in the use of horizontal wells in secondary recovery efforts in the Dundee Formation. For example, the most likely reasons they failed to produce economic quantities of hydrocarbons were because they were drilled off-structure and too high in the Dundee (i.e. they penetrated the tight limestone caprock rather than the reservoir). Also, for economic reasons, the operators on these two wells decided not to drill and log a vertical test or "probe" well, which was recommended. In spite of these two non-economic wells, seven additional horizontal wells are still planned for the Crystal Field and will further test the concept of recovering by-passed oil using horizontal drains. If these wells have vertical segments that penetrate the pay zone, and if they are logged, then we should be able to tell in the field the chances of success for that particular well. And we should be able to better guide the drilling of the horizontal leg. There is undoubtedly more oil to be recovered at Crystal Field, but better characterization of the interwell geology and more wire line measurements are needed. A 3D seismic survey would also be beneficial. However,

3D technology is just beginning to be applied in Michigan and operators are reluctant to make the expenditures for a survey without more assurance they will pay out. Lower seismic acquisition costs and improvements in interpretations will eventually result in these surveys being conducted at fields such as Crystal Field.

The technology transfer aspects of this project were also very successful. The regional characterization of the Dundee reservoir in 30 central Michigan Dundee fields has been completed and has been well received by the local industry. The results were transmitted to industry via workshops, papers, seminars, meetings and by distribution of the project CD ROM. The CD ROM in particular has proven to be an excellent technology transfer tool: demand for the ROM has been heavy and over 200 copies have been requested as of December, 1997. In addition, the project Web site has been a good tool: over 3,000 hits and over 50 downloads in the six months leading up to December, 1997. The regional characterization work will be published as an "Atlas of Michigan Dundee Reservoirs" sponsored by the Michigan Basin Geological Society. This Atlas should enhance the capability of the small operators in the state to independently explore and develop this neglected resource.

In summary, this cooperative project achieved nearly all its technical and economic goals and showed the value of federal seeding of high-risk projects with large potential payoffs. Many operators over the years since the TOW 1-3 HD was drilled have acknowledged the influence of that demonstration well. The subsequent drilling activity in the Michigan Basin that has continued through 1997 is a testimony to the program.

Recommendations

As a result of this program, a number of operators in Michigan have made several recommendations which involve using cutting edge technology to tackle high-risk but large potential payoff projects. The most timely would include:

1. Projects that would demonstrate the use and value of using 3D and 4D seismic surveys to delineate and characterize Dundee fields,
2. Programs that would help characterize the local and large-scale fracture patterns in the Michigan Basin,
3. research programs that combine seismic technology with potential field (gravity and magnetic) methodologies.

Michigan operators have expressed interest in these topics over the years since the Crystal Field project began, and a number are willing to participate in various aspects. Inexpensive reservoir characterization and delineation of the top of the Dundee Formation, the Traverse Formation, the Detroit River and the PDC (Prairie du Chein), including possible karstification and/or solution collapse, receive high priority among operators.

REFERENCES

- Carbonates International "Worldwide Carbonate Fields Database." Sun Quing, J. R. Allan, Eds. 1997
- AAPG, 1985, Midwestern basin and arches region, Correlation of stratigraphic units of North America (COSUNA) project. Lindberg, F.A. ed.
- Baldwin and Butler, 1985, Compaction curves: Am. Assoc. Petrol. Geol. Bull. V 69, p. 622-626.
- Bowers, T. L., 1989, Upper Niagara-Lower Salina (Mid-Silurian) sedimentology, and conodont-based biostratigraphy and thermal maturation of the southeast Michigan Basin: Unpub. M.S. Thesis, Detroit, Wayne State University, 119 p.
- Catacosinos, P.A., Daniels, P.A., Harrison, W.B., III, 1991, Structure, stratigraphy and petroleum geology of the Michigan Basin: in, Interior Cratonic Basins, Amer. Assoc. Petrol. Geologists Memoir 51, p.561-601.
- Cercone, K.R. and Pollack, H.N., 1991, Thermal maturity of the Michigan Basin: Geol. Soc. Am. Spec. Pap. 256, p. 1-11.
- Cercone, K.R., 1984, Thermal history of Michigan Basin: Am. Assoc. Petrol. Geol. Bull. p. 130-136.
- Cermak, V. and Rybach, L., 1984, Thermal properties, in, Hellwege, K.-H., and Madelung, O., eds., Landolt-Bornstein numerical data and functional relationships in science and technology, new series, group V: Geophys. Space Res.,

v. 4, p. 305-371.

Champion, B.L., 1969, Oil and gas producing zones in Michigan: in, Oil and Gas Fields Symposium, v. 1, Michigan Basin Geol. Soc., p. 17-36.

Chittick, S.D., 1995, Characterization of the Dundee Formation, Winterfield Field, Clare County, Michigan: unpubl. M.S. thesis, Michigan Technological University, 150p.

Combs, J.C. and Simmons, G., 1973, Terrestrial heat flow determinations in the north central United States: J. Geoph. Res., V 78, p. 441-461.

Crowley, K.D., 1991, Thermal history of Michigan Basin and southern Canadian shield from apatite fission track analysis: Jour. Geophys. Res., v. 96, p. 697-711.

Curran, B.C., and Hurley, N.F., 1992, Geology of the Devonian Dundee reservoir, West Branch Field, Michigan: Amer. Assoc. Petrol. Geologists Bull., v. 76, p. 1363-1383.

Everham, W. and Huntoon, J.; (1996) Dept. of Geological Engineering and Sciences, Michigan Technological University, Houghton, MI, GSA Abstracts with Programs. Vol. 28. No. 7. p. 265.

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

Furlong, K.P., and Edman, J.D., 1989, Hydrocarbon maturation in thrust belts: thermal consideration, in Price, R.A., ed., Origin and evolution of sedimentary basins and their energy and mineral resources: Am. Geophys. Union Geophys. Mon. 48, p.

137-144.

Gardner, W.C., 1974, Middle Devonian Stratigraphy and Depositional Environments in the Michigan Basin: Michigan Basin Geol. Soc. Spec. Paper No.1, 138p.

Harrison, W.B., III, 1992a, Devonian introduction: in, Wollensak, M.S. (ed.), Oil and Gas Field Manual of the Michigan Basin, v. 2, Michigan Basin Geol. Soc., p. 29-30.

Harrison, W.B., III, 1992b, South Buckeye Field: in, Wollensak, M.S. (ed.), Oil and Gas Field Manual of the Michigan Basin, v. 2, Michigan Basin Geol. Soc., p. 85-93.

Haxby, W.F., Turcotte, D.L., and Bird, J.M., 1976, Thermal and mechanical evolution of the Michigan Basin: Tectonophys. v. 36, p. 57-75.

Hogarth, C.G., and Sibley, D.F., 1985, Thermal history of the Michigan Basin: evidence from conodont color alteration indices, in, Cercone, K.R. and Budai, J.M., eds., Ordovician and Silurian Rocks of the Michigan Basin and its Margins: Mi. Bas. Geol. Soc. Spec. Pap. 4, p. 45-57.

Howell, P.D. and van der Pluijm, B.A., 1990, Early history of the Michigan Basin: Subsidence and Appalachian tectonics: Geology, V 18, p. 1195-1198.

Huntoon, J.E. and Furlong, K.P., 1992, Thermal Evolution of the Newark Basin: Jour. of Geol., v. 100, p. 579-591.

Huntoon, J.E., 1990, An integrated model of tectonics and sedimentation for the Newark basin: Unpub. Ph.D. dissertation, The Pennsylvania State University, University Park, 346 p.

Lilienthal, R.T., 1978, Report of Investigation 19 Stratigraphic Cross-sections of the Michigan Basin, Geological Survey Division MDNR.

Nunn, J.A., 1994, Free thermal convection beneath intracratonic basins: thermal and subsidence effects: *Bas. Res.* v. 6, p. 115-130.

Nunn, J.A., Sleep, N.H., and Moore, W.E., 1984, Thermal subsidence and generation of hydrocarbons in Michigan Basin: *Am. Assoc. Petrol. Geol. Bull.*, v68, p. 296-315

Price, K.L., Huntoon, J.E., and McDowell, S.D., 1996, Thermal history of the 1.1-Ga Nonesuch Formation, North American mid-continent rift, White Pine, Michigan: *Am. Assoc. Petrol. Geol. Bull.*, v. 80, p. 1-15.

Robertson, E.C., 1988, Thermal properties of rocks: Open file report 88-441, Geological Survey U.S. dept. of Interior.

Sloss, L.L., 1963, Sequences in the cratonic interior of North America: *Geo. Soc. Am. Bull.*, V 74, p. 93-114.

Sweeney, J.J., and A.K. Burnham, 1990, Evaluation of a simple model of vitrinite reflectance based on chemical kinetics: *Am. Assoc. Petrol. Geol. Bull.*, v. 74, p. 1559-1570.

Upp, J.E., Jr., 1969, Reed City Field: in, *Oil and Gas Fields Symposium*, v. 1, Michigan Basin Geol. Soc., p. 149-160.

Wang, H.F., Crowley, K.D., and Nadon, G.C., 1994, Thermal history of the Michigan Basin from apatite fission-track analysis and vitrinite reflectance: *Am. Assoc. Petrol. Geol. Mem.* 61, p. 167-177.

Waples, D.W., 1980, Time and temperature in petroleum formation:

application of Lopatin's Method to petroleum exploration: Am. Assoc. Petrol. Geol. Bull., v 64, p. 916-926.

Waples, D.W., 1985, Geochemistry in Petroleum Exploration: Boston, International Human Resources Development Corporation, 232 p.

FIGURES

Figure 1. Basemap showing locations of all gas and oil wells in Michigan. There are over 50,000 wells spotted on the map, inclusive of January, 1995. Data from MTU database.

Figure 2. Detailed basemap showing locations of Crystal Field and the 29 other fields with Dundee production

Figure 3. Stratigraphic column of central Michigan. The Dundee Formation is indicated by the label and the main gas and oil producing horizons are indicated by the filled circles.

Figure 4. Cross section across central Michigan illustrating stratigraphic relations, lithology and inferred depositional environments for Devonian age rocks.

Figure 5. Structure contour map, top Dundee Formation, Crystal Field, Montcalm County, MI. This map shows the gentle anticlinal structure that defines Crystal Field. Note the nearly closed -2400 foot contour.

Figure 6. Detailed structure contour map on the top of the Dundee formation at Crystal Field, Montcalm County, MI. This map illustrates the irregular surface topography typical of the Dundee in this field. This topography is consistent with an karstic erosional contact between the Dundee Formation and the overlying Bell Shale.

Figure 7. Location map for the TOW 1-3 demonstration well in the Crystal Field, Montcalm County, MI. The well trends E-W between two rows of vertical production wells that were active in the early stages of development but are now abandoned.

Figure 8. Cross-section through Crystal Field along the trace of the TOW 1-3 horizontal well. Formation top picks and the porosity zone were picked from the two rows of vertical wells on either side of the TOW 1-3. The porosity zone is defined as the dolomitic zone lying just below the top of the Dundee Formation. In this interpretation, the TOP 1-3 is assumed to have encountered a “compartment” of previously untapped hydrocarbons, either “attic” or by-passed oil.

Figure 9. Detailed well location map for Crystal Field, Montcalm County, MI showing field development prior to drilling the TOW 1-3 HD demonstration well.

Figure 10. Well history graph for Crystal Field, Montcalm County, MI. showing wells drilled, wells active and wells abandoned from 1935 to 1985.

Figure 11. Base map showing E-W trend of additional Dundee fields studied in project. Approximately 137 wells are spotted on the map.

Figure 12. Bubble map of initial production rates at Crystal Field, Montcalm County, MI.

Figure 13. Bouguer gravity anomaly map with superimposed oil fields for lower Michigan Peninsula.

Figure 14. Detailed well location map for Crystal Field, Montcalm County, MI showing all wells as of October, 1995 with their permit numbers.

Figure 15. Isopach map of Dundee Formation at Crystal Field, Montcalm County, MI

Figure 16. Detailed cross-section along A-B at Crystal Field, Montcalm County, MI

Figure 17. Location map showing location of cross-section A-B at Crystal Field, Montcalm County, MI.

Figure 18. Detailed cross-section along C-D at Crystal Field, Montcalm County, MI.

Figure 19. Location map showing location of cross-section C-D at Crystal Field, Montcalm County, MI.

Figure 20. Detailed base map showing development wells at Crystal Field with permit numbers.

Figure 21. Structure contour map of top of Dundee Formation at Crystal Field, Montcalm County, MI

Figure 22. Isopach map of Dundee Formation at Crystal Field, Montcalm County, MI

Figure 23. Contour map of top of porosity zone at Crystal Field, Montcalm County, MI

Figure 24. Contour map of initial production rates at Crystal Field, Montcalm County, MI.

Figure 25. Contour map of top of porosity zone at Crystal Field, Montcalm County, MI. with oil production values and water production codes.

Figure 26. Schematic diagram showing dimensions for kickoff point for horizontal leg of demonstration well and the cored section of the vertical leg. Casing and tubing data are also shown.

Figure 27. Detailed description of cored interval of TOW 1-3 HD demonstration well.

Figure 28. Map showing locations of deep wells in Michigan. Black circles indicate well that were digitized as part of this study.

Figure 29. Isopach map of Bass Island through Niagarian Brown. Contour interval is 100 feet and 10,813 well were used to produce the map. See text for discussion.

Figure 30. Plot of %R0 (vitrinite reflectance) versus depth for data from Mobil-Jelinek well.

Figure 31. Geohistory plot of depth versus time for Mobil-Jelinek well.

Figure 32. Plot of Temperature versus time for Mobil-Jelinek well.

Figure 33. Plot of TTI (Time-Temperature Index) versus time for Mobil-Jelinek well.

Figure 34. Plot of %R0 versus time for Mobil-Jelinek well.

Figure 35. Map showing locations of the two additional horizontal wells drilled at Crystal Field (Montcalm County, MI) in addition to the TOW 1-3 HD. HH stand for Happy Holidays well and FROST is the name of the Frost well.

Figure 36. Comparison with BWAB-Johnson 4-31: The BWAB-Johnson well provides an example of a purely limestone Dundee interval to a depth of 3810 ft, underlain by dolomite, as indicated by the porosity logs.

Figure 37. Comparison with DART-AUSTIN 3-31: The Dart-Austin well intersected an unswept zone of dolomitic Dundee (from the porosity curves) that are oil-saturated (from the high resistivity values). This well was completed as a producer in the Dundee.

Figure 38. Comparison with DART-THAYER 3-29: The Dart-Thayer well was drilled into a dolomitic Dundee interval (from the porosity logs) that has been swept by previous production, although it appears (from the resistivity logs) that there are two short intervals of high oil saturation, perhaps a result of post-production gravity drainage.

Figure 39. Comparison with BWAB-Marion 33-21-1: The BWAB-Marion well demonstrates the log character of a dolomitic zone (as shown by the porosity logs) that is water-saturated (as indicated by the low resistivity readings).

APPENDIX I. Using Production History Data to Evaluate Recovery Potential

Production history data is an readily accessible and easily used resource to evaluate the past performance and management history of an oil field. Using digital data sets and off-the shelf software, even relatively inexperienced personnel can produce comprehensive analyses and visualizations of oil field performance and development history.

Several public domain sources of data are available in Michigan. Individual field production history (annual and cumulative) has been published by the Michigan Geological Survey in their Annual Statistical Summaries of Michigan's Oil and Gas Fields. Unfortunately this series was discontinued in 1987, however there are annual reports from 1934 to 1986. For many fields in Michigan (including Dundee fields) this data set covers the complete life of the field.

The Michigan Geological Survey also maintains a data set called the "brine reports" or AWSUM reports. This data is annual reports by lease from all fields producing water. Early records from the 1930's and 1940's are very spotty, but information is nearly complete from 1946 to 1994. The earliest reports contain only water production data, however oil production data was incorporated from 1950 to 1994. The information is reported by lease (not individual well, although there are many one well leases in Michigan) within each field. Data is reported as barrels of water (or oil) produced daily. We have found that the daily reported water values are, when summed, very consistent with the daily field totals published in the Annual

Statistical Summaries. Because of averaging or rounding, the daily reported oil production values do not correlate well with other sources of oil production data (Annual Statistical Summaries or MOGA). Oil production data from these “brine reports’ should only be used if no other source of information is available.

A third source of oil production data is the Michigan Oil and Gas Association’s (MOGA) Annual Production reports. This series was published annually from 1945 to 1972. Data was reported by lease within each field (similar to the State “brine reports”). Oil production is given as barrels annually per lease. Although there are many leases with one well per lease, as many as eight wells may be combined into a single lease number.

Combining information from these three data sets will provide annual field oil and water production histories, daily (or annual) lease oil and water production histories and annual status of wells within fields (active, newly drilled, abandoned, shut-in). At present most of this data is only available in paper or microfilm format. For analysis and interpretation of Michigan’s oil production history data it is recommended that the available data be put into digital form in a spreadsheet format. We have found that Microsoft Excel works very well for this purpose, however other software, such as Lotus or Quattro Pro could be equally effective.

As part of this Class 2 reservoir study on Crystal and 29 other Dundee fields in Michigan, we have compiled an MS-Excel data set of oil production history. Figures and tables, herein, demonstrate the properties of these data sets and some of the visualization products that can be produced to help interpret the historical performance and management of these Dundee reservoirs. Some criteria have also

been established in this project to evaluate the potential additional oil recovery from these Dundee fields.

- 1) Steepness or rate of decline during the early years of production. Declines of more than 20-25 % per year are suspicious.
- 2) High rate of abandonment of wells. Abandonment of more than 5 or 10 percent of a field's wells during the early life of the field should be an indicator of inefficient reservoir management.
- 3) In water-drive reservoirs, rapidly increasing water cut may suggest that production flow rates are too high resulting in up-coning of water from the aquifer. Eventually the large amount of water to be handled results in the abandonment of the well. Premature abandonment of wells results in mobile oil being left in the reservoir in the interwell locations.
- 4) Sites for recovery of bypassed oil is likely to be in the interwell areas at maximum distances from the old boreholes.

EVART FIELD PRODUCTION DATA

DATE	ACTIVE OIL WELLS	DRILLED IN YEAR	ABANDONED IN YEAR	OIL PROD.(BBLs)
1935				
1936				
1937				
1938				
1939				
1940				
1941				
1942	13	13	0	198,192
1943	28	15	0	1,031,310
1944	28	0	0	725,431
1945	27	0	1	447,477
1946	26	0	1	310,627
1947	26	0	0	220,401
1948	25	0	1	156,899
1949	23	0	2	121,751
1950	23	0	0	100,681
1951	23	0	0	80,453
1952	23	0	0	68,482
1953	21	0	2	56,849
1954	17	0	4	47,784
1955	16	0	1	37,960
1956	12	0	4	30,917
1957	12	0	0	27,262
1958	10	0	2	21,821
1959	10	0	0	19,837
1960	10	0	0	17,626
1961	10	0	0	16,324
1962	10	0	0	13,568
1963	9	0	1	12,967
1964	9	0	0	11,981
1965	9	0	0	10847
1966	8	0	1	8,437
1967	3	0	5	5,243
1968	3	0	0	5,535
1969	3	0	0	4,476
1970	0	0	3	989
1971		Field Abandoned in 1970		
1972				

Table 1. Example of Excel spreadsheet for production and well status data

EVART FIELD PRODUCTION HISTORY

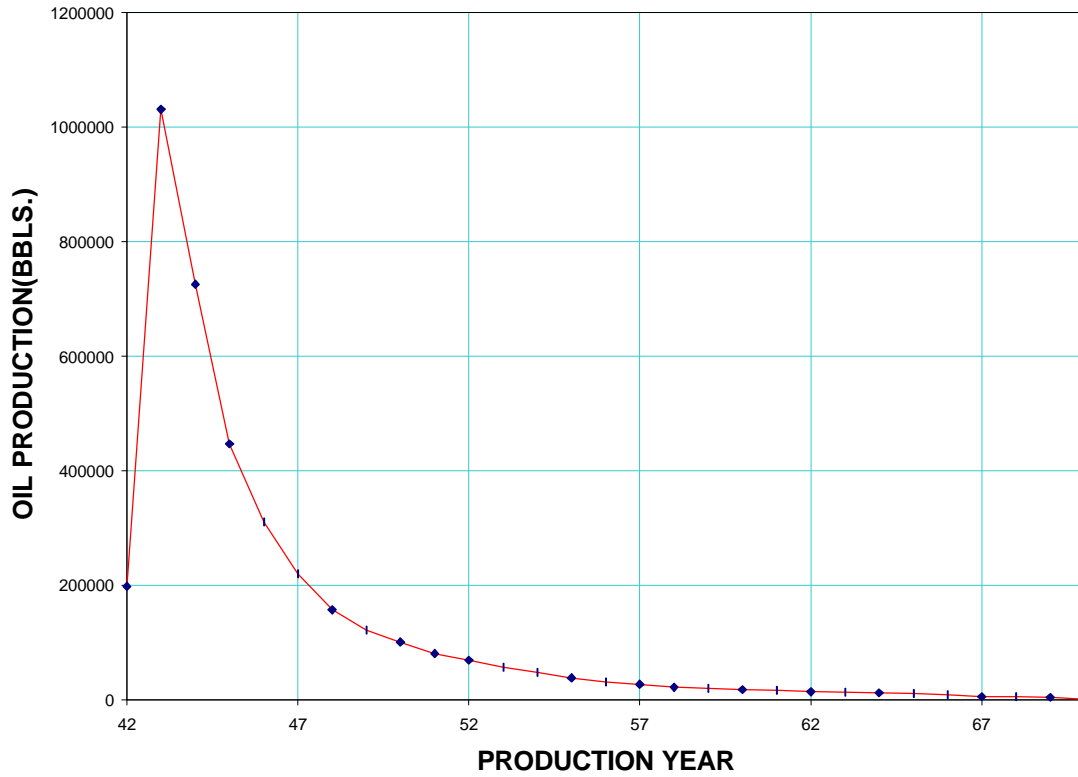


Figure 1. Oil production history Evart field Dundee Fm.

EVART FIELD WELL HISTORY

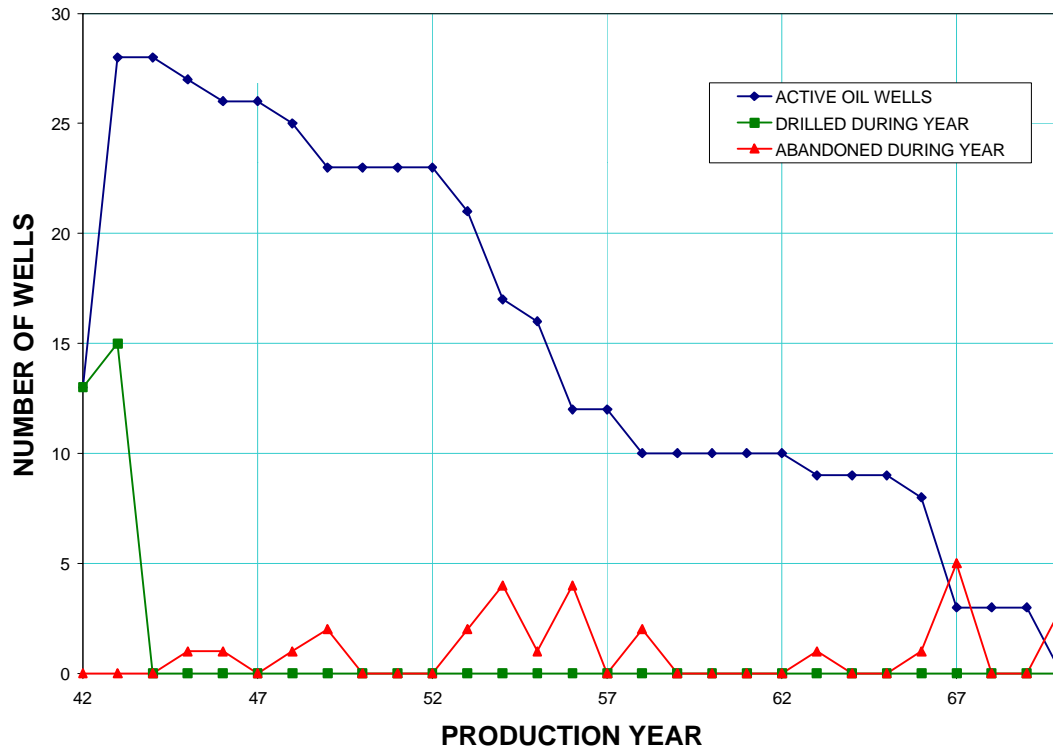


Figure 2. Oil well history Evart Field Dundee Fm.

APPENDIX II. SUMMARY OF PROJECT CD ROM

WWW WEB PAGES

As part of this project, a system based on CD-ROM technology was developed to track and report progress and to serve as a data repository. It was also decided that the project data would be available on the Internet as well as on a CD-ROM. After evaluating the pros and cons of using Asymetrix Toolbook and the HTML Internet Language, it was decided to use HTML coding and discontinue use of Asymetrix Toolbook. We found that Asymetrix Toolbook had a plug-in for viewing Toolbook applications online, but too many of the features would not work correctly. Instead of duplicating our efforts by bringing data into Toolbook and also constructing a Web page with the same data, we made the decision to drop Toolbook and put everything on the Web page using HTML coding.

We are using Microsoft Internet Explorer as our browsing program. For our end users that do not have Internet access, we can put all of our files and HTML code onto a CD-ROM with Microsoft's Internet Explorer as a browser. Microsoft Internet Explorer is available for us to re-distribute royalty-free as long as we register the number of copies we distribute on a quarterly basis and we must use the Microsoft Internet Explorer Logo on our Web page.

Some advantages of putting project data onto the Internet include downloading capabilities, easy access for our viewers, and attractive visual displays. In addition, even though Microsoft Internet Explorer is our chosen Internet browser, other viewers can be used as long as they can handle the Table feature of HTML.

The direct address to the Subsurface Visualization Lab is:

<http://www.geo.mtu.edu/svl/>

Click on Michigan Project to view data from this project.

WEB CONTENT

The following information is now available on our Web site above:

Michigan Project

- The quarterly and annual reports to date
- Well Rig Photos
- Project Personnel
- Link to Western Michigan University Web Site

Regional Geology (Project Study Area)

- Dundee Structure map of the project study area
- Oil Field Location Map
- Table of general information of all the oil fields in our project
- Atlas of Michigan Dundee Reservoirs
- (Includes Autocad Maps, production graphs and tables for the 30 fields in the project)

Michigan Basin Geology

- Stratigraphic Column of Michigan Formations
- Michigan Basin Formations Table
- Isopachs and Structure Contour Maps
- 3-D Isopachs and Structure Contour Maps
- Bouguer Anomaly Map

- Oil Wells of the Michigan Basin

- 1996 GSA Presentation

- Sample Driller's Log

TOW 1-3 HD Well

- Cronus Development Letter

- Core Analysis Charts

- Core Gamma Surface Log

- Core Description

- Horizontal Well in Crystal Field

- Proposed Horizontal Leg

- Horizontal Well Cross Section

- Horizontal Well Diagram

- TOW 1-3 HD Production

- Pressure Build-up Test

- Static Pressure Gradient

- Core Photos

Project Data Download Options

- Oil Field Production Data

- Well Data

- Oil Field Statistics

- TOW 1-3 HD Data

The scrolling menu along the left side of the web page can be used to view any of the above items. Many graphics are displayed small, and when clicked on,

will show a larger image. The large image may be clicked on to return to the previous page, or another menu item may be selected.

Data

A wealth of data on the subsurface of Michigan were collected during the course of this project, primarily in the Dundee and Traverse Formations. A project database was constructed using Microsoft Access and the bulk of the data were inputted into this database. Where appropriate, the data are also given in Microsoft Excel files and as plain ASCII files. All of these files are on the project CD ROM. In this section, a description of each of the main data categories will be given, with brief examples. The CD ROM should be consulted for the main body of data.

In addition to digital data on well locations, formation tops, production parameters and engineering parameters, topographic and cultural data files for Michigan were located and downloaded from the USGS. These files permit a user of construct essentially complete prospect level maps for any of the 30 fields studies in this project. Project maps have been constructed using the GeoGraphix GES software program and the native GeoGraphix files are also on the CD ROM. A user should be able to directly load these files into his own copy of GeoGraphix and manipulate them from there.

An electronic atlas was also generate using TerraStation. This consists of location, structure, isopach production history maps. These maps are also on the CD ROM as Adobe Acrobat PDF files and as AutoCAD .DXF files. The data used to generate all of these maps is present on the CD ROM in Excel spreadsheet and plain ASCII files.

Finally, approximately 273 well logs from the deepest wells in Michigan were located and studied. 114 of these wells logs were digitized and the digital well logs are on the CD ROM under “ Well Logs”. Also, the well logs for the TOW 1-3 demonstration well, are provided in digital (LAS) format on the CD ROM. The open circles indicate the digitized wells. Also of particular interest is the Sparks, Eckelbarger, Whightsil #1-8 well drilled in Gratiot County, Michigan, by McClure Oil Company on January 4, 1976. This is the deepest well ever drilled in Michigan at 17,479 feet. The LAS file for this well contains curves for: Deep Resistivity, Gamma Ray, Caliper, Bulk Density, Neutron Porosity, Density Correction, Deep Laterolog, Shallow Laterolog, Medium Resistivity , Deep Conductivity , Density Porosity, Bit Size, Gamma Ray, Sonic Transit Time, Caliper and Sonic Porosity.

The following description of the data collected is intended as an overview and is by no means complete. Often, descriptions are given for only one or two representative files or examples, while upwards of 30 or more fields are actually present on the CD ROM. It is estimated that producing paper copies of just the map files would be on the order of 200-300 pages. These maps are usually present as PDF files and these files may be sufficient for most needs. Users should consult the Figure Index for these maps.

CD ROM CONTENT

The format of the project CD ROM itself was designed to be as self-explanatory as possible. The ROM is divided into 5 main categories, represented as sub-directories: (1) reports, (2) data files, (3) maps, (4) the MTU WEB site for the project and (5) miscellaneous.

Oil Field Data Files

For each of the 30 Dundee fields studied, the data files containing the formation top picks and initial production numbers are presented in as Microsoft Excel files. Table III-1 lists the fields by file name and size.

FIELD	SIZE (bytes)	FIELD	SIZE (bytes)
belly1.xls	35328	broom.xls	47104
catol.xls	22016	cedar.xls	25088
cldwtr.xls	51200	cranb1.xls	76800
crysprod.xls	90624	crystall.xls	67072
currie.xls	17920	doug.xls	18944
evart.xls	29184	filelist.txt	378
fork1.xls	44544	free.xls	56320
gilmor.xls	18944	hardy.xls	22016
index~1.htm	3753	isabel.xls	25600
leaton.xls	30208	lkgeo.xls	20992
mcbain.xls	34816	miprod.xls	231936
oilstats.xls	23040	prosp.xls	27136
rey.xls	54784	river1.xls	26112
skee.xls	27648	sylvan.xls	18944
vernrose.xls	68608	wis1.xls	38400

A portion of the Crystal Field Excel file is shown in Table III.1. The complete file contains about 278 rows. The permit number is a six-digit code representing the number assigned the well by the State of Michigan at the time the permit to drill the well was approved. The well status is a one-digit code reflecting the current status of the well: 1 = active, 2 = producing, 3 = abandoned, 4 = dry. The latitude and longitude were obtained from footage calls taken from drillers reports and scout

tickets. The rest of the data report, the KB (Kelly bushing, the tops picks for the Antrim, Traverse and Dundee Formations , the initial production, the initial water production, the porosity (%) and the total depth (TD) were also taken from these original sources. The formation tops and the TD are in feet subsea. The Traverse Limestone isopach numbers (TLISOPACH) were calculated from the tops reported top picks for the Traverse and Dundee Formations.

CRYSTAL FIELD												
PERMIT #	STATUS	LATITUDE	LONGITUDE	KB	ANTRIM	TRAVLS	TLISOPACH	DUNDEE	IP	IPW	POROSITY	TD
P#002423	1	4327907	8485395	786	-1504	-1959	505	-2448	0	*****	*****	-2522
P#002431	3	4329122	8485386	781	-1519	-1964	*****	-2405	450	*****	3193	-2412
P#002447	1	4327906	8485147	785	-1615	-1943	*****	-2439	0	99999	3246	-2523
P#002527	1	4328783	8484896	778	*****	*****	*****	*****	*****	*****	*****	-241
P#002531	4	4327846	8485481	786	*****	*****	*****	*****	*****	*****	*****	-203
P#003186	4	4328942	8485388	781	*****	*****	*****	*****	*****	*****	*****	-207
P#003267	3	4328944	8485372	780	-1540	-1940	*****	-2404	60	*****	3187	-2407
P#003490	1	4328329	8484773	776	*****	*****	*****	*****	*****	*****	*****	-253
P#002395	1	4327909	8486383	787	-1494	-1936	464	-2398	1	3	3185	-2414
P#002406	3	4328245	8487129	790	-1495	-1935	*****	-2396	739	*****	3186	-2408
P#002407	2	4327909	8486631	787	-1515	-1952	435	-2387	25	*****	3192	-2421
P#002415	3	4327909	8486135	784	-1512	-1926	467	-2393	100	*****	3183	-2400
P#002459	10	4328245	8486631	787	-1498	-1953	448	-2401	60	*****	3198	-2581
P#002460	3	4329124	8486631	786	-1484	-1930	472	-2395	1500	*****	3182	-2398
P#002462	3	4328427	8486631	788	-1479	-1927	460	-2397	350	*****	3189	-2404
P#002463	3	4328099	8486383	784	-1496	-1916	491	-2407	180	*****	3197	-2418
P#002464	3	4328583	848663	790	-1495	-1930	464	-2394	710	*****	3185	-2398
P#002465	3	4329124	8486395	792	-1508	-1925	470	-2395	442	*****	3190	-2400
P#002466	3	4328428	8486383	788	-1497	-1931	468	-2399	140	*****	3192	-2405
P#002467	3	4328942	8485884	792	-1536	-1923	473	-2396	311	*****	3195	-2403
P#002495	2	4328599	8487374	792	-1496	-1905	487	-2392	30	3	3189	-2398
P#002497	3	4328786	8487371	791	-1499	-1923	476	-2399	351	*****	3191	-2406
P#002505	3	4328245	8486878	785	-1495	-1935	449	-2386	50	*****	3192	-2412

Table III. 1 Abbreviated Microsoft Excel table of field data illustrating format and content of project field data files on CD ROM. The same data are also presented in ASCII format on the ROM. There are 60 total files of this type.