February 18, 2001

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National Energy Technology Center
U.S. Department of Energy
P.O. Box 10940
Pittsburgh, PA 15236

RE: Semi-Annual Technical Progress Report for DE-AC26-98BC15100 for period ending September 30, 2001

Enclosed is the sixth Semi-Annual Technical Progress Report for the period ending September 30, 2001 for the project titled ADVANCED CHARACTERIZATION OF FRACTURED RESERVOIRS IN SHALLOW SHELF CARBONATE ROCKS: THE MICHIGAN BASIN. The DOE project number is DE-AC26-98BC15100, and the reporting period is from April 1, 2001 through September 30, 2001. This submission contains 1 hardcopy and 1 electronic copy on a CD-ROM.

If you have any questions, please contact me at (906) 487-2894 or email jrw@mtu.edu, or contact Carol Asiala at (906) 487-2033, email cjasiala@mtu.edu .

Sincerely,

(Original Signed by James R. Wood)

James R. Wood

Att: Semi-Annual Report

cc: A. Quinn, MTU #970820

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

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ABSTRACT

This project is now in a 1-year continuation for the purpose of completing and summarizing the major results of the study.

The purpose of the study was to collect and analyze existing data on the Michigan Basin for fracture patterns on scales ranging form thin section to basin. The data acquisition phase has been successfully concluded with the compilation of several large digital databases containing nearly all the existing information on formation tops, lithology and hydrocarbon production over the entire Michigan Basin. These databases represent the cumulative result of over 80 years of drilling and exploration.

Plotting and examination of these data show that contrary to most depictions, the Michigan Basin is in fact extensively faulted and fractured, particularly in the central portion of the basin. This is in contrast to most of the existing work on the Michigan Basin, which tends to show relatively simple structure with few or minor faults. It also appears that these fracture and faults control the Paleozoic sediment deposition, the subsequent hydrocarbon traps and very likely the regional dolomitization patterns.

Recent work ahs revealed that a detailed fracture pattern exists in the interior of the Central Michigan Basin, which is related to the mid-continent gravity high. The inference is that early Precambrian, (~1 Ga) rifting events presumed by many to account for the gravity anomaly subsequently controlled Paleozoic sedimentation and later hydrocarbon accumulation. There is a systematic relationship between the faults and a number of gas and oil reservoirs: major hydrocarbon accumulations consistently occur in small anticlines on the upthrown side of the faults.

The main tools used in this study to map the fault/fracture patterns are detailed, close-interval (CI = 10 feet) contouring of the formation top picks accompanied by a new way of visualizing the data using a special color spectrum to bring out the third dimension. In addition, recent improvements in visualization and contouring software were instrumental in the study.

Other accomplishments of this past reporting period include obtaining a complete landgrid for the State of Michigan and further processing of the high and medium resolution DEM files. We also have measured new fluid inclusion data on dolomites from several fields that suggest that the dolomitization occurred at temperatures between 100 and 150 C. Finally, we have extracted the lithologic data for about 5000 wells and are in the process of integrating this data into the overall model for the Michigan Basin.

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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 7672 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

The main focus of this study is on the fracture and fault patterns in the Michigan Basin and their relation to hydrocarbon deposits. Michigan is a mature basin with abundant data that could perhaps serve as an analog for other intercratonic basins, such as the Williston and Illinois Basins.

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.

Previously we reported that there are two types of large-scale fractures in the Michigan Basin: those associated with anticlines and those indicated by hydrothermal dolomitization. We now report that many of these fractures have been identified as faults with substantial vertical displacement. This identification is based on the tight packing of structural contours and by the presence of long, linear pods of dolomite mapped in the subsurface. In addition to the large faults mapped in the southeastern quadrant of the Michigan Basin and in the Thumb area, we have now mapped an extensive array of faults in the Central Michigan 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.

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. 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

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. In this report, a summary of progress for Chapter 3 will be presented.

Chapter 1. Introduction – History and Background of the Michigan Basin

THE MICHIGAN BASIN

The Michigan Basin is a large (~200,000 km2) ovate basin, approximately 200 mile East-West and 300 miles North-South. It is similar in some respects to other intercratonic basins such as the Williston and Illinois Basins. These basins are characterized by having well-defined depocenters rather than depositional axes, such the Denver and Anadarko Basins. The Michigan Basin is bounded by the Wisconsin highlands to the west, the Precambrian Algonquin, the Ordovician Kankakee and post-Silurian Findlay arches to the south and the Precambrian rocks of the Upper Peninsula to the North. The arches were all low relief and were in place by the end of the Silurian.

GRAVITY ANOMALY

A major (positive) gravity anomaly (Figure 1) runs through the center of the Michigan Basin. It is part of a larger gravity high that runs up to the Upper Peninsula, then turns and runs southwest to form the mid-continent gravity high. This is clearly a major structural feature and has been postulated to play a role in the development of the Michigan Basin. It is widely regarded as representing a “failed arm” of a transcontinental rift zone, similar in some respects to the present day Red Sea – East African Rift System. Very few wells have penetrated the rift zone all the way to the Precambrian; the McClure-Sparks well in Gratiot County is the only deep test in Michigan to have done so. This well penetrated the complete sedimentary section all the way to the Precambrian (Keweenawan) Red Beds.

BASEMENT STRUCTURE

The basement structure is of critical important in the development of the Michigan Basin, including the sedimentation and subsequent folding, fracturing and faulting. It is generally thought to consist of a melange of various terranes juxtaposed and fused in the

Precambrian but well control is largely lacking, particularly in the central portions of the Basin and only a few wells in total penetrate to the Precambrian, most around the periphery of the Basin. The Grenville Metamorphic Front extends from Ontario into Eastern Michigan and gneiss and schist are found in the basement rocks in Michigan east of the Grenville Front. Rocks to the west are granite and granite wash, while basement rocks to the north (in the Upper Peninsula) are quartzite. The Sparks well is the only Precambrian test on the gravity anomaly and encountered Keweenawan red beds.

SEDIMENTOLOGY

The stratigraphic section for the State of Michigan extends from the late Precambrian to late Jurassic (Figure 2). The sedimentary record can be divided into three main stages, clastics, chemical sediments including carbonates and evaporites, and back to fine-grained clastics. All stages are Paleozoic. Stage 1 is dominated by clastic sedimentation, mainly sandstones, that begins into the Early Cambrian with the Jacobsville Sandstone, and ends in the Early Ordovician with the St. Peter Sandstone. Stage 2 is marked by the deposition of a thick section of chemical sediments, beginning with carbonates in the Early-to-Middle Ordovician Trenton-Black River, proceeding through the Silurian Evaporites and ending with the Late Devonian Squaw Bay Limestone. The Late Devonian Antrim Shale signals the beginning of the clastic-dominated 3rd stage that ends in the Late Jurassic with the Red Beds on top of the Late Pennsylvanian Grand River Formation. The cycle is clastics to chemical sediments (evaporites) back to clastics. Summing the maximum thickness for all formations yields about 18000 feet for the aggrate thickness of sedimentary fill in the Michigan Basin, a value that agrees with the aggrate thickness found in the State's deepest well, the McClure-Sparks in Gratiot County. The McClure-Sparks penetrates the entire section from Jurassic to Precambrian.

One of the most striking characteristics of the Michigan Basin sedimentation is the large volume of chemical sediments (carbonates, sulfates and salts) relative to clastic materials (sandstones and shales). The Salina (Middle Silurian) and the Detroit River Early Devonian Formations are the principal times of salt deposition in which over 3150 feet of salts were deposited in the Salina and over 1450 feet in the Detroit River. If the maximum thickness of all chemical sediments (carbonates, sulfates and chlorides) is compared to the aggregate maximum thickness of all the sandstones and shales, the ratio is about 10:1, chemical sediments to clastics.

Chapter 2. Data and Databases

One of the major tasks of this project was to obtain a comprehensive database of the Michigan subsurface. To that end we have compiled over 500,000 top picks covering 50+ horizons (Formations and marker beds) over the entire basin. To date, over 53,000 wells have been drilled in Michigan for gas and oil and most of these report anywhere from 1 or 2 to as many as 20+ formation tops. These data were originally compiled in "driller's reports" and scout tickets, typewritten data that covers the years 1922 to the present. The challenge was to obtain these documents and then extract the data in a digital form. We have largely accomplished that task and can now turn to the second major task of this proposal, analyzing and interpreting the data.

Although a number of databases were constructed for this project, the relevant data can all be summarized in a single table that contains the surface location and the subsurface

elevations for all formations. This table contains 640,000 records, each corresponding to a single top pick. Dividing by about 30 major mappable horizons, this gives an average of about 10,000 data points for each major horizon. Table 2 summarizes the data by formation and actual data count. Most of the following discussion is based on various plots and displays of these data. However it should be mentioned that work is still proceeding to correct the data since it appears that a significant number (~10% ?) of the recorded entries were in error, either from the original data sheets or during transcription. As a result, the maps displayed in this report may undergo further correction and revision with time. However, it is thought that the bulk of the data, probably 95 + %, is now essentially correct.

Chapter 3. Faults and Fractures in the Michigan Basin

The thick blanket of glacial drift deposits has prevented detailed mapping of the bedrock geology of the Michigan Basin from outcrop. Almost all the data available for reconstruction of the State geologic map is derived from subsurface data, which is fortunately available in abundance. Unfortunately, the nature of the data is such that it is difficult to map linear features such as faults and fractures, particularly over long distances. The result is that only a few faults are ever displayed on basin-scale maps of the Michigan Basin. Most workers in the Basin would agree that the Howell Anticline and the associated Lucas-Monroe structures in the Southeast corner of the Basin are well-defined features. Almost no other basin-wide faults have been consistently recognized.

However, plots of the Formation Tops data reveals a number of generally Northwest-Southeast trending lineations that are best interpreted as faults (Figure 3). They are basin-scale ion length (10s of kilometers) and occur both near the basin depocenter and on the basin margins. These are previously unmapped faults but are clearly present in maps of formations ranging from the Upper Devonian Dundee Formation to the Late Mississippian Marshall and perhaps younger. Formations older than the Detroit River (Middle Devonian) have relatively few penetrations in the basin center and so do not define the faults as well. In fact, there is some doubt that the faults penetrate to the basement at all, but the interpretation favored here is that they do. Detailed mapping of formation tops also reveals the presence two interior sub-basins and as well as two well-developed anticlines to the Northeast and a set to the Southwest and a number of smaller anticlines aligned along definite trend lines (Figure 4).

High-resolution contour or surface relief maps (SRMs) were used to map these structural trends (Figure 6), using the formation tops data. By trial and error, it was determined to be necessary to plot the data for the entire State of Michigan on a 1000 x 1000 grid (e.g. approximately 200 miles in both East-West and North-South directions or about 0.2 mile or 1000 feet node-to-node) in order to obtain adequate fault resolution. However, the best results were obtained by plotting on a 3000 x 3000 grid (approximate spacing of 330 feet node to node)). 330-foot spacing turns out to be nearly the same as 5-acre spacing. In Michigan, most development is on 10-acre or greater spacing, so that a grid equivalent to 2.5-acre spacing is about the maximum density that can be resolved by the closest spacing of any data points. A 3000 x 3000 point grid would appear to be the optimal resolution over the entire Lower Peninsula of Michigan. A grid this dense is about 72 Mb in size. It seems likely that one reason these relatively large faults remained unnoticed until now was because the data were not plotted at sufficiently high resolutions. Lower

resolution maps tend to show that same lack of features that are apparent in most of the previous maps of the Michigan Basin.

The basic steps involved in manipulating the top pick data using Golden Software's Surfer © plotting package are:

1. obtain a digital file of formation top picks with surface latitudes and longitudes,
2. edit the file for errors
3. create a 1000 x 1000 grid over the entire State
4. create closely spaced contours (5-10 foot contour intervals) a shaded relief maps for further editing (e.g. spotting bad picks)
5. edit the dataset and eliminate the bad picks,
6. re-grid the data on a 3000 x 3000 node grid
7. again plot closely spaced contours and shaded relief maps
8. use the shaded relief map to pick the faults,
9. use Surfer's built-in digitizing capability to digitize the faults

Chapter 3. Relation of Faults and Fractures to Reservoirs

The basin-scale faults described here (Figure 4) are closely related to many gas and oil deposits in the Michigan Basin. A number of highly productive fields, usually shallow anticlines, lie close to the upthrown edge of the faults and tend to parallel the fault trace. It is likely that there is a causal relationship between the faults and the traps. Although there is no evidence for strike-slip (lateral) movement, the vertical movement on many faults exceed 300 feet and the stresses involved could have deformed the nearby strata enough to produce mild anticlinal folds. The association between faults and traps would appear to be sufficient to warrant examining the undrilled segments of the faults for the presence of hydrocarbons.

Chapter 4. Conclusions

The principal conclusions of this study are that the Michigan Basin is cut by numerous (12+) major faults lying below the glacial drift and below the topmost Jurassic sediments. The faults generally trend Northwest – Southeast. These faults ("lineations") are dominant features of the subsurface topography and are well documented from at least the Late Devonian (Dundee time) to the Mississippian. These faults carve out large depressions in the Central Michigan Basin and appear to be responsible for shallow anticlines that hold or held a significant portion of the hydrocarbons in the Michigan Basin.

An obvious question is "What is the origin of these large-scale faults?" One explanation, and perhaps the simplest, is that they are expression of deep-seated normal basement faults rooted in the Precambrian rift sequence. This explanation has been invoked for the Howell Anticline Fault and the Lucas-Monrow Faults to the South – Southeast of the Central Basin (Figure 5) and it seems natural to extend it to the Central Basin itself. In this model a typical horst-graben environment, similar to the U. S. Basin and Range or the East African Rift, is envisioned for the Michigan Precambrian, with later sediments draped over preexisting faults followed by relatively minor vertical movements during the Paleozoic.

Appendices

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 Denver in 2001 and will attend the Houston meeting in 2002.

We are now in the process of wrapping up this project, which has been extended to end in October 2002. 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.

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 2.3.1 above 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 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, dates spudded, drilled, and 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 (Table 2). 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 it 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

Michigan Atlas – 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 indicating diagenetic dolomite and plotted the distribution in the Basin.

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 last spring, was rescheduled for the Fall Eastern Section AAPG meeting in Kalamazoo. This was a better format and reached 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 attended the annual AAPG meeting in Denver, CO in June 2001 and 1 paper was presented.

Project personnel will also attend the annual AAPG meeting in Houston, TX in March 2002.

Project personnel also attended and participated in the Eastern Section AAPG meeting in September 2001 in Kalamazoo, MI. Harrison was one of the convenors and scheduled a section devoted to the Dundee Formation in Michigan. Results from this study were 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 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.

REFERENCES

"Oil and Gas Fields of the Michigan Basin" 1968, Vol. 1, Michigan Basin Geological Society, M. S. Wollensak, Ed., Department of Geological Sciences, Michigan State University, E. Lansing, MI.

"Oil and Gas Fields of the Michigan Basin" 1968, Vol. 2, Michigan Basin Geological Society, M. S. Wollensak, Ed., Department of Geological Sciences, Michigan State University, E. Lansing, MI.

Bulloch, T., The Investigation of Fluid Properties and Seismic Attributes for Reservoir Characterization: M.S. thesis, Michigan Technological University, Houghton, Michigan, 113p.

FIGURE CAPTIONS

Figure 1. Bouger gravity anomaly for the State of Michigan.

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

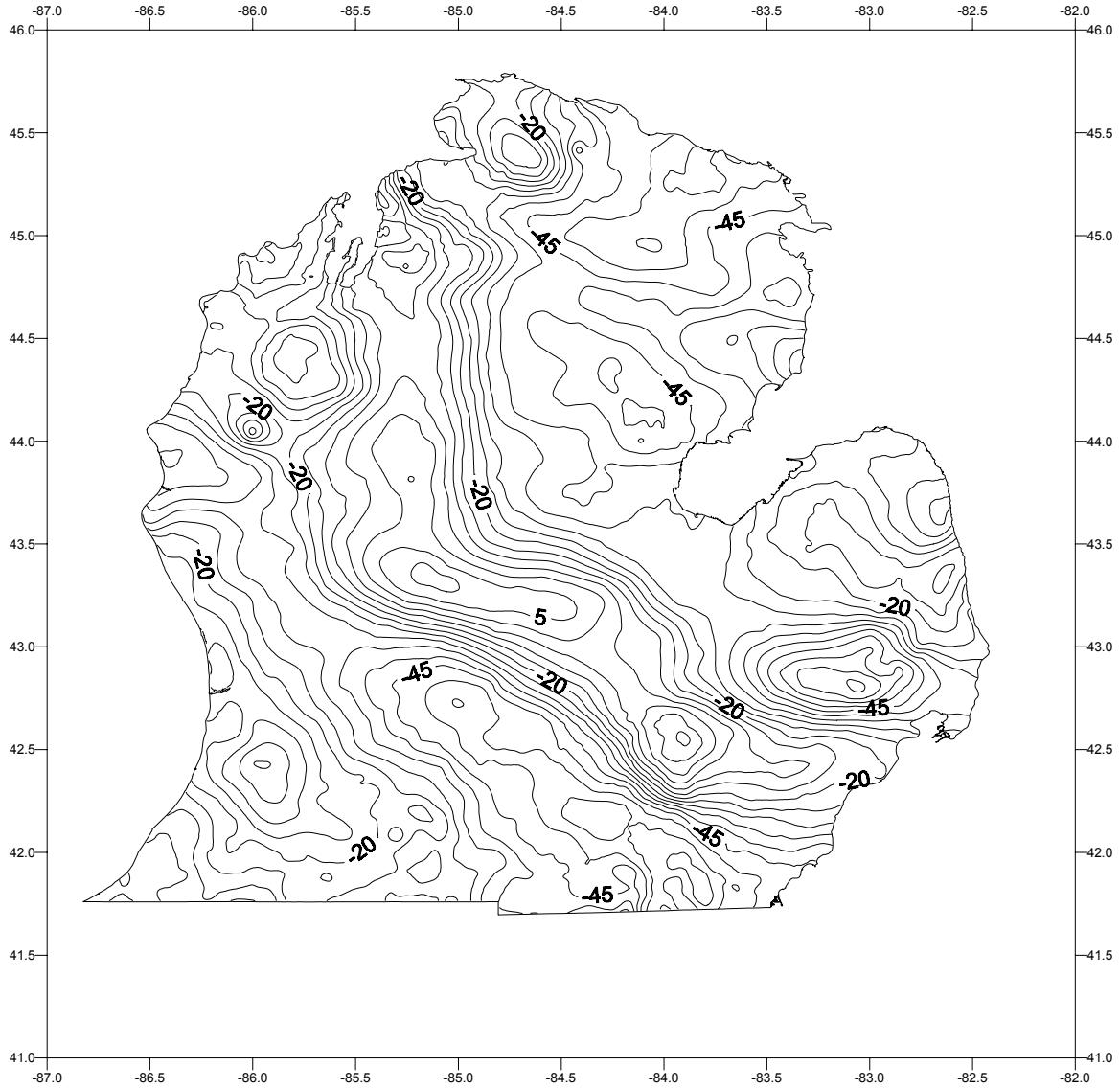
Figure 3. Map for Lower Michigan Peninsula showing Northwest – Southeast orientation of major lineations mapped from formation tops data.

Figure 4. Structure contour map of Top of the Dundee Formation for the Central Michigan Basin showing how the central basin is split into to sub-basins.

Figure 5. Howell Anticline Fault and Lucas-Monrow faults mapper from Dundee formation top picks.

Figure 6. Surface relief map of Michigan based on the gridding tops data for the Dundee Formation.

FIGURES



BOUGIER GRAVITY ANOMALY
CI = 5.0

Figure 1. Bouger gravity anomaly for the State of Michigan.

PERIOD	EPOCH	SEQUENCE	Rock Groups	Formations
QUATERNARY				Red Beds
JURASSIC		ABSAROKA		Grand River Fm.
PENN.	LATE			Saginaw Fm.
	EARLY	KASKASKIA	GRAND RAPIDS	Bayport Ls.
MISS.	LATE			Michigan
	EARLY			Marshall Fm.
				Coldwater Sh.
				Ellsworth Sh (W.)
MISS./DEV UNDIVIDED				Antrim Sh. (E.)
DEVONIAN	LATE		TRAVERSE	Squaw Bay Ls
				Alpena Ls
				Bell Sh
	MIDDLE			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
				St. Peter Ss
	MIDDLE	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 2. Stratigraphic column for central Michigan Basin showing location of Dundee Formation (Middle Devonian)

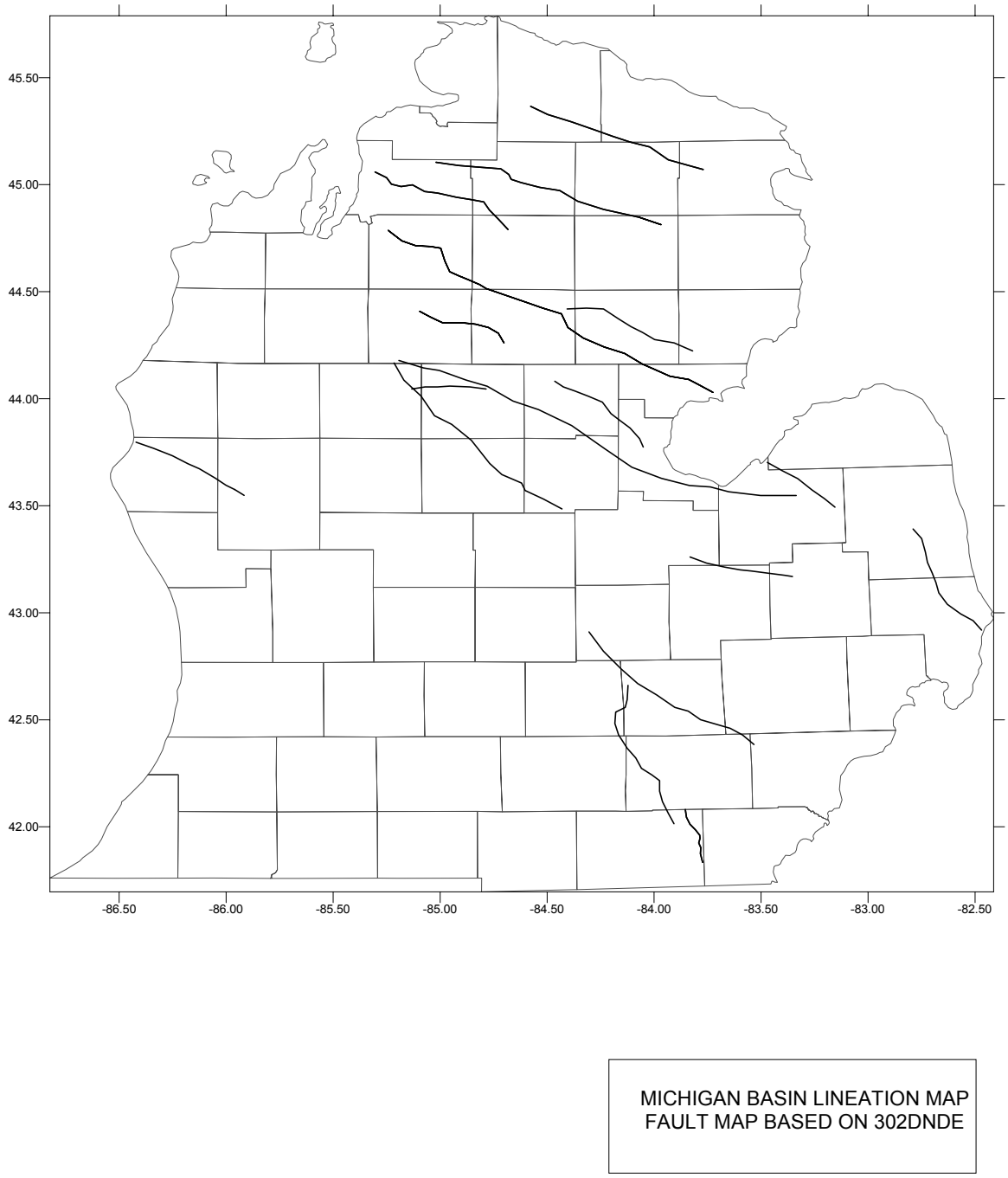
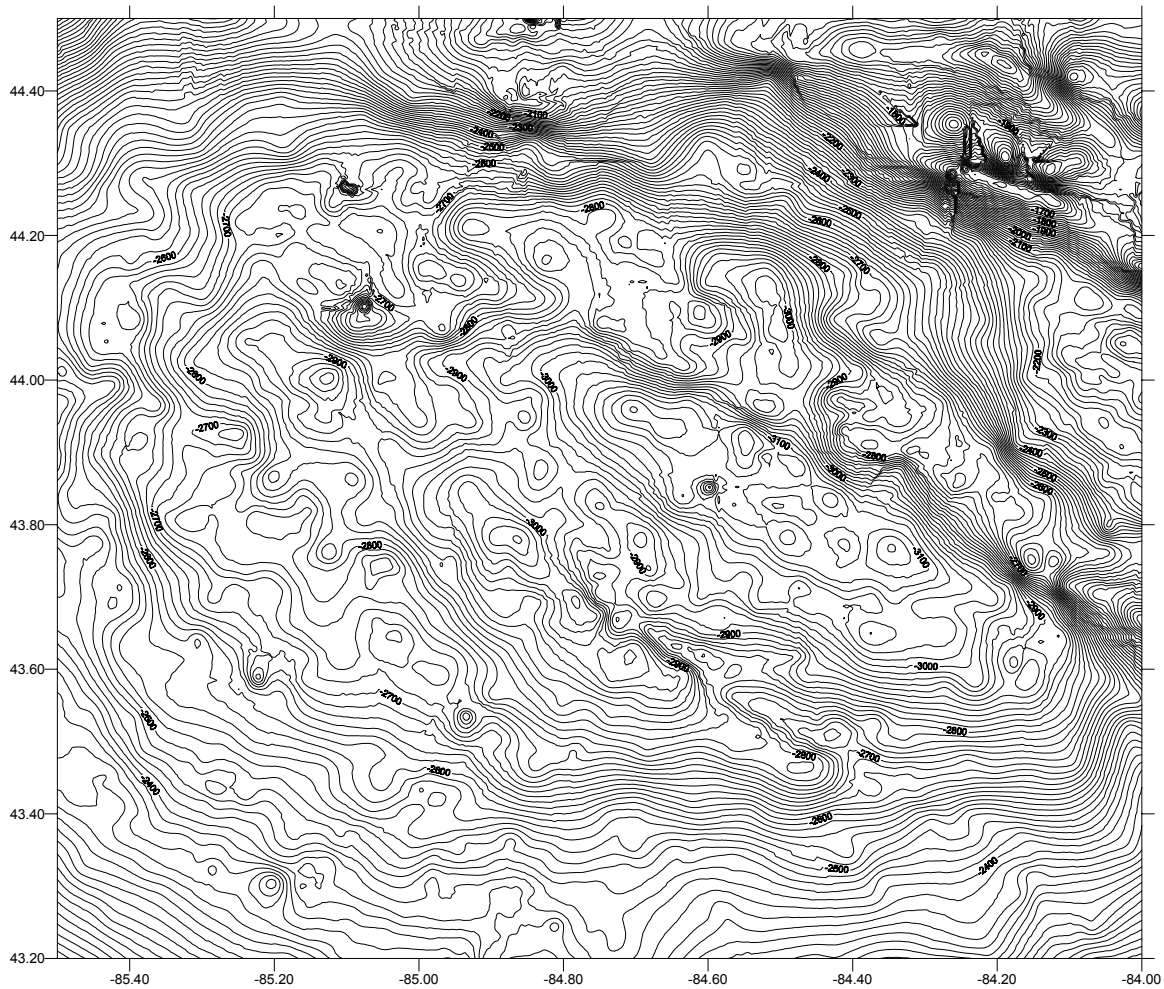


Figure 3. Map for Lower Michigan Peninsula showing Northwest – Southeast orientation of major lineations mapped from formation tops data.



STRUCTURE MAP
TOP OF DUNDEE FORMATION
CI = 10 FT.

Figure 4. Structure contour map of Top of the Dundee Formation for the Central Michigan Basin showing how the central basin is split into to sub-basins.

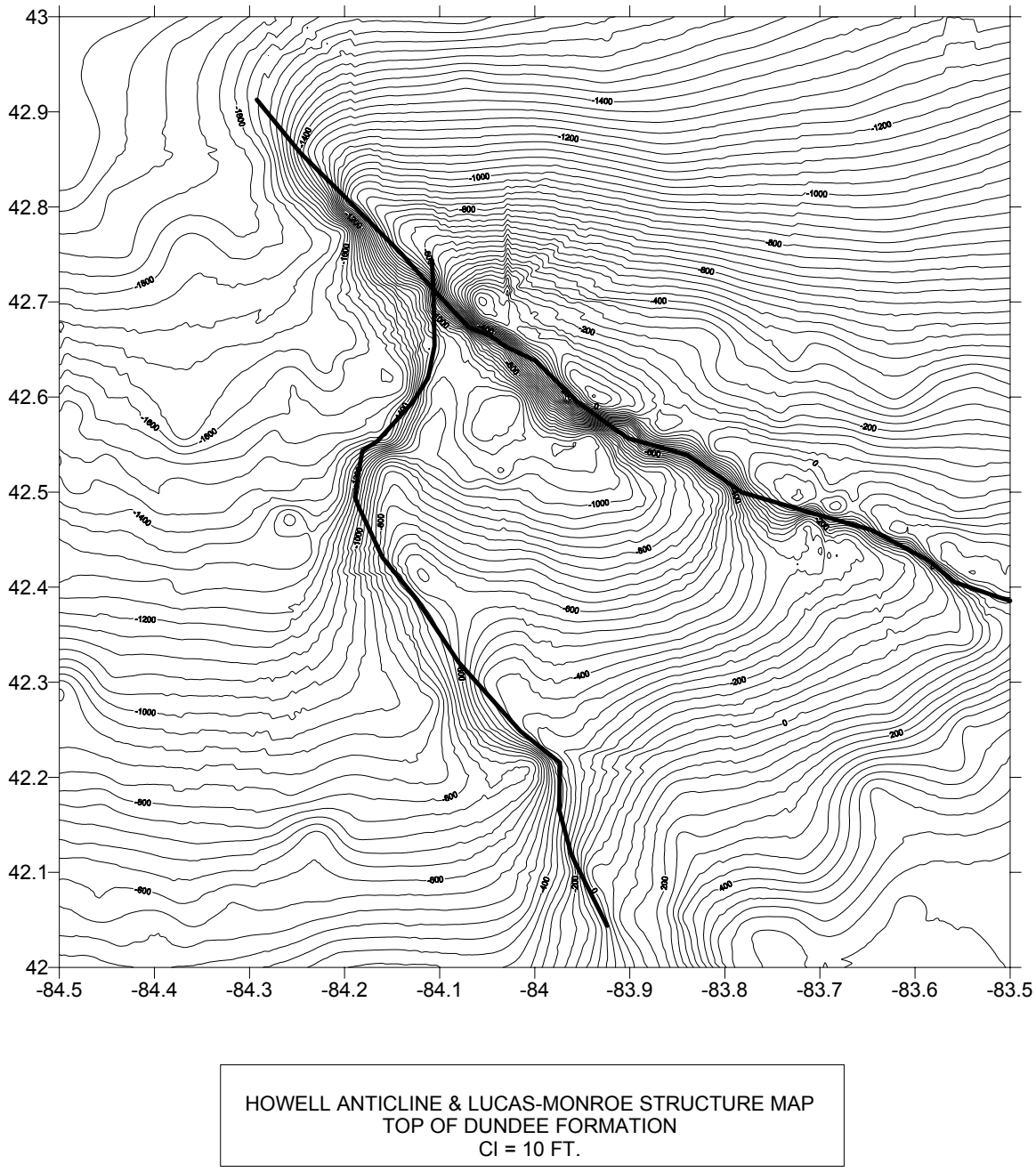


Figure 5. Howell Anticline Fault and Lucas-Monrow faults mapper from Dundee formation top picks.

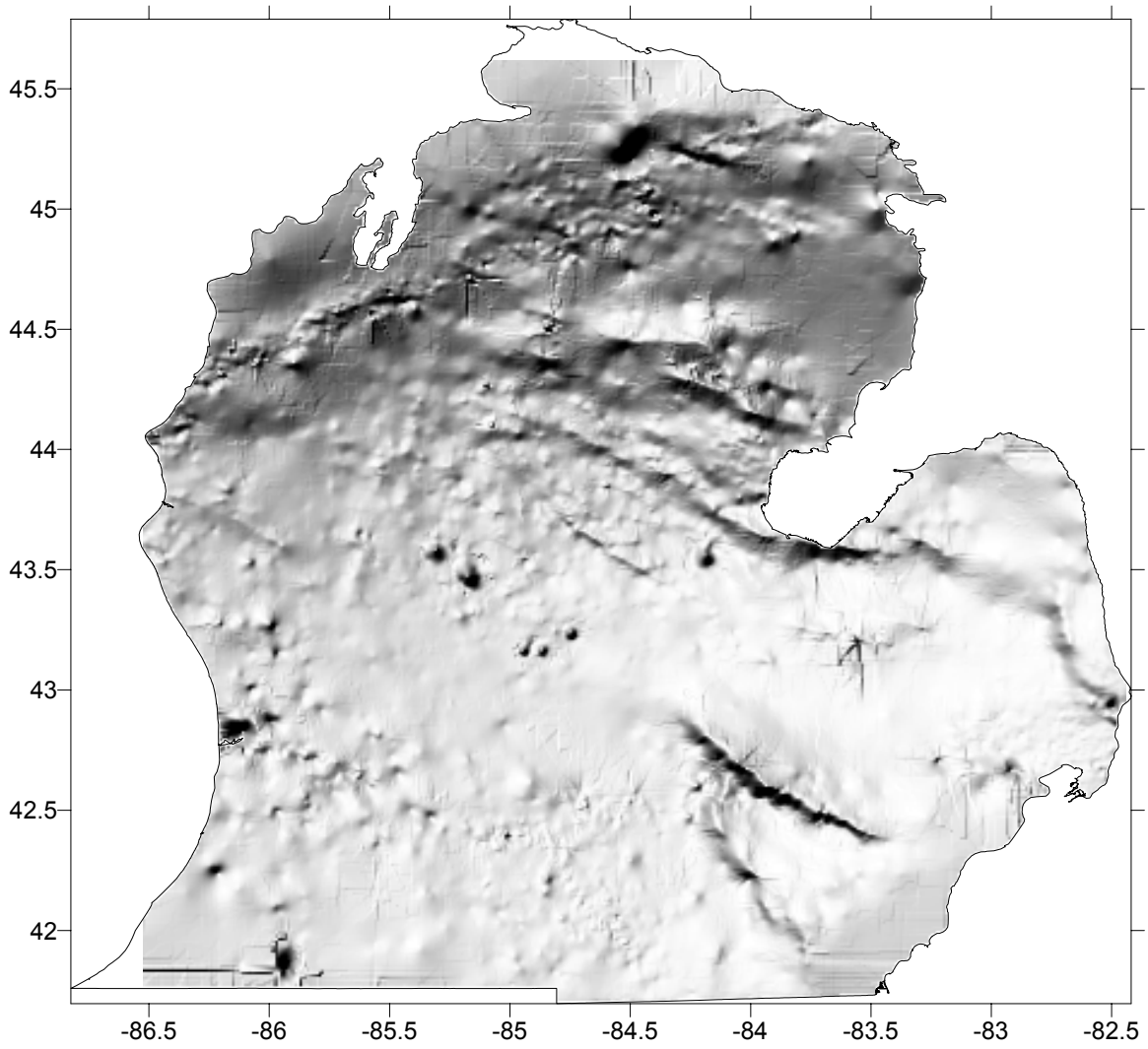


Figure 6. Surface relief map of Michigan based on the gridding tops data for the Dundee Formation.

TABLES

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