**TITLE:** ADVANCED CHARACTERIZATION OF FRACTURED RESERVOIRS IN CARBONATE ROCKS: THE MICHIGAN BASIN

**TYPE OF REPORT**: SEMI-ANNUAL

**REPORTING PERIOD START DATE**: OCTOBER 1, 2000

**REPORTING PERIOD END DATE**: MARCH 31, 2001


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**DATE REPORT WAS ISSUED**: APRIL 2001

**DOE AWARD NUMBER**: DE-AC26-98BC15100



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## DISCLAIMER

# ABSTRACT

Among the accomplishments of this past reporting period are obtaining a complete landgrid for the State of Michigan and the digital processing of the high and medium resolution DEM files. We can now extract lineations from the DEMs automatically using machine algorithms. One tentative result that may be very significant is that we may be seeing manifestations of buried structures in the DEM data. We are looking at a set of extracted lineations in the northern lower peninsula that appear to follow the trend of the pinnacle reefs (Silurian) which had relief approaching 300 feet but are now buried to greater than 3000 feet.

We have also extracted the dolomite alteration data from all fields and can show that this is mainly confined to the basin center. It may be related to the paleo-rift suggested by the paleomagnetic and gravity data.

As reported last time, the acquisition of a 3D seismic dataset over Stoney Point Field from Marathon Oil Company, is complete and attention is being devoted to incorporating the data into the project database and utilizing it. The surface lineation study is focussing on Stoney Point Field using the high-resolution DEM data and plotting of subsurface formation top data for the main reservoir, the Trenton (Ordovician) Formation. The fault pattern at Stoney Point is well documented by Marathon and we are looking for any manifestations on the surface.

The main project database is now about as complete as it will be for this project. The main goals have been met, although the scanning of the paper records will have to continue beyond the scheduled end of the project due to the sheer number of records and the increased donations of data from companies as word spread of the project. One of the unanticipated benefits of the project has been the cooperation of gas and oil companies that are or were active in the Michigan Basin in donating material to the project. Both Michigan Tech and Western Michigan continue to receive donations at an accelerating pace.

The data management software developed to handle the data, *Atlas*, is scheduled to undergo a 3rd revision before the project ends. The goals are to streamline access to the data by improving the display and add several new features, including the ability to turn the landgrid on and off. We may also be able to include the capability to calculate or recalculate footage calls as well.

We discovered the reason that some of the 1/24,000 USGS DEM (Digital Elevation Models) for the State of Michigan contain high levels of noise and are making one last attempt to acquire a set of good files before the project ends. This will greatly improve the large-scale map (48 inches x 84 inches) that has been constructed by mosaicing of the high-resolution files. This map shows excellent ground surface detail and has drawn much comment and requests for copies at the venues where it has been displayed. Although it was generated for mapping of surface lineations the map has other uses, particularly analysis of the glacial drift in Michigan.

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# EXECUTIVE SUMMARY

The main objective of this project is to develop a comprehensive dataset of geologic data for the subsurface of the Michigan Basin and use this data to explain the origin and distribution of the fractured carbonate reservoirs in the Basin. The database is based on the “data cube” concept in which the Michigan Basin is divided into a 3-dimensional grid, which is then populated with appropriate attributes, such as depths of formation tops, and lithology. The basic data used was the latitude – longitude coordinates of gas and/or oil wells coordinated with the appropriate depth for the specific attribute. These data were obtained from existing digital databases supplemented with a database of raster images of the original paper reports, which for Michigan consists of driller’s reports and scout tickets.

To date 6985 driller's reports (1- 8 pages each) and over 17,000 scout tickets have been scanned and organized in a digital database. These are tiff files organized in subdirectories labeled by county name in a PC (e.g. Microsoft Windows) environment.  A digital dataset of formation tops has also been compiled. Presently, this consists of over 700,000 top picks, of which about 50% can be considered public domain. (The rest can still be purchased from vendors.) Work is continuing to expand the public domain database.

To help organize and access the large amount of data compiled in this project, a program was written that allows a user to access all the data via a simple graphical interface. This is the ATLAS program now in version 3 and being updated to a version 4 currently. ATLAS displays the data on a State map in a variety of ways and will also export subsets of the data to MS Access file for use by other programs. A unique feature of ATLAS is that it will also access our database of raster images and allow the user to update or expand the digital database in ATLAS. This is a timesaving feature that can be used for any properly structured database.

The fracture study based on these data has been expanded in the past year from a, detailed mapping of several key fracture-dominated fields (Deep River and N. Adams), to over 2 dozen fields which appear to include all the hydrothermally altered dolomite reservoirs in the Basin.  The distribution of these altered fields is discussed in this report.

As reported last time we were successful in obtaining a 3D seismic survey shot by Marathon Oil Company over Stony Point Field. We now have a large data set (>4 Gb) that we are in the process of examining. Adding the Stoney Point data approximately doubles our data inventory.

The general fracture picture that is emerging in the Michigan Basin is a dominant NW – SE trend that manifests itself on a field scale and can be mapped in outcrop. The conjugate direction, roughly, a NE – SW trend is also established in some fields. Data (mainly gravity) suggests that this trend is related to a deep basement structural trend coincident with the Michigan Basin Gravity High. This data has been interpreted as evidence for an old rifting episode early in the Proterozoic history of the Basin. The locations and geometry of many gas and oil fields in the central part of the Michigan Basin are consistent with this interpretation: elongated fields oriented NW – SE or SE – NW with many on the margins of the gravity high.

# INTRODUCTION

This is a study of the fractures in the Michigan Basin and their relation to hydrocarbon deposits. Michigan has produced nearly a billion barrels of oil from the 1920's to the present, as much as 50% from fractured carbonates. (Much of the rest of the production is from the Silurian pinnacle reef trend in Northern Michigan.) Michigan is a mature petroleum province now and has been extensively drilled for over 80 years. As such it provides a wealth of information in an area where companies are now inclined to release proprietary data. Consequently the two goals of this study were to (1) collect and organize this data, and (2), use it to see if any new light could be shed on the nature and origin of the fractured reservoirs.

There are two types of large-scale fractures in the Michigan Basin: those associated with anticlines and those indicated by hydrothermal dolomitization. The presence of fractures in the Michigan Basin can be inferred by the tight packing of structural contours on most any of the post-Cambrian sediments while the hydrothermal faults are indicated by the presence of long, linear pods of dolomite mapped in the subsurface. The large-scale faults are located in the southeastern quadrant of the Michigan Basin and in the Thumb area while the hydrothermal faults are clustered in the center of the basin. These faults are not always indicated on geologic maps of the Michigan Basin due to lack of surface exposure, but their presence can be inferred by the tight packing of contours on most any of the post-Cambrian sediments. This study has explored the origin and nature of these large-scale faults by analyzing the subsurface data described above and through the use of DEM (Digital Elevation Model) data on the 1:250000 and 1:12000 scales.
The fractured carbonate reservoirs selected for this study are unusual in that the main trapping mechanism is the generation of enhanced porosity caused by hydrothermal dolomitization. They are similar to reservoirs in many basins worldwide where fractured dolomites zones form important oil and gas reservoirs. Termed "dolomite chimneys", in the Michigan Basin, they have long been among the most prolific producers of hydrocarbons in the world. However, key aspects of their origin(s), distribution and architecture have been enigmatic. They have been difficult to find and once found, many have proven difficult to produce efficiently. The Michigan Basin is well suited to serve as a model for fractured reservoirs. It is a mature basin that contains almost 50,000 gas and oil wells with extensive data and rock samples. Over 150 million barrels oil has been produced from fractured carbonate reservoirs in Michigan and adjacent states. The Dundee Formation alone has produced over 350 million barrels, approximately 40-50 million from fractured, dolomitized reservoirs. It has been estimated that nearly this amount of hydrocarbons remains to be recovered.

The data from driller's reports continues to be collected and scanned and results to date are now on the Internet. Several counties are now complete and work is in progress on several others (Figure 1). We are working to make the software packages required to display and manipulate the data available as well. The software will permit visualization and interpretation on both large and small scales. The main deliverable will be a data cube for the Michigan Basin that will include:

- A library of formation tops picks (300,000+)
- digitized well locations (latitude & longitude; 50,000+)
- scanned images of well header records

- digitized and interpreted logs of key wells
- hydrocarbon logs,
- engineering data, and key horizons picked from 2D & 3D seismic data
- a landgrid for the State of Michigan
-

FINAL REPORT – FORMAT AND CONTENT

As this project winds down, it is becoming apparent that reporting the conclusions and making the fruits of the project available to the public constitute separate and special problems. It is clearly impossible to convey the enormous amount of data in a paper report. The only reasonable mechanism is that a summary report be issued and that the data itself be placed in an electronic repository and made available over the World Wide Web (www). It is proposed that the summary final report be organized in chapters along the following lines. That separate chapters cover: (1) the background and history of the petroleum industry in Michigan, (2) the available data and its quality, (3) the nature and distribution of fractures in the Michigan Basin and (4) Conclusions. The suggested chapter headings and suggested lengths are:

Chapter 1. Introduction – History and Background of the Michigan Basin (10 pp)

Chapter 2. Data and Databases (10 pp)

Chapter 3. Fractured Reservoirs in the Michigan Basin (30-50 pp)

Chapter 4. Conclusions (5-10 pp)

Appendix I. Web Content

Thus the final report will be a document 60-80 pages in length, exclusive of figures, and will contain an appendix that will describe the digital data on the Web site. The web site will allow access to the project data via FTP downloads. The *Atlas* software should also be available. In addition a library of figures with captions and all PowerPoint presentations made over the duration of the project will be available.

The present capacity of CD ROMs is only 640 Mb and 4-5 would be required to hold all the (present) project data. Larger formats, DVD, are becoming more prevalent and some thought will be given to creating a 6-8 Gb DVD disk. This should be sufficient capacity to hold all the project data and would be a convenient transfer medium.

# TASK STATUS

## *Task 1. Project Management*

### Subtask 1.1 Technical Aspects

Project management continues to operate smoothly: links have been established between the main Michigan Tech operations site and the sites in Kalamazoo, Traverse City and Tampa FL. Two face-to-face meetings with all personnel were held, one meeting in Traverse City, and one in Tampa. All senior team members (Wood, Harrison, Luo, Chittick) attended the spring AAPG meeting in New Orleans in 2000 and will attend the Denver meeting in 2001.

We are now in the process of wrapping up this project, which is scheduled to end in October, 2001. We are checking the task list and making sure all goals either have been reached or can be reached in time. So far, everything appears to be on schedule. It may be necessary to ask for a short extension to meet cost-share requirements.

### Subtask 1.2 Financial Reports and Accounting

Project expenditures are proceeding according to plan. All necessary reports have been filed with DOE Pittsburgh.

## *Task 2. Basin Analysis*

### Subtask 2.1 Geology

Lineation Analysis

The DEM data has been successfully integrated into the project and is now bearing results. Most of the technical problems have been resolved to the extend possible. It appears that the 7 ½ minute quadrangles with obvious noise has been traced to a bad conversion from the DEM format to the SDTS format by a USGS contractor. The USGS is aware of the problem and is moving to correct the files. It does not appear to be a problem that we can fix, or one that the USGS will have fixed in time for the high resolution data to be used in this project. However, it may be possible to purchase good files from vendors at a reasonable price. We are currently looking into that possibility.

### Subtask 2.2 Geophysics

2.2.1 Seismic

The 3D seismic data package over Stoney Point field arrived from Marathon Oil Company in December and has been loaded onto MTU computers. Work is in progress to register the data and display it on our hardware. One Ph.D student is employed full-time on this project as part of his thesis. Although the data was received late in the project we plan to make as much use of it as possible in the remaining time. One goal is to image the reservoir zone at Stoney Point with the aim of relating it to fracture patterns.

Three 2D seismic lines were obtained from Marathon Oil Company near the Crystal Field in Montcalm county (MOC), loaded into GeoQuest and processed in an attempt to elucidate Dundee structure. The seismic data was shot targeting deeper plays and thus has low fold and offset to adequately resolve shallower plays such as the Dundee. From structure maps, isopach maps and initial production bubble plots, it is apparent that the Dundee of the Crystal field was faulted and probably karstified. The low fold and offset coupled with unknown static conditions creates a condition of low signal to noise ratio, making it difficult to resolve the shallow structure and fractured nature of the Dundee in the Crystal field (T. Bulloch, 1999). Bay Geophysical of Traverse City, Michigan has however, indicated that they have exclusive processing techniques, which may be able to resolve shallow low fold structure. This project will attempt to acquire data processed by Bay Geophysical, which resolves shallow structure with 2D data.

#### 2.2.2 Borehole

The use of borehole data in this project is continuing, mostly at Western Michigan University.

### Subtask 2.3 Hydrology

This task has started with the analysis of the main hydrologic units in the Michigan Basin, the basement configuration, the Traverse and Dundee Formations. Work is continuing on this subtask.

#### 2.3.1 Fluid Pathways

This task is proceeding in tandem with the basin model. It has much the same problems as the mapping of the Top of Porosity in that it is necessary to read each driller's report for mention of hydrocarbon shows.

#### 2.3.2 Flow Model

#### 2.3.3 Gas and Oil Trapping

The show data discussed in 2.3.1above should point toward known gas and oil fields. Thus the trapping mechanisms may be elucidated as well since we would anticipate that the shows would terminate at seals, which are generally shales, tight limestone or salt in the Michigan Basin. We will plot the oil and gas shows along with producing oil plays in a three dimensional display to show migration routes and oil and gas trapping mechanisms.

## *Task 3. Quantification and Mapping*

This task is approaching completion. Nearly one hundred fields in the Michigan Basin were studied as part of this project (Table 1). Well locations and formation top data (Figure 2) were collected in paper records, scanned into images (tiff raster images), and the translated by hand into digital form. In addition, header information on each well (latitude, longitude, permit number, Kelly bushing, driller, operator, etc) was assembled in digital format and input into a (MS Access) database. These fields cover virtually the entire Michigan Basin and account for over 90% of the total cumulative production in the State from inception of drilling (~1920) to present. For the most part, these fields are described in the two-volume reference set published by the Michigan Basin Geological Society.

## Subtask 3.1 Data Acquisition

Data Cleanup and Digitization

This task is now competed except for scanning the driller's reports, which is on-going. Over 17,000 scout tickets have been digitized as TIF images and added to the Atlas database. These are all of our currently available scout tickets. We have begun work digitizing driller's reports as multiple page TIF images. Digital well logs are being acquired from oil and gas company donations and in house digitizing. Recently, over new 5,400 wells were added to our database, bringing the total number of well locations to approximately 54,000.

Acquisition and digitization of formation top data for the Michigan Basin is essentially complete. Three digital databases, one commercial, one State of Michigan and one from this project, have been examined as well as paper datasheets at Michigan Tech and Western Michigan Universities for subsurface data. Three types of data have been extracted: formation top picks, well headers (including geographical location) and production/lithology data.

Well Headers
This category includes all relevant information about an individual well: name, location, operator, date spudded, drilled, completed, fluids produced, fluid intervals, and so on. In general, these data are the beginning for all subsequent analysis as it containing the surface and bottom hole locations as well as the elevation datum (usually the Kelly bushing). For Michigan in 2000, there are over 53,000 well, gas, oil, disposal and other, in the State.

Formation Top Picks

This type of data is by far the most valuable in reconstructing the subsurface and accordingly more attention has been paid to gathering and verifying it. The three databases yielded nearly 900,000 (880,386 to be exact) top picks for over 140 formations in the Michigan Basin ((Figure 2 and Table 1). Of these, 243,546 were duplicates leaving 636,880 separate top picks.

Some Statistics

The character of this dataset can be appreciated by looking at some statistics. Although there are 146 separate formation names included in the databases, only 12 account for 50% of the picks and 50 account for 99% of the picks (Table 2). In addition, some formation names refer to the same top, but were spelled or indicated differently in the different databases. For example, the Aangstom database refers to the Salina "D" Horizon as the "Salina D Evaporite/Salt" while the State of Michigan refers to it as the "Salina D Unit". In addition, some names are obsolete and have been superceded. When these issues are resolved, the total number of units in the Basin shrinks to around 75, of which 50 or less are important on a basin-wide scale.

Quality Control

The issue of quality control is important as it relates to the accuracy, absolute and relative, of the top ticks. Generally, the smallest unit of measurement is 1 foot, so in an ideal situation, all top picks would be accurate to within 12 inches. The relative accuracy is the depth reported by the driller to each horizon and refers to each separate top pick in one well. The absolute accuracy is the subsea depth which permits comparison of one well top pick to another and is dependent on both the relative accuracy and the accuracy to which the surface elevation was measured.

Errors are also introduced when measurements are recorded or transcribed. This is not uncommon when dealing with databases this large compiled over decades by different personnel. A common error is to transpose two numbers. The only recourse here is to re-examine the original documents (driller's reports) and hope they do not contain the same error. Finally, errors are introduced when different methods are used to pick a top. For example, the logger at the well site will make picks based on the cutting brought up and later the logger will make picks based on logs. In many cases, the type of log used will make a difference in the pick, sometimes by 10s of feet.

During this reporting period, a student reviewed all the available data for the Dundee Formation (e.g. top picks) by examining large-scale contour plots and then checking any wells that produced "bulls eyes" in the plot with the paper records. In this way he located a number of errors in the database and corrected them and reduced the occurrence of "bulls eyes" to practically zero for the Dundee Formation by correcting about 1500 wells (out of nearly 25,000). We now believe we have the best set to top picks for this important horizon. However, we also now believe that the rest of datasets likely contains similar erroneous data that will have to be similarly corrected. Given the large amount of data (see above) it is clearly a task that is unfortunately beyond the scope of this project. While we will be able to deliver a large number of public domain data on formation tops in the Michigan Basin, we will have to cite the experience with the Dundee formation and caution the user that errors still exist in the database.

### 3.1.2 Gridding

The 7 ½ minute DEM grid for the entire State of Michigan has been completed. Work is now focussed on upgrading the individual data elements and plotting the large-scale maps.

### 3.1.3 Database Management

All data associated with this project to date has been placed into an MS Access database as promised. In addition, all documents related to the project (reports, software, etc.) have also been placed in a digital database that consists of the MS Windows normal file structure. The database can be accessed using *Atlas*.

### Subtask 3.2 Mapping and Visualization

#### 3.2.1 2D Mapping

This task is now completed with regard to the surface grid. This includes cultural data, as well as hydrologic. Attention is now focussed on mapping the key subsurface horizons now that the database containing the formation tops is available.

As reported last time, basin wide mapping has begun with all Michigan well locations and formation tops input into ArcView. However we now prefer to use Golden Software Surfer © program for contouring because it is easier to use and provides superior results. Part of the reason for Surfer's superiority is the number of gridding algorithms it offers together with a higher degree of user control. However, the main reason is that it can be used in tandem with ATLAS to automatically generate contour plots. As we now have over 100 fields to analyze, automating the plotting save time and dollars and permits changes and refinements that would otherwise not be possible.

#### 3.2.2 3D Mapping

The 3D code for displaying the gridded data described in 3.1.2 above is also finished and has been incorporated into the project software library. The code has been written in Visual Basic (VB) and preliminary plots are being generated.

#### 3.2.3 Reports and Maps

<u>Michigan Atlas</u> – In addition to the DEM data described above, most of the progress for this reporting period has come in the development of the Atlas software. This program is turning out to be a very effective tool for consolidating and displaying the project results. We have begun to release the program to a few selected operators in the Michigan Basin for evaluation and feedback. Atlas can be used effectively to determine if certain data exists for a specific well or a group of wells. Well locations are color-coded indicating which wells have the user-requested data.

### Subtask 3.3 Fracture Analysis

Literature data has been compiled on outcrop fractures in the Michigan Basin. Samples for petrographic examination have been collected and are being prepared for petrographic examination. These data will be digitized and plotted.

## *Task 4 Geochemical Studies*

### Subtask 4.1 Diagenesis

We now have retrieved diagenetic data for the entire central Michigan Basin (Table 1) These data were retrieved from the database of scanned driller's reports, using the program Atlas 3.0. We took reported "Top of porosity" data indicate diagenetic dolomite and plotted the distribution in the Basin (Figure 3).

### Subtask 4.2 Fluid Geochemistry

A database on subsurface fluid chemistry is being compiled for the Michigan Basin as part of a student project. Results will be presented in the annual report. Fluid analyses will be correlated with position in the Basin and plotted according to the formation of origin to see if any significant trends or correlations are present.

### Subtask 4.3 Hydrocarbons

2D and 3D maps showing the distribution of hydrocarbons in the Basin are being prepared.

## *Task 5. Technology Transfer (WBH & JRW)*

### Subtask 5.1 Public Outreach

#### 5.1.1 Internet (WWW)

A new Internet site for this project has been constructed on the Michigan Tech server. Additional information and reports continue to be placed on this site and the site at Western Michigan.

#### 5.1.2 Newsletter

The newsletter has been incorporated into the Web site to make it more readily available and to ease distribution problems and costs.

### Subtask 5.2 Workshops (WBH)

The PTTC workshop reported to being organized by Harrison and Wood and held in Mt. Pleasant this spring has been rescheduled for the Fall Eastern Section AAPG meeting in Kalamazoo. This is a better format and will reach more interested parties. Plans to distribute a project DVD ROM are being considered.

### Subtask 5.3 Meetings

#### 5.3.1 DOE Contractor Meetings

None scheduled

#### 5.3.2 National and Regional Meetings

Project personnel will attend the annual AAPG meeting in Denver, CO in June, 2001 and 1 paper will be presented.

Project personnel will also attend and participate in the Eastern Section AAPG meeting this September in Kalamazoo, MI. Harrison is one of the convenors and has scheduled a section devoted to the Dundee Formation in Michigan. Some results from this study will be presented there. (Also at the included workshop, see above.)

## CONCLUSIONS

This is the last report before the final report and the overall status of the project is good. Several projects have produced results that exceed original expectations, notably the DEM task, the databases and the visualization. The fracture study is on track but needs to be pulled together. To achieve this, two meetings, one in June and another in September have been scheduled to bring the team together in a neutral site to focus on the final report. The overall project is still on schedule and is still meeting all major goals. However attention has to be directed toward the geochemical and hydrology goals.

The Atlas program has emerged as a particularly strong contribution from the project and efforts will be made to publicize and distribute it along with the project databases. The DEM data and lineation models have also drawn interest from industry both from the approach and results points of view. We will continue to work on these aspects even after the termination of the project since they have potential to continue to grow. At present the Atlas program does not incorporate the DEM data, but that is technically possible if a suitable display medium can be found. Efforts to write code to do this have been marginally successful but so far are not up to acceptable standards. Work will continue on code development.

The acquisition of a landgrid (Figure 4) for Michigan has greatly contributed to the essentially completed the data cube for the Michigan Basin. The landgrid allows data from the project's digital database to be presented in the standard industry practice of maps keyed to the section-township-range system. Conversion of the landgrid for the entire state of Michigan to latitude-longitude put it in the same units as the rest of the database. It should also be possible to add capability to Atlas that will convert footage calls to lat-long coordinates and visa versa.

Sufficient digital data has been collected to begin analysis of basin scale. In the next period we expect to have structure contour maps completed for all the key horizons in the Michigan Basin. The work done on the Dundee Formation shows "stacked" contours indicative of large-scale faults. We will see if these patterns are present in formations above and/or below the Dundee.

Work is still continuing on mapping the Top of Porosity in the Basin, as well as data for hydrocarbon shows. This is time-consuming since the data have to be read off the driller's reports or scout tickets. Scanning the images and incorporating them into the Atlas program has greatly facilitated this work.

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## FIGURE CAPTIONS

**Figure 1**. Map of Michigan Basin with county outlines showing progress on scanning driller's reports. Scanning is complete for Arenac, Isabella, Lapeer, Montcalm, and Tuscola Counties. Other counties are partially scanned.

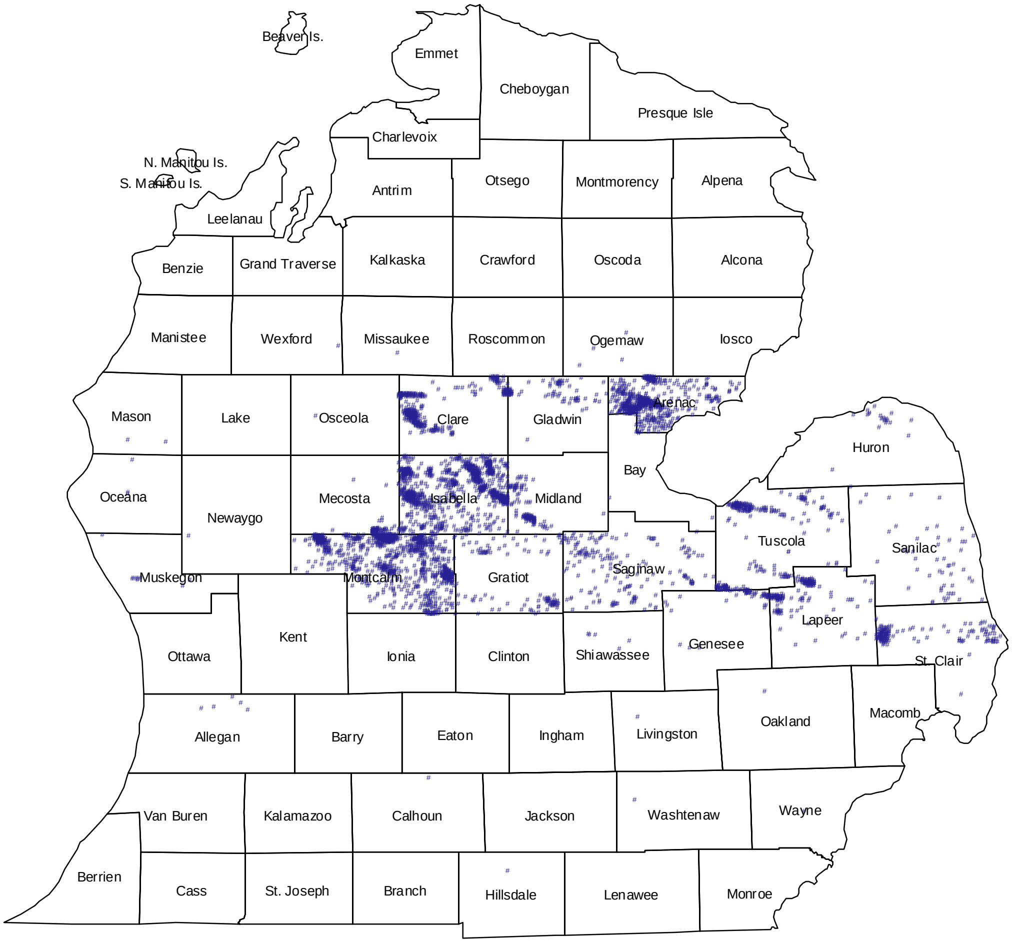
**Figure 2**. Stratigraphic column for the central Michigan Basin showing location of Dundee Formation (Middle Devonian).

**Figure 3.** Distribution of dolomite reservoirs in the Michigan Basin

**Figure 4.** Illustration of the Michigan landgrid for Isabella County, Michigan

**Figure 1**. Map of Michigan Basin with county outlines showing progress on scanning driller's reports.

(Scanning is complete for Arenac, Isabella, Lapeer, Montcalm, and Tuscola Counties. Other counties are partially scanned.)

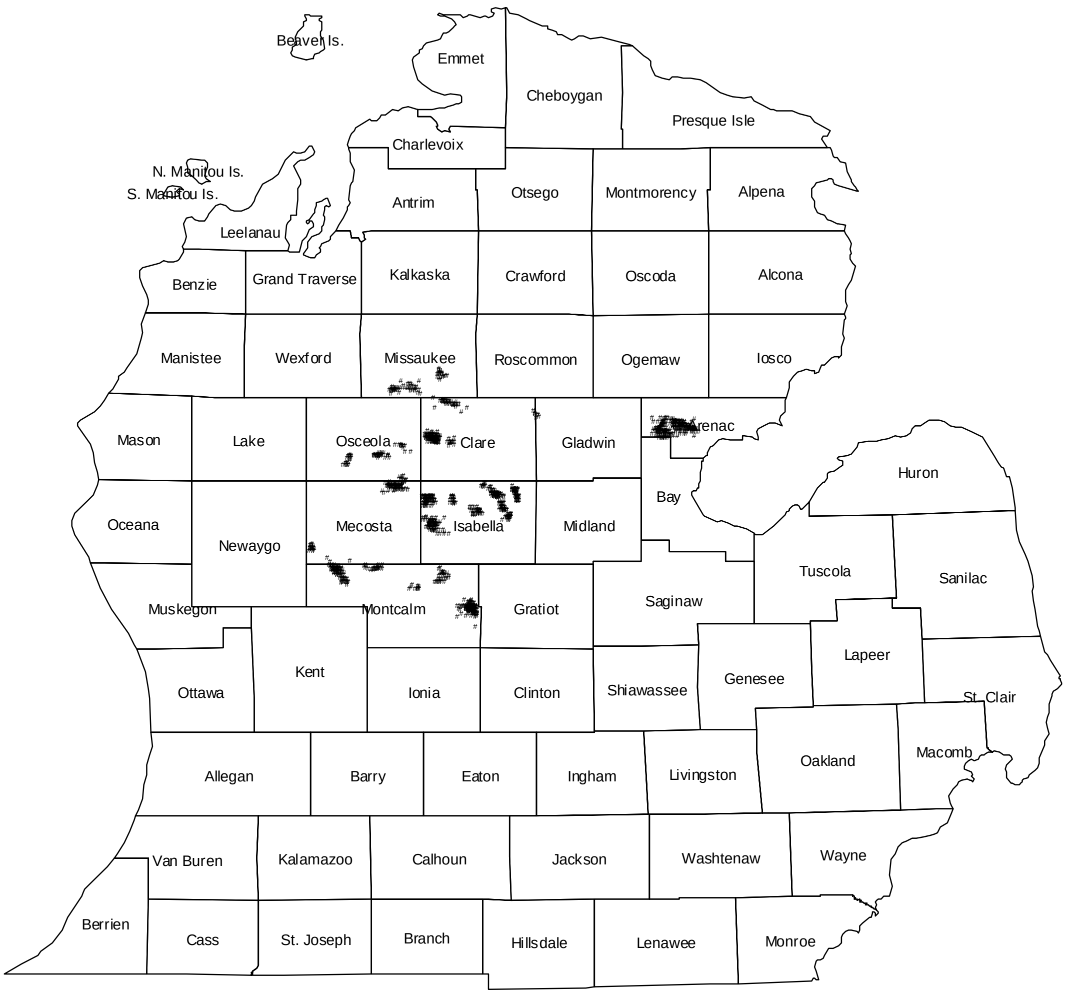



Driller Report Scanning Progress (April 2001)

**Figure 2.** Stratigraphic column for central Michigan Basin showing location of Dundee Formation (Middle Devonian)

| PERIOD | EPOCH | SEQUENCE | Rock Groups | Formations | Lithology |
|---|---|---|---|---|---|
| QUATERNARY | | | | Red Beds | |
| JURASSIC | | ABSAROKA | | Grand River Fm. | |
| PENN. | LATE | | | Saginaw Fm. | |
| | EARLY | KASKASKIA | GRAND RAPIDS | Bayport Ls. | |
| MISS. | LATE | | | Michigan | |
| | | | | Marshall Fm. | |
| | EARLY | | | Coldwater Sh. | |
| | | | | Ellsworth Sh (W.) | |
| MISS./DEV UNDIVIDED | | | | Antrim Sh. (E. ) | |
| DEVONIAN | LATE | | TRAVERSE | Squaw Bay Ls | |
| | MIDDLE | | | Alpena Ls | |
| | | | | Bell Sh | |
| | | | | Rogers City Ls | |
| | | | | Dundee Ls | |
| | | | DETROIT RIVER | Lucas Fm. | |
| | | | | Amherstburg Fm. | |
| | | | | Bois Blanc Fm. | |
| | | | | Garden Island Fm. | |
| | EARLY | TIPPECANOE | BASS ISLANDS | | |
| SILURIAN | LATE | | SALINA | G Unit | |
| | | | | F Evaporites | |
| | | | | E Unit | |
| | | | | D Evaporite | |
| | | | | C Unit | |
| | | | | B Evaporite | |
| | | | | A-2 Carbonate | |
| | MIDDLE | | | A-2 Evaporite | |
| | | | | A-1 Carbonate | |
| | | | | A-1 Evaporite | |
| | | | NIAGARA | Brown Niagaran | |
| | | | | Gray Niagaran | |
| | | | | White Niagaran | |
| | | | | Clinton Sh. | |
| | | | CATARACT | Cabot Head Sh | |
| | | | | Manitoulin Dol. | |
| | | | RICHMOND | Queenston Sh | |
| | EARLY | | | | |
| ORDOVICIAN | LATE | | EDEN | Utica Sh | |
| | | | | Collinwood Sh. | |
| | | | TRENTON - BLACK RIVER | Trenton Group | |
| | | | | Glenwood | |
| | MIDDLE | | | St. Peter Ss | |
| | | SAUK | PRARIE du CHIEN | Shakopee Dol. | |
| | | | | New Richmond Ss. | |
| | EARLY | | | Oneota Dol. | |
| | | | | Trempealeau Fm. | |
| CAMBRIAN | LATE | | LAKE SUPERIOR | Franconia Ss. | |
| | | | | Dresbach Ss. | |
| | | | | Eau Claire Fm. | |
| | | | | Mt. Simon Ss. | |
| | EARLY & MID. | | | Jacobsville Ss. | |

**Figure 3.** Distribution of dolomite reservoirs in the Michigan Basin




Top of Dundee Porosity Distribution

**Figure 4.** Illustration of the Michigan landgrid for Isabella County, Michigan

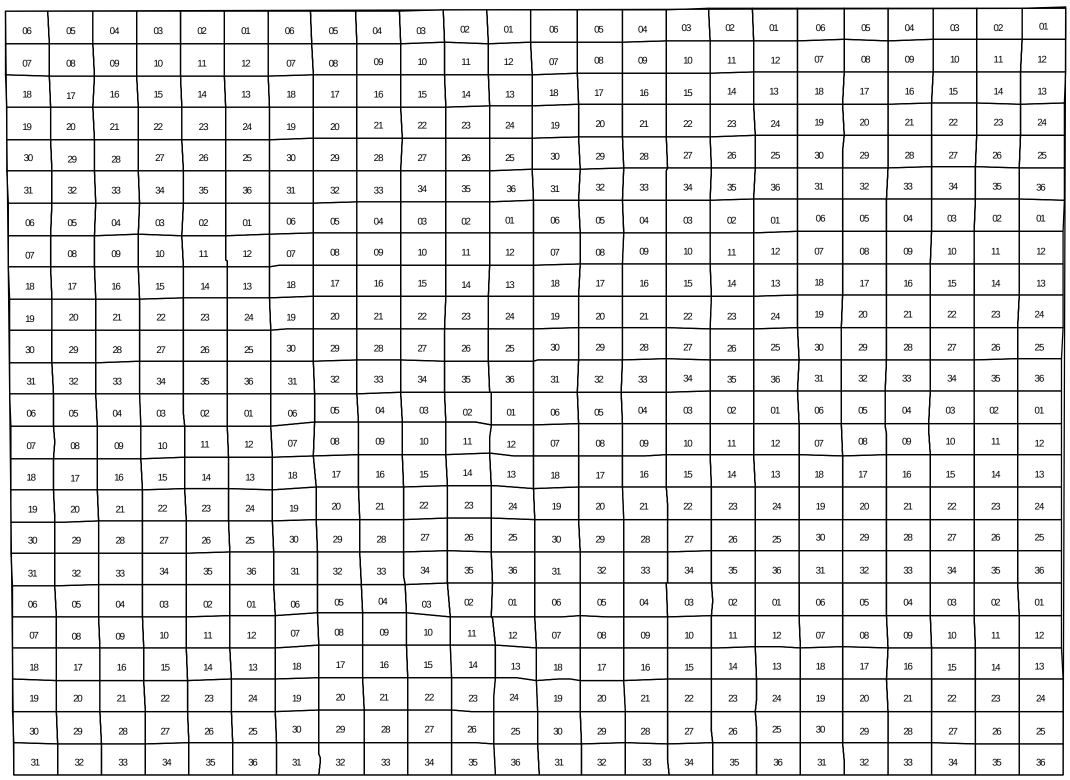


Table 1. List of Project Fields

| MICHIGAN BASIN | | | | |
|---|---|---|---|---|
| | | | | |
| 1 | AKRON | | 51 | LEROY |
| 2 | ALBION-SCIPIO | | 52 | LIME LAKE |
| 3 | BEAR LAKE 22 | | 53 | LYON 34 |
| 4 | BELLE RIVER MILLS | | 54 | MANISTEE 24 |
| 5 | BELLY ACHERS | | 55 | MCBAIN |
| 6 | BLUE LAKE 18 | | 56 | NEW LOTHRUP |
| 7 | BROOMFIELD | | 57 | NORTH ADAMS |
| 8 | BURDELL | | 58 | NORTH CHESTER 18 |
| 9 | CALVIN 28 | | 59 | NORTHVILLE |
| 10 | CAPAC | | 60 | NORWICH |
| 11 | CAT CREEK | | 61 | OIL SPRINGS POOL |
| 12 | CATO | | 62 | ONONDAGA 21A |
| 13 | CEDAR | | 63 | OVERISEL |
| 14 | CHARLTON 19 PROJECT | | 64 | PEACOCK |
| 15 | CHATHAM A POOL | | 65 | PENNFIELD 35 |
| 16 | CHESANING 20 | | 66 | PETERS |
| 17 | CLAYBANKS 2 | | 67 | PETROLIA EAST POOL |
| 18 | CLAYTON | | 68 | PORTER |
| 19 | COLDWATER | | 69 | PROSPER |
| 20 | COLUMBUS | | 70 | PROSPER SOUTH |
| 21 | CRANBERRY LAKE | | 71 | RAY |
| 22 | CRANBERRY LAKE EAST | | 72 | REDDING |
| 23 | CRYSTAL | | 73 | REED CITY |
| 24 | CURRIE | | 74 | REYNOLDS |
| 25 | DEEP RIVER | | 75 | RIVERSIDE |
| 26 | DEERFIELD | | 76 | ROSE CITY |
| 27 | DOUGLASS | | 77 | ROSEBUSH |
| 28 | EATON RAPIDS 7 | | 78 | SALEM |
| 29 | ENSLEY | | 79 | SAUBLE |
| 30 | ENTERPRISE | | 80 | SHAVER |
| 31 | EVART | | 81 | SHERMAN |
| 32 | FALMOUTH | | 82 | SIX LAKES |
| 33 | FLETCHER POND | | 83 | SKEELS |
| 34 | FORK | | 84 | SOUTH BUCKEYE |
| 35 | FOWLERVILLE | | 85 | SOUTH BUCKEYE |
| 36 | FREEMAN | | 86 | SOUTH CHESTER 21 |
| 37 | GILMORE | | 87 | SOUTH VIENNA 30 |
| 38 | GOODWELL | | 88 | STONEY LAKE |
| 39 | HANDY 27 | | 89 | STONEY POINT |
| 40 | HARDWOOD POINT | | 90 | SYLVAN |
| 41 | HARDY DAM | | 91 | UNADILLA 2 |
| 42 | HEADQUARTERS | | 92 | VERNON |
| 43 | HILLMAN POOL | | 93 | WAYLAND |
| 44 | IOSCO 20 | | 94 | WEST BRANCH |
| 45 | IOSCO 24 | | 95 | WHITE OAK 15 |
| 46 | ISABELLA | | 96 | WILLIAMS |
| 47 | KAWKAWLIN | | 97 | WINTERFIELD |
| 48 | KIMBALL-COLLINVILLE POOL | | 98 | WISE |
| 49 | LAKE GEORGE | | 99 | WOODVILLE |
| 50 | LEATON | | 100 | |

Table 2. Formations with Largest Number of Top Picks in the Michigan Basin

| Formation Code | Formation Name | Aangstrom | DNR | MTU | Total | w/o Dups |
|---|---|---|---|---|---|---|
| 701GCDF | Base of Glacial Drift | 38,720 | 23,870 | 1,408 | 63,998 | 45,623 |
| 319ANRM | Antrim Shale | 32,599 | 22,703 | 818 | 56,120 | 38,690 |
| 302TRVR | Traverse Formation | 27,841 | 21,842 | 983 | 50,666 | 35,991 |
| 302TRVRL | Traverse Limestone | 29,599 | 17,979 | 760 | 48,338 | 35,759 |
| 351CLDR | Coldwater Limestone | 28,699 | 15,785 | 1,016 | 45,500 | 32,760 |
| 302DNDE | Dundee | 23,539 | 14,791 | 1,500 | 39,830 | 26,114 |
| 351SNBR | Sunbury | 19,215 | 13,609 | 613 | 33,437 | 23,168 |
| 352MRLL | Marshall Sandstone | 17,594 | 6,495 | 1,070 | 25,159 | 18,481 |
| 351CLDRR | Coldwater Redrock | 15,443 | 4,010 | 264 | 19,717 | 17,836 |
| 351BERE | Berea | 16,705 | 5,953 | 386 | 23,044 | 17,610 |
| 302DRRV | Detroit River | 14,271 | 7,409 | 83 | 21,763 | 15,750 |
| 319ELSR | Ellsworth Shale | 11,401 | 7,230 | 153 | 18,784 | 14,736 |
| 302BELL | Bell Shale | 11,225 | 8,513 | 490 | 20,228 | 13,441 |
| 253SLGU | Salina G Unit | 11,052 | 9,054 | 67 | 20,173 | 13,230 |
| 253SLA2 | A2 Carbonate | 10,452 | 9,294 | 100 | 19,846 | 12,772 |
| 252NGRNB | Brown Niagaran | 10,367 | 9,103 | 11 | 19,481 | 12,710 |
| 253BSIL | Bass Island | 10,361 | 8,760 | 74 | 19,195 | 12,498 |
| 353MCGN | Michigan | 10,294 | 3,783 | 950 | 15,027 | 11,757 |
| 403SGNW | Saginaw | 10,413 | 3,497 | 1,339 | 15,249 | 11,675 |
| 302BBLC | Bois Blanc | 9,155 | 7,984 | 72 | 17,211 | 11,343 |
| 253SLCU | Saline C Unit | 8,965 | 8,533 | 80 | 17,578 | 11,249 |
| 253SLBUS | Salina B Evaporite/Salt | 8,935 | 7,533 | 103 | 16,571 | 11,024 |
| 253SLA2E | A2 Evaporite/Salt | 8,433 | 8,221 | 88 | 16,742 | 10,633 |
| 253SLA1 | A1 Carbonate | 8,402 | 8,287 | 84 | 16,773 | 10,613 |
| 252NGRNG | Gray Niagaran | 7,574 | 6,282 | 3 | 13,859 | 9,380 |
| 253SLEU | Salina E Unit | 5,723 | 7,822 | 72 | 13,617 | 9,290 |
| 353STRY | Stray Sandstone | 8,123 | 2,156 | 1,409 | 11,688 | 8,584 |
| 319BDFD | Bedford Shale | 5,893 | 3,732 | 66 | 9,691 | 7,445 |
| 253SLBU | Salina B Unit | 2,936 | 5,946 | 4 | 8,886 | 7,208 |
| 302AMBG | Amherstburg | 4,773 | 5,929 | 69 | 10,771 | 7,179 |
| 353BRLM | Brown Limestone | 6,591 | 1,443 | 899 | 8,933 | 6,936 |
| 253SLDU | Salina D Unit | 6,917 | | 3 | 6,920 | 6,917 |
| 253SLDUS | Salina D Evaporite/Salt | | 6,598 | 48 | 6,646 | 6,615 |
| 353BPRT | Bayport Limestone | 5,853 | 1,882 | 832 | 8,567 | 6,548 |
| 253SLA1E | A1 Evaporite/Salt | 5,214 | 4,769 | 74 | 10,057 | 6,465 |
| 253SLFU | Salina F Unit | 3,301 | 3,809 | 13 | 7,123 | 6,082 |
| BRBD | Berea-Bedford | | 5,483 | | 5,483 | 5,483 |
| 319ANRMD | Dark Antrim | 1,469 | 4,897 | 6 | 6,372 | 5,430 |
| 352MRLLR | Marshall Redrock | 4,972 | | 273 | 5,245 | 5,091 |
| 302SYLN | Sylvania | 4,394 | 1,821 | 45 | 6,260 | 4,945 |
| 252CLNN | Clinton Shale | 4,191 | 2,436 | 84 | 6,711 | 4,618 |
| 403PARM | Parma Sandstone | 3,497 | 932 | 511 | 4,940 | 3,921 |
| 302RCFD | Richfield Zone | 3,416 | 1,727 | 41 | 5,184 | 3,830 |
| 202TRNN | Trenton | 3,395 | 2,026 | 69 | 5,490 | 3,715 |
| 203CNCN | Cincinnatian | 3,199 | 1,869 | 85 | 5,153 | 3,538 |
| 559JRSCR | Red Beds | 2,924 | 425 | 715 | 4,064 | 3,245 |
| 302DRRVA | Detroit River Anhydrite | | 2,999 | 58 | 3,057 | 3,040 |
| 202BKRV | Black River | 2,696 | 1,737 | 69 | 4,502 | 3,016 |
| 203UTIC | Utica Shale | 2,688 | 1,173 | 76 | 3,937 | 2,948 |
| 353TPGP | Triple Gypsum | 1,924 | 1,330 | 323 | 3,577 | 2,352 |
| | TOTALS | 495,343 | 333,461 | 18,359 | 847,163 | 609,284 |

# APPENDIX 1. Autoplot – A Program to Automate Contour Plots Using Surfer ©

### *Automated Plots*

This project has reached the point where it has generated data for a large number of oil and gas fields (~100), each with multiple surfaces that need to be contoured in order to be interpreted. This is a daunting task that in the past could only be done once, if at all. Today, however, it is possible to use products such as Surfer©, a 2D and 3D plotting package, to handle the plotting details automatically. AUTOPLOT is a software program that we have written to handle this chore.

Surfer© builds grid files, 2D and 3D plots, contour maps, etc., which are all needed to interpret and model the geologic data in the Atlas Database. Surfer has defined objects, methods, and properties, which can be accessed by MS Visual Basic© to automatically generate plots. AutoPlot has been written to import the MS Access tables exported from another project software product, ATLAS, and create multiple surfer files with the plotting features needed to portray each oil field defined in the Atlas Database. AutoPlot then creates a composite plot of 6 maps involving different aspects of the Top of Dundee and Top of Dundee Porosity. Optionally, it will also create sets of 2D and 3D contour maps of the Top of Dundee for the oil fields that do not have a value for Top of Dundee Porosity.

### *Michigan Atlas Database*

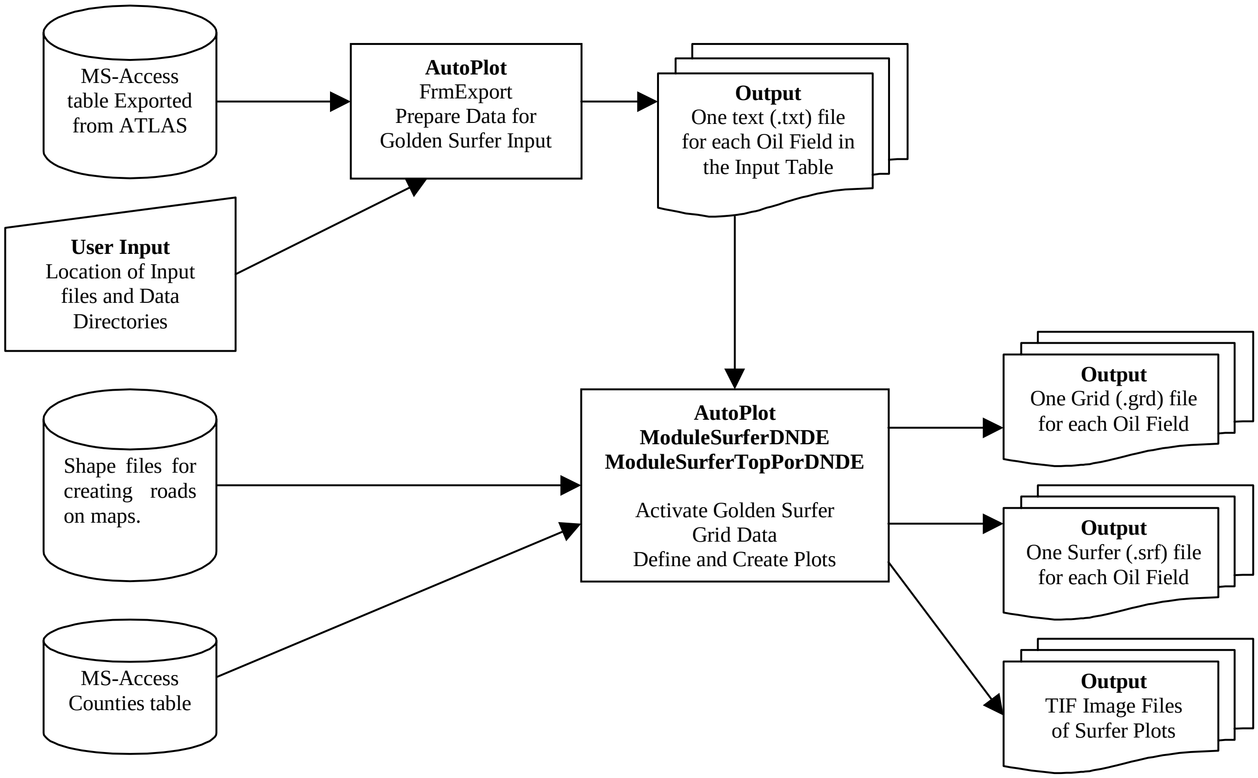
The Atlas Database contains Well Information, including formation tops and some Top of Dundee Porosity picks for oil, gas, and brine disposal wells in the state of Michigan from Permit number 00001 to 52125. This data has been acquired from scout tickets, driller's reports, and well logs to obtain data. It has been compiled into one MS-Access database.

### *Exporting data using ATLAS 3.2*

The ATLAS 3.2 Visual Basic software package accesses the ATLAS Database, maps the wells, and displays information about the wells. ATLAS has an export feature, which outputs data according to user selections. Users plot wells by county, field, or selected area. When one or more formation types are selected, ATLAS outputs a separate MS-Access database table either in a new or existing database. Permit number, Oil field, County, Latitude, Longitude, Kelly Bushing, Top of Dundee Porosity, and the subsea depths of the selected formations are exported.

(Note: ATLAS has been coded so that it does not export records with a null Kelly Bushing value. All other records will have null values (usually –99999) for non-existent data. )

### *AutoPlot Program Flow*




### *AutoPlot Input*

The following items are the AutoPlot user input parameters and the steps to create an input file for AutoPlot using the project ATLAS program.

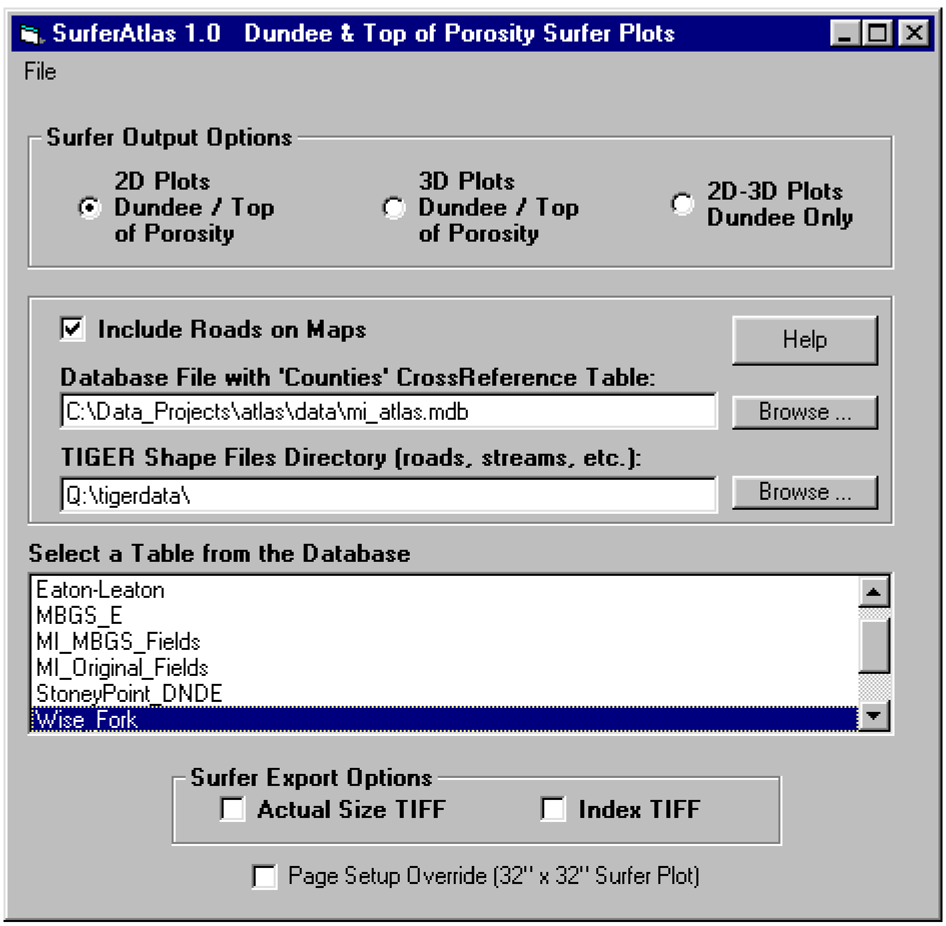
1. **Dundee Formation Table**
   (MS-Access Database Table is generated in ATLAS using the Export feature with 302DNDE as the selected formation. The table is named by the user.)
   **Permit**
   **OilField**
   **County**
   **Latitude**
   **Longitude**
   **KB**
   **TopPorosityDNDE** (in Subsea Depth)
   **302DNDE** (in Subsea Depth)

2. **Counties Table**
   (MS-Access Table in Atlas Database; Only required if plotting Roads)
   **County**
   **FIPSCode**
   **CountyCode**
   **StateAbbr**
   **StateFIPS**

3. **User Defined Input Parameters**

- Option Selection:
  2D Plots (Dundee/Top of Porosity)
  3D Plots (Dundee /Top of Porosity)
  2D-3D Plots (Dundee Only)
- Option to Include Roads on Plot
  Path to database that holds Counties table for identifying road files
  Path to Directory that contains TIGER/Census shape files for roads
- Path to database that holds Dundee Formation Table
- Path to Directory where .txt, .grd, .srf files will be written
- Surfer Export Options
  Actual Size TIF
  Index TIF
- Page Setup Override Option (Forces page size to 32"x32")

## 4. County Shape files for roads (point to directory)



### *Convert Atlas Export Table to Surfer Format*

The following steps convert the ATLAS table to a format compatible with Surfer ©.

1. Read the Dundee Formation Table and create a text file for each Oil Field.
2. Save Oil Field Names and County Names in an array
3. Loop through the Oil Fields to create the Surfer Plots

   **Oil Field Text Files**
   One Text file for each Oil Field (*.txt)
   If 302DNDE or TopPorosityDNDE = -99999 (null value) then
      Limestone Cap Thickness = -99999
      **Column A:** Longitude
      **Column B:** Latitude
      **Column C:** 302DNDE
      **Column D:** TopPorosityDNDE
      **Column E:** Limestone Cap Thickness
      **Column F:** Permit
      **Column G:** *Symbol Code for 302DNDE
      **Column H:** *Symbol Code for TopPorosityDNDE
      **Column I:** *Symbol Code for Limestone Cap Thickness

      ***Symbol Code is a numeric index that indicates a triangle symbol for null values and a circle for a well location with valid data.

### *Create Surfer Plots*

Finally, follow these steps to create the Surfer plots.

For each Oil Field,

1. Import Roads shape file as a Base map
   Find County in Counties Table and construct shape file name with State and County FIPS codes
   **ModuleSurferTopPorDNDE:** Import once for roads to be displayed on upper left map (Top of Dundee)
   **ModuleSurferDNDE:** Import twice for roads to be displayed on both the 2D and 3D maps

2. Create a Wireframe map for each map in the plot to define the scale, rotation, tilt, and base shape of the map.

3. Create a Contour map for each map in the plot to define the color levels and contours of the overlying map.

4. Create a Post map for each map in the plot to define Well Locations.

5. Scale the Maps to fit the paper size.
   **Paper Size** must be defined in Page Setup by selecting a printer and page size. This paper size is used to automatically create the correct plot size for the Surfer Plots, even though printing is done from within Surfer and not from AutoPlot. The Page

Setup Override check box was added so that large plots (32"x32") can be created on computers that are not connected to a large plotter.

**Longitude and Latitude** scaling is done by adjusting the Maps Per Unit for the X and Y axes using the following formula:
MapsPerUnitY = COS (center Latitude of map) * MapsPerUnitX

6. Order the layers from bottom to top in this order:
   Contour (overlying map)
   WireFrame (z contour lines only of base)
   Base (Roads)
   Post (Well Locations)

### *Surfer Grid and Plot files*

The following files are created by Surfer© and written to the local hard drive.

1. **Grid Files (*.grd)**
   Created by the GridData function in Surfer with the following options:
   - **datafile:** Oil Field Text File
   - **zcol:** 3 for 302DNDE; 4 for TopPorosityDNDE; 5 for Limestone Cap Thickness
   - **exclusion filter:** z=-99999
   - **DupMethod:** srfDupMaxZ (Choose the shallowest depth for Z)
   - **Algorithm:** srfKriging

2. **Surfer Plots (*.srf)**
   **ModuleSurferTopPorDNDE** creates a plot of six 2D or 3D contour maps (See Figure A1.1 for Sample AutoPlot Output)
   (For Oil Fields with values for Top of Dundee Porosity)

1. Top of Dundee
2. Top of Porosity
3. Top of Dundee Overlaid by Top of Porosity
4. Limestone Cap Thickness
5. Top of Dundee Overlaid by Limestone Cap Thickness
6. Top of Porosity Overlaid by Limestone Cap Thickness

**ModuleSurferDNDE** creates a plot of 2 contour maps
(For Oil Fields with no Top of Dundee Porosity values)

1. Top of Dundee (3D)
2. Top of Dundee (2D)

**Figure A1.1** Sample 3D Output from AutoPlot.