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

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DISCLAIMER

ABSTRACT

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 fractures and faults control the Paleozoic sediment deposition, the subsequent hydrocarbon traps and very likely the regional dolomitization patterns.

Recent work has 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.

Dolomitization is common in the Michigan Basin, and it is crucial in developing reservoir quality rocks in some fields. Data on the occurrence of dolomite was extracted from driller's reports for all reported occurrences in Michigan, nearly 50 fields and over 500 wells. A digital database was developed containing the geographic location of all these wells (latitude-longitude) as well as the elevation of the first encounter of dolomite in the field/reservoir. Analysis shows that these dolomite occurrences are largely confined to the center of the basin, but with some exceptions, such as N. Adams Field. Further, some of the dolomite occurrences show a definite relationship to the fracture pattern described above, suggesting a genetic relationship that needs further work. Other accomplishments of this past reporting period include obtaining a complete land grid 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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1.0 Executive Summary

1.1 Introduction

The main results of this study can be summarized under three topics: (1) data acquisition, (2) faults, (3) fractures and (4) diagenesis. Accordingly this report is organized into four main chapters under these headings (Chapters 2-5). All of this refers to the Michigan Basin and it is therefore appropriate to preface the discussion with a brief discussion of the Michigan Basin and it petroleum history.

1.2 Basic Geology of the Michigan Basin

The Michigan Basin is one of several intercratonic basins of N. America. Others include the Illinois, Williston and Hudson Bay basins (Figure 1.1). These basins are all characterized by large volumes of sedimentary fill, both clastic and carbonate, and relatively mild deformation. The Michigan Basin is characterized by Cambrian and Ordovician basal clastics followed by a large volume of Silurian and Devonian chemical sediments, carbonates and evaporites, and a general absence of Mesozoic and Cenozoic rocks, except for a scattering of Jurassic rocks in the center of the Basin (Figure 1.2). The basin itself is often characterized as a gently dipping circular or slightly elliptical bowl (Figure 1.3) with little structural character and generally conformable sedimentary relationships.

The basement rocks below the sedimentary fill in the Michigan Basin is known to be fairly complex, with at least 3 structurally different provinces characterized by rocks of different compositions and ages split by the extension of the mid-continent gravity high (Figure 1.4), which is considered to be mainly Keweenaw-type basalts.

This simple picture is complicated by the presence of a significant geologic structure in the SE corner of the basin, the Howell Anticline and the associated Monroe-Lucas Anticlinal structures (Figure 1.4). The Howell Anticline is thought to represent basement uplift and is often interpreted as a normal fault with 800+ feet of throw and undisclosed (negligible?) lateral offset. This structure is often the only fault shown on a geologic map of Michigan, and even then is often omitted, although the evidence is persuasive if not compelling. The Monroe-Lucas structures are likewise almost certainly faults, with a more complex history and a definite but ambiguous relationship to the Howell structure.

1.3 The "Central Michigan Basin"

The Central Michigan Basin is that part of the Michigan Basin that occupies the very center of the basin and appear to be bounded in almost all directions by a break in slope as evidenced by structural contours on a number of different formations, including the Dundee Formation. On the Dundee Structure map, the Central Michigan Basin can be defined as the -2900 foot subsea contour, a closed contour that encompasses most of what we refer to as the Central Michigan Basin (Figure 1.5). It appears that tectonic events that occurred in the basin were most intense here and that most of the structural deformation (excepting the Howell-Monroe-Lucas Anticlines) occurred here. Much of the gas and oil in the basin are also located here, with the exception of Albion Scipio, West Branch and Deep River fields.

In the course of this study is was observed that the Central Michigan Basin appeared to be a logical separation of processes and structures that appeared limited to that portion of the basin and the gently dipping rocks leading into the basin center.

1.4 Figures

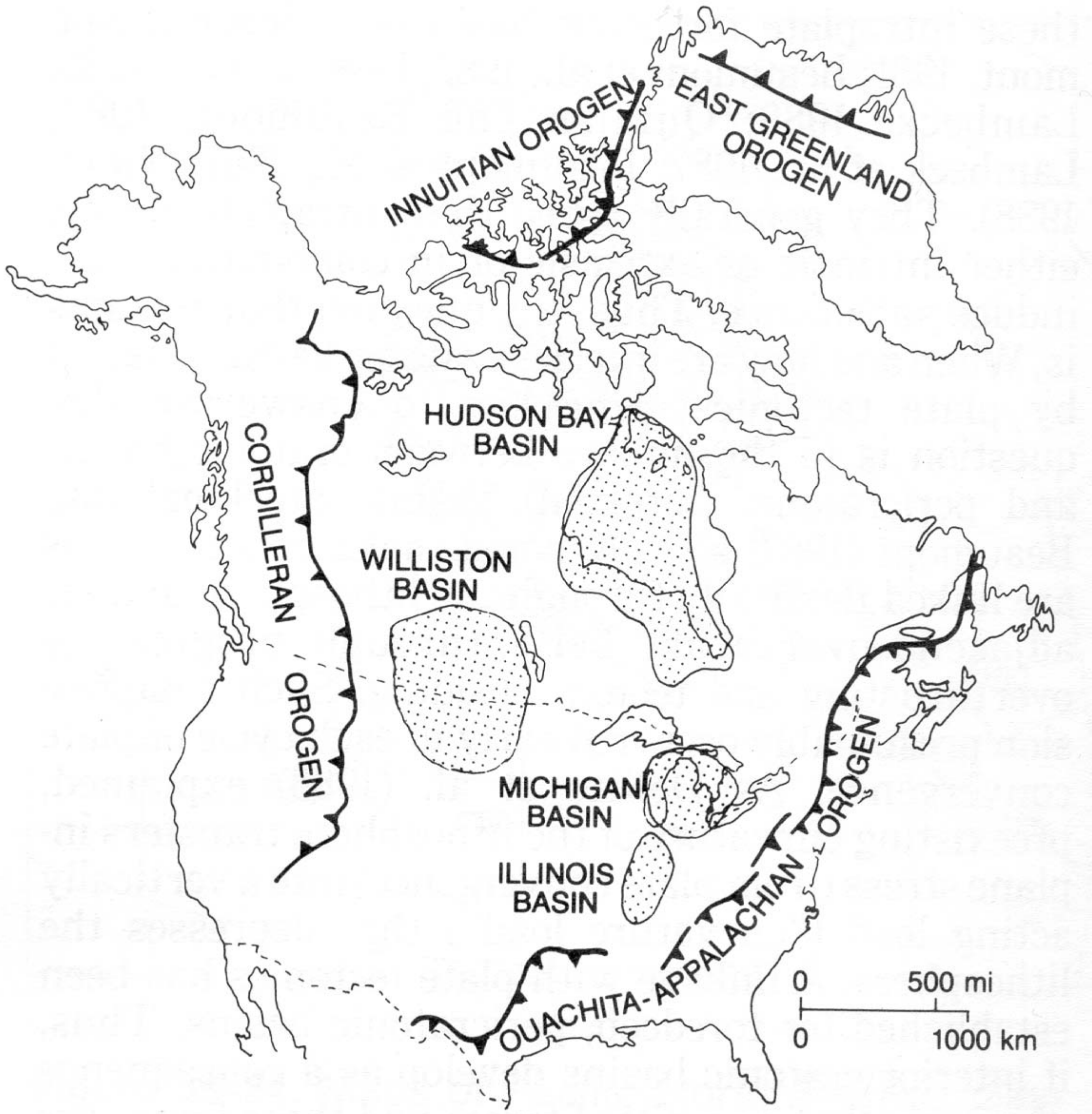


Figure 1.1 Map showing locations of North American intracratonic basins, Michigan, Illinois, Williston and Hudson Bay basins.

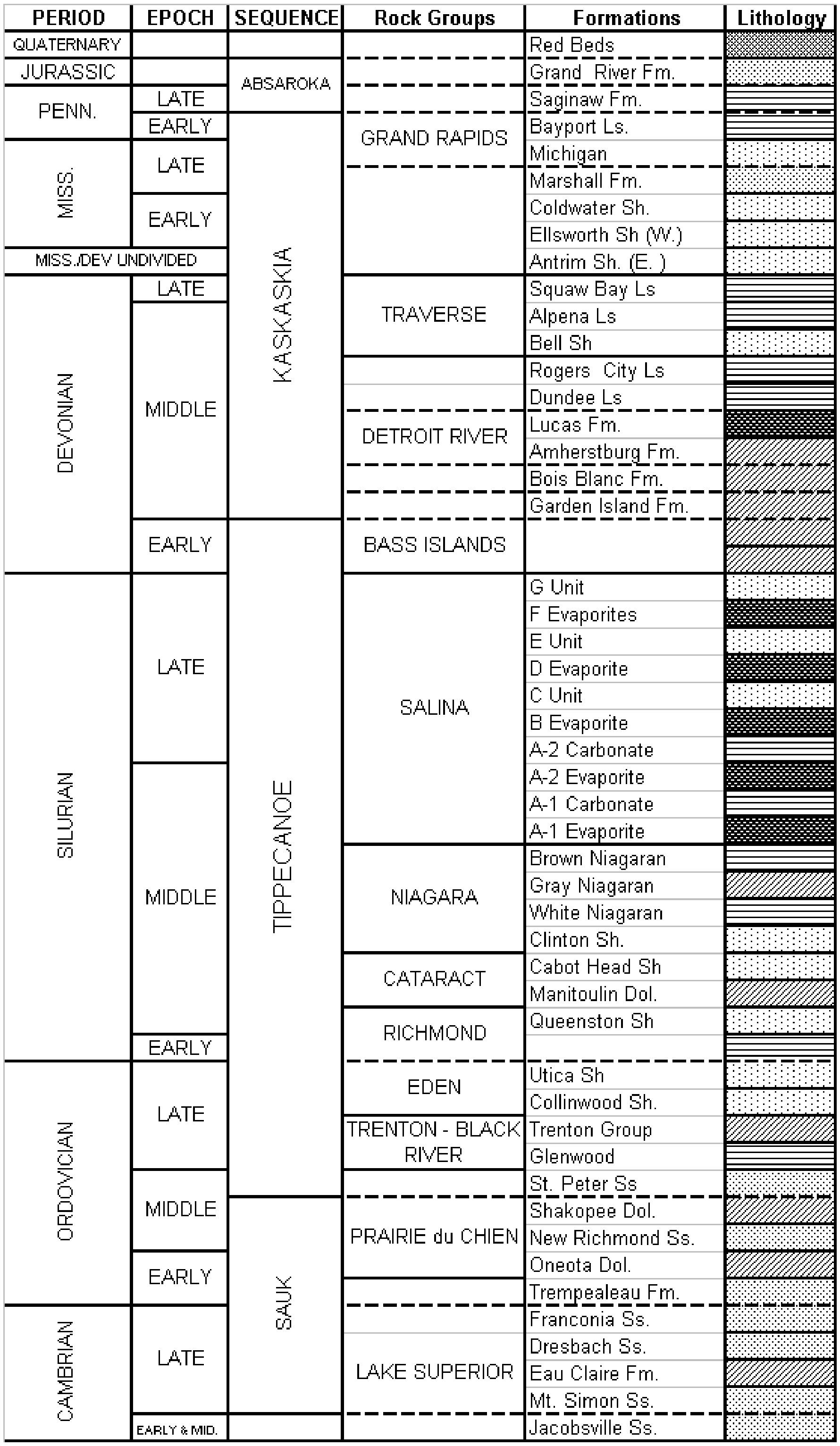


Figure 1.2 Stratigraphic column for Michigan Basin.

Figure 1.3 Generalized geological map of Michigan Basin.

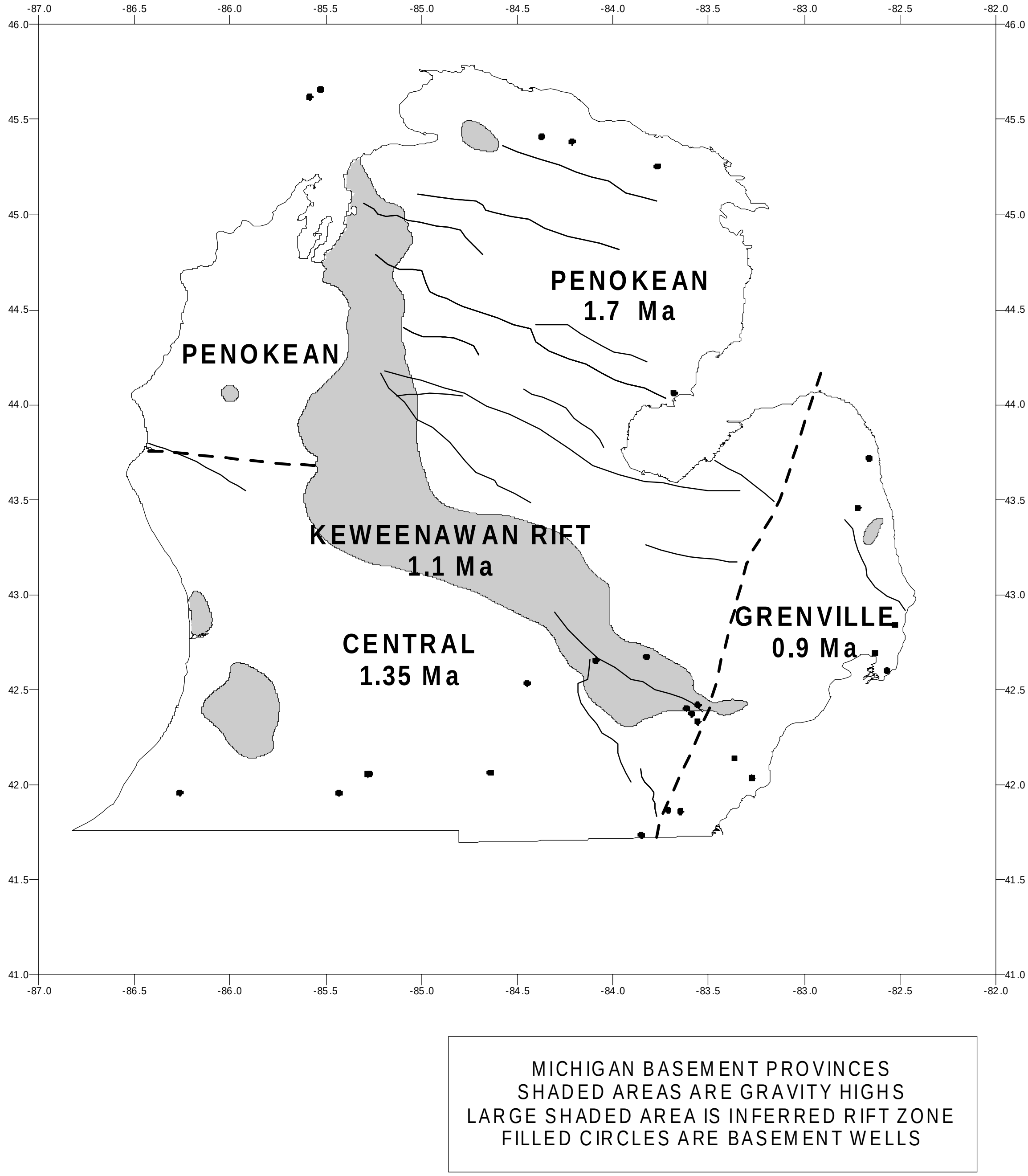


Figure 1.4 Map of basement in Michigan Basin showing different provinces and mid-continent gravity high.

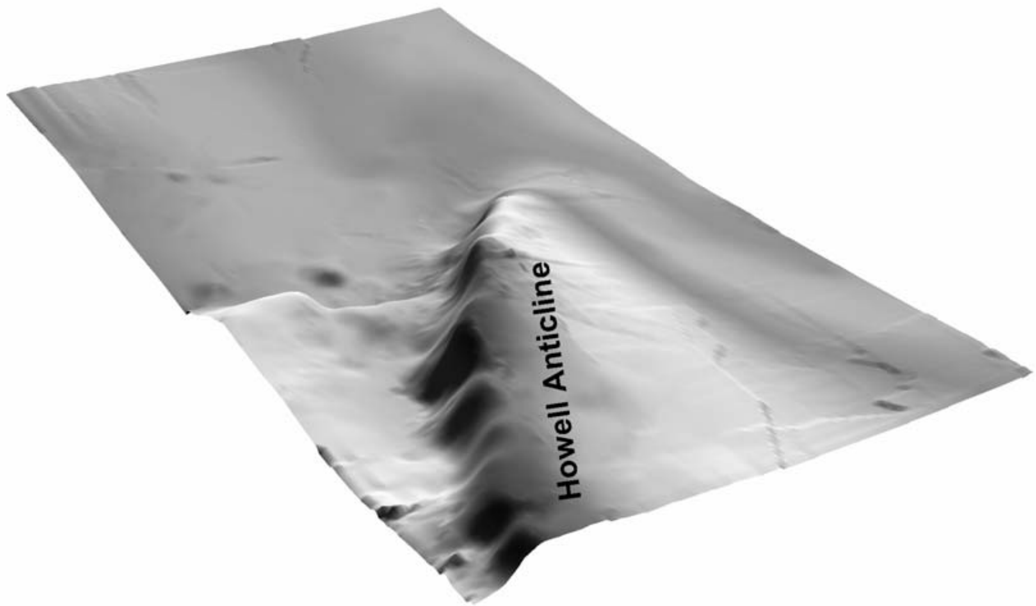


Figure 1.5 3D-surface map of Howell Anticline in SE Michigan. Contoured on top of Dundee Formation. View is looking northwest.

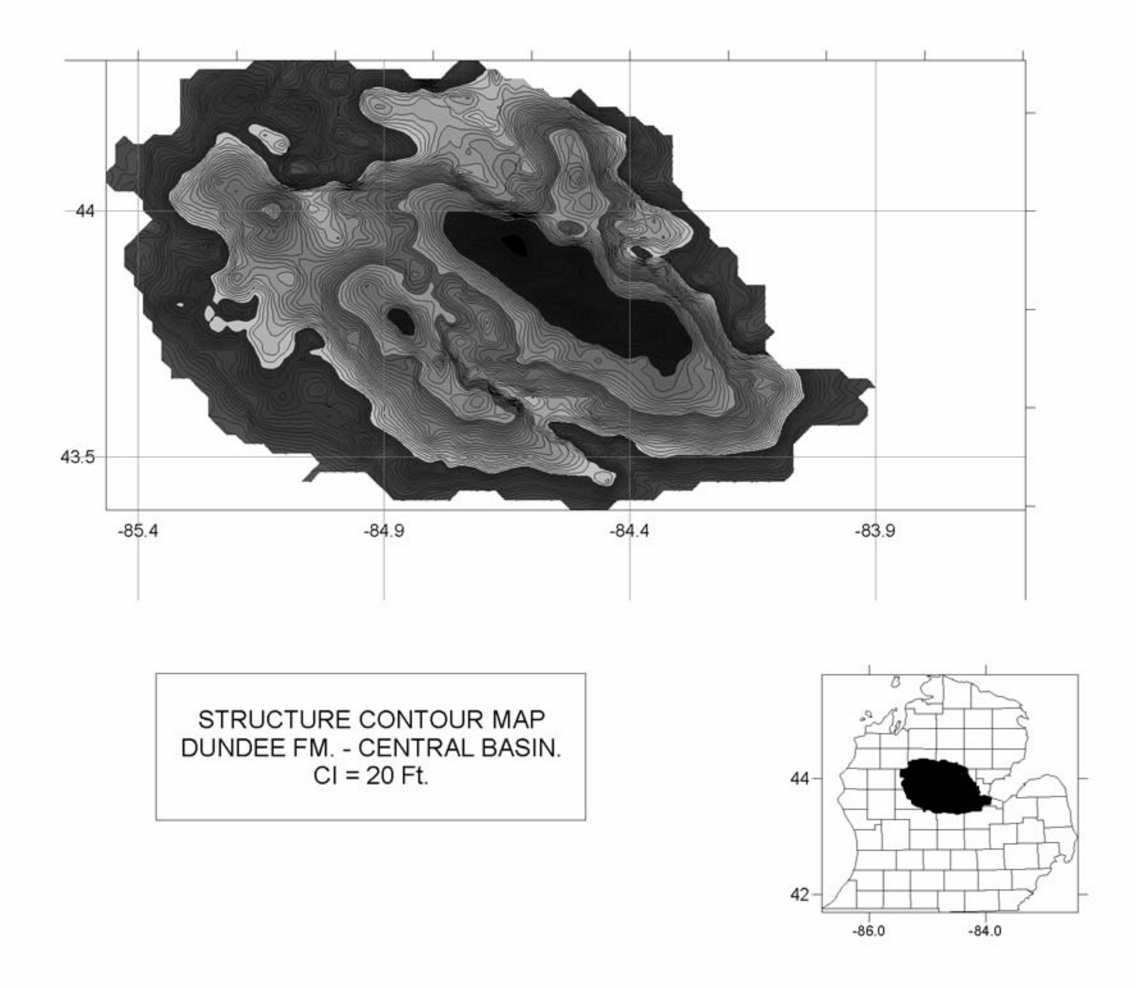


Figure 1.6 Location map of Central Michigan Basin as defined by the -2900 foot subsea contour on the top of the Dundee Formation structure.

2.0 Data Acquisition

2.1 Introduction

A major part of this investigation was assembling a database for the subsurface of the Michigan Basin. This database was to include formation tops, well locations, gas and oil shows, lithologic data and diagenetic data as well as header information for all wells. Data was accumulated on 55,000+ wells and over 450,000 formation tops, nearly the entire drilling history of the Michigan Basin from 1930 to present. Early on it became apparent that it was difficult to work with the data simply because it was so large and the ordinary database format, based on tables, was inadequate for what was essentially a spatial database. Since the data all referred to a well with a single definite location on the earth surface, it was decided to continue development on ATLAS, a spatial database that had been under construction for several years on previous projects, and adapt that database to the present purposes.

ATLAS is a spatial database program, written in Visual Basic©, using the ESRI MapObjects control. The data itself is contained in a Microsoft Access database and all pertinent data is displayed on a base map, which consists of the State of Michigan with counties. This permits the user to obtain an overview of the data rapidly and accurately, as well as manipulate the data to some degree, as for example, extracting a subset of the database such as all Ordovician tops or all wells within a given geographic area or both. In essence, ATLAS writes a complex query (SQL) using graphical input from the user. It is an excellent tool for quickly obtaining the available data needed for input into other software either as an ACCESS file or as an EXCEL file. ATLAS also has the capability to reading scanned (raster) data for a well of interest, for example a driller's report or a scout ticket, and then permits the user to update records in the master database. ATLAS is versatile and can be used to display data from other states simply by changing the databases. Note that ATLAS uses the U. S. TIGER files for a State to display information such as roads, cities, etc.

Since ATLAS is a major deliverable for this project and because it also is an easy way to display and discuss many of the other deliverables for this project, this chapter will be devoted to a discussion of ATLAS and the databases developed for it. The program is available as well as a sample database containing all the public domain data for Michigan gathered in this project.

2.2 ATLAS Program

2.2.1 Databases

Project List Database

The Project List database allows users to define multiple projects in ATLAS. A project is defined by a regional area or by a subset of oil and gas wells. For example, a project can be the oil and gas data for a state, or it can be a subset of data that includes several oil fields or counties. Each project will have a unique name and a separate ATLAS database.

“Projects” is the only table in the Project List database and it holds one record for each project. It tracks the paths for the following files and directories needed for ATLAS: (1) the ATLAS database associated with the project; (2) the shape files for displaying the project map; and (3) the root directories of the U.S. TIGER shape files, the Driller Report image files, the Scout Ticket image files, and the LAS files. It also holds the longitude/latitude corners of a rectangle that represents the physical area of the ATLAS database.

ATLAS Database

The ATLAS database consists of 13 tables, which are used by the ATLAS program to display the oil and gas well data. Some tables contain specific data for each well, keyed by Permit number, and other tables are cross reference tables for looking up codes for general well data such as county and formation names.

ATLAS Tables

All_Well_Headers:	Header information for each Permit and each deepening or reworked well that was assigned a Permit Suffix to an existing Permit. Permit is the primary key for indexing the table and is represented by a zero-filled character field that holds a 5-digit Permit appended by any Permit suffixes. This table includes data such as Oil Field, Well Status and Type, Longitude, Latitude, Operator, Well Name, Well Number, County, Kelly Bushing, SPUD and Completion dates, etc.
All_Well_Tops:	Formation Top Depths are represented by one record for each Formation Top in each well. The table is keyed on Permit and Formation Code, and the top depths are measured depths.
Counties:	Cross reference of DNR county codes to FIPS county codes and County names.
FormationNames:	Formation Names, descriptions and Lithologic order of the formations.
OilFields:	Oil Field Names and approximate rectangular outline of the oil fields.
DrillerReports:	Cross reference table of Permits to Driller Report path within the Driller Report root directory.
ScoutTickets:	Cross reference table of Permits to Scout Ticket path within the Scout Ticket root directory.
LASFiles:	Cross reference table of Permits to LAS File path within the LAS File root directory.
LithologyWells:	Cross reference table of Permits to range of Lithology data. This table is used to do a visual display of wells which have Lithology data available.

ATLAS Tables

DetailMapLayers:	List of U.S. TIGER shape files available for enhancing maps. The codes in this table are used to construct the shape file name, and predetermine the color, layer drawing order, and field name from the shape file to used in labeling map features. Typical shape files displayed are section lines, streets, and rivers.
UserMaps:	Temporary list of shape files chosen by the user to display on the map. This list changes as the user chooses different counties and features.
GeoChem_Headers:	Location information for Geochemical soil samples taken in the area of the database. Keyed on a unique ID number given to each soil sample.
GeoChem_Samples:	Concentrations of the different geochemical analyses performed on each soil sample. Keyed on unique ID number and the chemical analyzed.

External Data

ATLAS accesses directories of external data to display more information about the wells and also to enhance the visual display of the maps it creates.

Project Base Map:	ESRI shape file of the project area. Typically, this file is a county outline map of an entire state.
U.S. TIGER Data:	A directory by county of the U.S. TIGER shape files for roads, rivers, water bodies, township and section lines, and other special features.
Scout Tickets:	A directory by county of the Scout Ticket TIF image files. The original paper Scout Tickets were scanned and saved as multiple-page TIF images and are available for viewing from within ATLAS.
Driller Reports:	A directory by county of the Driller Report TIF image files. The original paper Driller Reports were scanned and saved as multiple-page TIF images and are available for viewing from within ATLAS.
LAS Files:	A directory of LAS Files which are available for viewing from within ATLAS from the Edit Screen.

Export Database

ATLAS uses an MS-Access database to export the formation tops in subsea depth for a selected group of wells. It creates a single table with Longitude, Latitude, and multiple columns for user-selected formation depths. An additional export option allows the user to create the export table along with a subset of the ATLAS database to be used in a smaller ATLAS project.

2.2.2 Basic Capabilities

Create and Open Projects

The "Project Information" screen is used to set parameters for the projects created in ATLAS (Figure 2.1). The user selects the ATLAS database path for each project and sets directory paths to the U.S. TIGER shape files and image documents associated with the wells in the project. The parameters are written to the ProjectList database and saved for future reference to the project.

Display Well Locations

The focus of the main ATLAS window is the map display. The top and left side of the map are set up with the controls that define the map's content (Figure 2.2). ATLAS has several built-in queries that are used to plot wells on the map. The option buttons, within the "**Plot Wells By"** frame, are used to select a subset of wells from within the project to display on the map. Toolbar buttons for zooming, panning and returning to full extent are located above the map.

All Wells:	Displays all wells in the ATLAS database
County:	Displays all county names for the project in the List box. The user can select one or more counties to plot.
Oil Field:	Displays all Oil Fields defined for the project in the List box. The user can select one or more Oil Fields to plot
Permit/Radius:	User enters a Permit number and a radius to plot the permit and all wells within the radius of the well.
Arrow Toolbar Button:	A user-drawn rectangle will display all wells within the selected longitude/latitude range.

Edit Well Data

Once a selection of wells has been plotted, ATLAS uses two methods for accessing the Edit Screen. The "*Edit Plotted Wells*" toolbar button allows access to all of the wells displayed on the map. The "*Select Wells to Edit"* toolbar button turns the cursor into a cross hair so a rectangle can be drawn around one or more wells for a small subset of wells to edit.

The Permit numbers selected for editing are listed in the Selected Wells list box in Permit number order. Wells are displayed on the Edit screen, as they are selected in the list box (Figure 2.3). Well header information and formation tops can be added, edited, and deleted. The formation tops data is displayed in a small table on the Edit screen and includes the formation code, description and the top of formation depth. When available, Scout Tickets and Driller Reports are displayed in a pop-up window for user reference.

Driller Reports and Scout Tickets

Original paper Scout Tickets and Driller Reports for the Michigan Basin wells have been scanned and stored as multiple-page TIF images. ATLAS tracks the path of the image file, and allows users to display the image while editing well records (Figures 2.4 and 2.5). The document viewer can zoom in and out on a page and the Next and Previous buttons navigate between pages. The documents are invaluable for verifying data, viewing additional information about each oil and gas well, and adding additional formation top picks to existing data records.

Exporting Data from ATLAS

The export feature in ATLAS extracts data from the ATLAS database into another MS-Access database. Formation top depths are exported only for the wells displayed on the ATLAS map, and for the formation codes selected in the "Export Screen" (Figure 2.6). The export table can be added to a newly created database, or it can be added to an existing export database as a new table.

The exported table contains Longitude, Latitude, multiple columns for each formation top selected for export in subsea depth, Permit, Oil Field, County, and Kelly Bushing (Figure 2.7). The user can select the option to create the export database with this table alone, or the option to export all of the ATLAS files needed to create a subset of the ATLAS database to be used in another smallerATLAS project.

The export table can be converted to a text file or an Excel spreadsheet for input into a gridding and mapping program such as Golden Software's Surfer©. Surfer© can be used as a stand-alone program, or it can be driven by Visual Basic © to automatically create 2D and 3D surface contour maps and isopach maps.

2.2.3 Special Functions

Visual Well Queries

The option buttons located to the left of the map display are used to provide a visual query of the well attributes (Figure 2.2). Wells are symbolized in red if the database has supporting data for the chosen attribute, and in blue if there is no supporting data available.

Formation Tops:	When the Formation Tops option is selected, the list box is filled with all of the formation codes available for the wells currently displayed on the map. When a formation code is selected from the list, the red well symbol indicates which wells have a top pick for that formation. The number of wells with the specified formation top is displayed beneath the formation code list box.
Well Status/Type:	By setting the check boxes and selecting values from list boxes, the user displays wells by choosing a Well Status or a Well Type, or a combination of a Well Status and a Well Type.
Lithology:	Indicates the wells that have Lithology data. Because the Lithology data in MTU's possession is restricted, it is not presented in any further detail in the ATLAS program and it is not included in the ATLAS database.
LAS Files:	Indicates the wells with LAS files attached to the ATLAS database.
Scout Tickets:	Indicates the wells with Scout Ticket image files attached to the ATLAS database.
Driller Reports:	Indicates the wells with Driller Report image files attached to the ATLAS database.

Display wells by Permit and Radius.

When displaying well locations by Permit and Radius, ATLAS accepts the Permit number without leading zeroes and plots the location with a green symbol. The radius selection calculates an approximate latitude/longitude range around the point. All of the wells within this rectangle are plotted with their Permit numbers. If a formation code is also selected, the subsea depth of the formation top is displayed in red along with the permit number (Figure 2.8).

This feature is helpful when error-checking the formation tops data. When peaks and holes appear on contour maps, surrounding wells can be compared to check for the probability of an error in the data.

U.S. TIGER data and MIRIS Land grid

The U.S. TIGER data and the MIRIS Land grid are compiled of separate shape files for each map feature by county. Each county has a directory of shape file for roads, rivers, and section lines, etc. The "*Add Map Features*" button is used to add layers to the map (Figure 2.9). One or more counties are selected, and then one or more layers of map features are selected. The new layers are added to the map in the order that is specified in the DetailMapLayers table in the ATLAS database (Figure 2-10). The "*General Map*" button will clear all extra layers from the map, leaving only the base map the project started with.

The check boxes to the upper right of the map make it simple to change the most common features added to the base map. The initial map setting must be set with the "*Add Map Features*" button, and then the layers can be added and removed by using the check boxes. The *Map Features* tab displays mapping options chosen by the user when the U.S. Census 2000 TIGER/Line Data is added to the map. When a feature is selected on the left side of the map, its name will appear on the bottom right status bar if the feature is named in the shape file. The Status Bar at the bottom of the screen describes the location of the cursor on the map in Latitude/Longitude coordinates, County name, Oil Field name, and Map Feature name.

Fault Lines and Oil Field Outlines

ATLAS displays fault lines in a shape file (Figure 2.11). The Michigan fault lines defined in this project were exported to a shape file for the whole state. This shape file was added to the root of the directory created for the U.S. TIGER data with "999" as the state code. The "999" code signifies there is one shape file for the entire state and not separate shape files for each county. The fault lines are selected with any county using the "*Add Map Features*" button and can be removed or added using the faults check box.

The "Oil Field Outlines" check box uses the corner coordinates from the OilFields table to draw an approximate outline around the physical area of the Oil Fields as defined in the ATLAS database (Figure 2.12). When the cursor is dragged over an Oil Field, the name is displayed on the status bar at the bottom of theATLAS screen.

LAS Files

ATLAS tracks path information for LAS (Log ASCII Standard) files associated with oil and gas wells. Wells with LAS files attached to the database are symbolized in red when the *LAS Files* option button is clicked. When the Log Viewer toolbar button is clicked, the cursor changes to a cross hair and the user draws a rectangle around a group of wells with LAS data. The wells with attached LAS files are then opened in **LogVu**, a separate software program attached to ATLAS, and displays Log Curves with the Formation Tops depths overlaid on the curve.

2.3 Figures

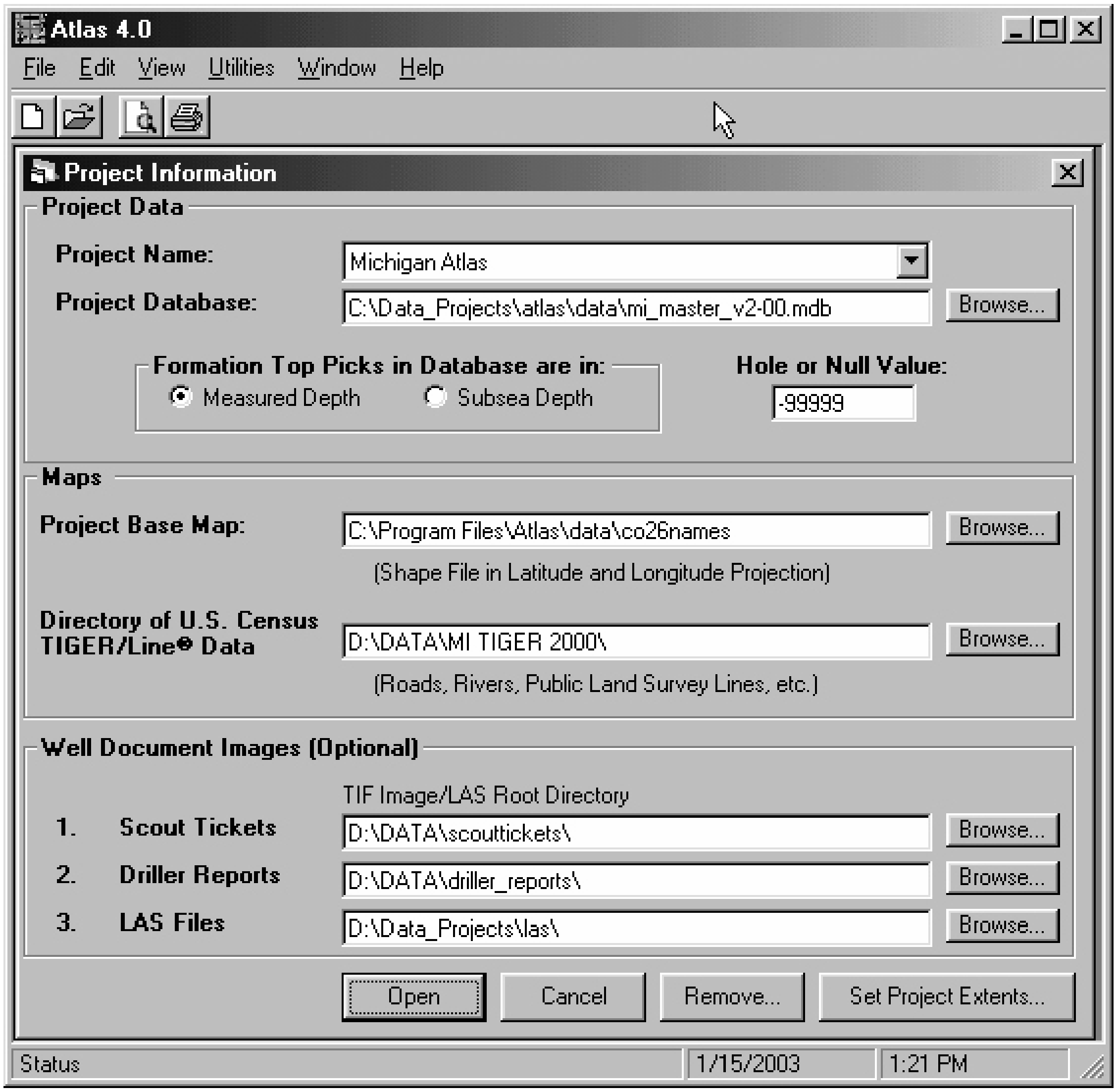


Figure 2.1. Project Information Screen for setting project paths and parameters.

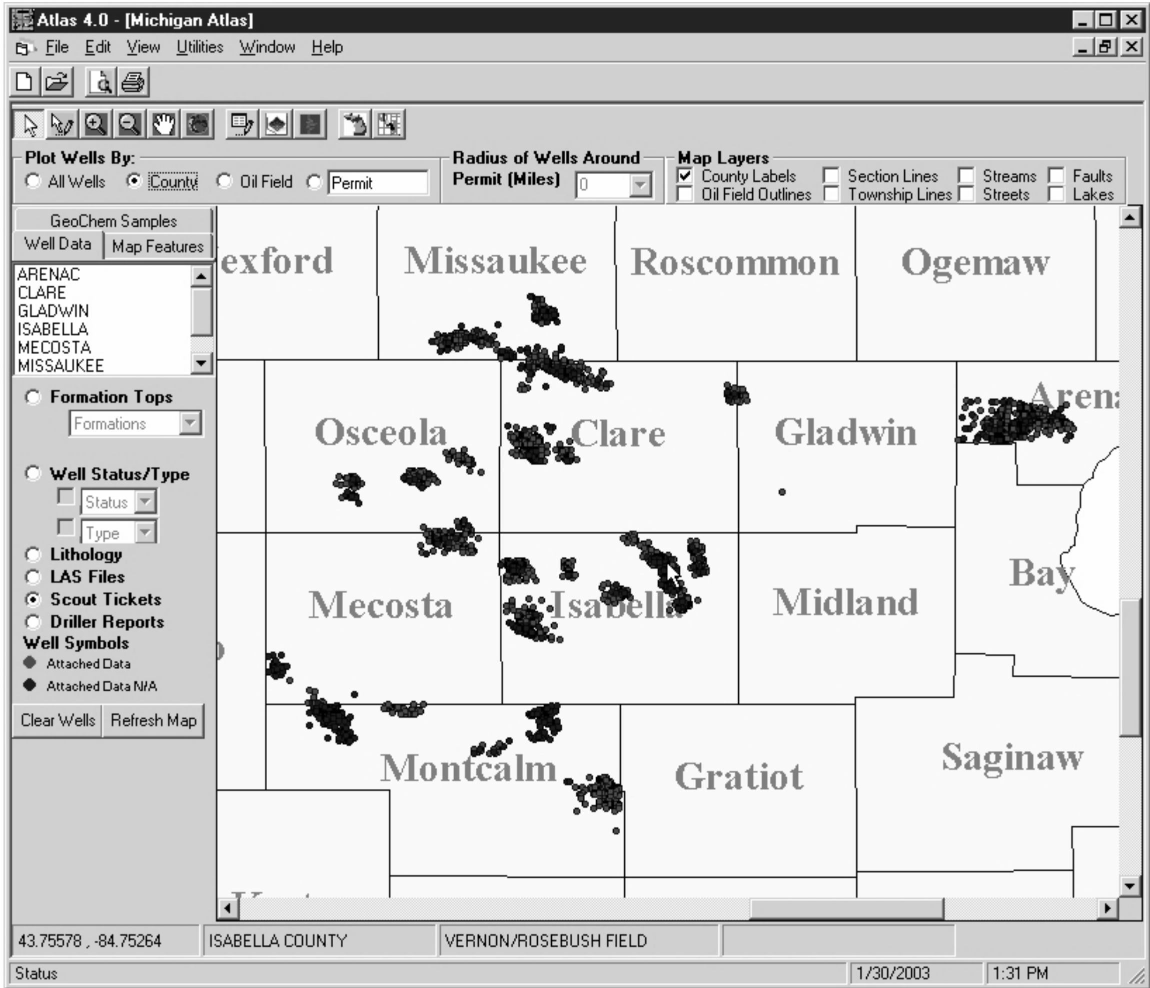


Figure 2.2. Main ATLAS screen displays oil and gas well locations.

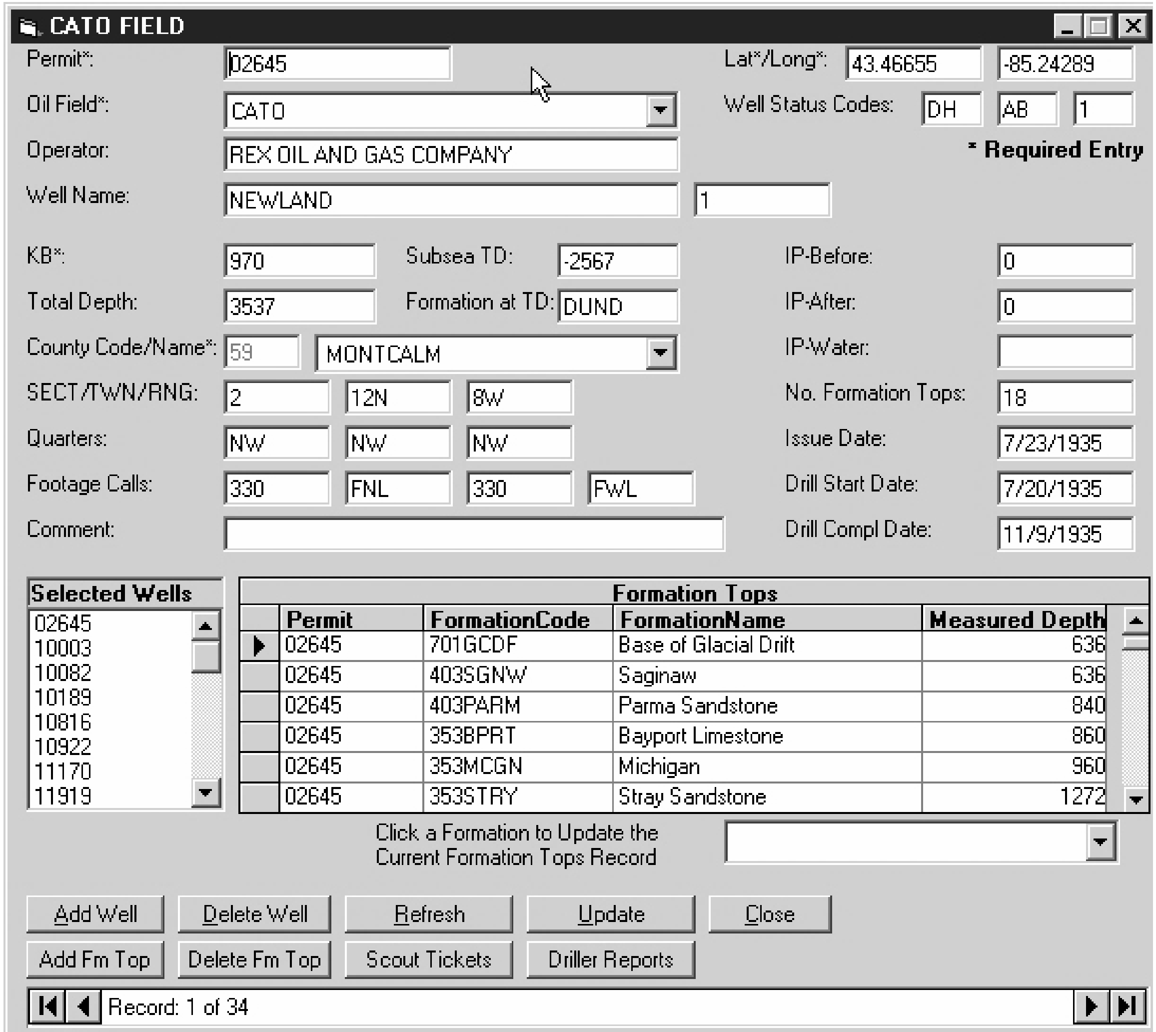
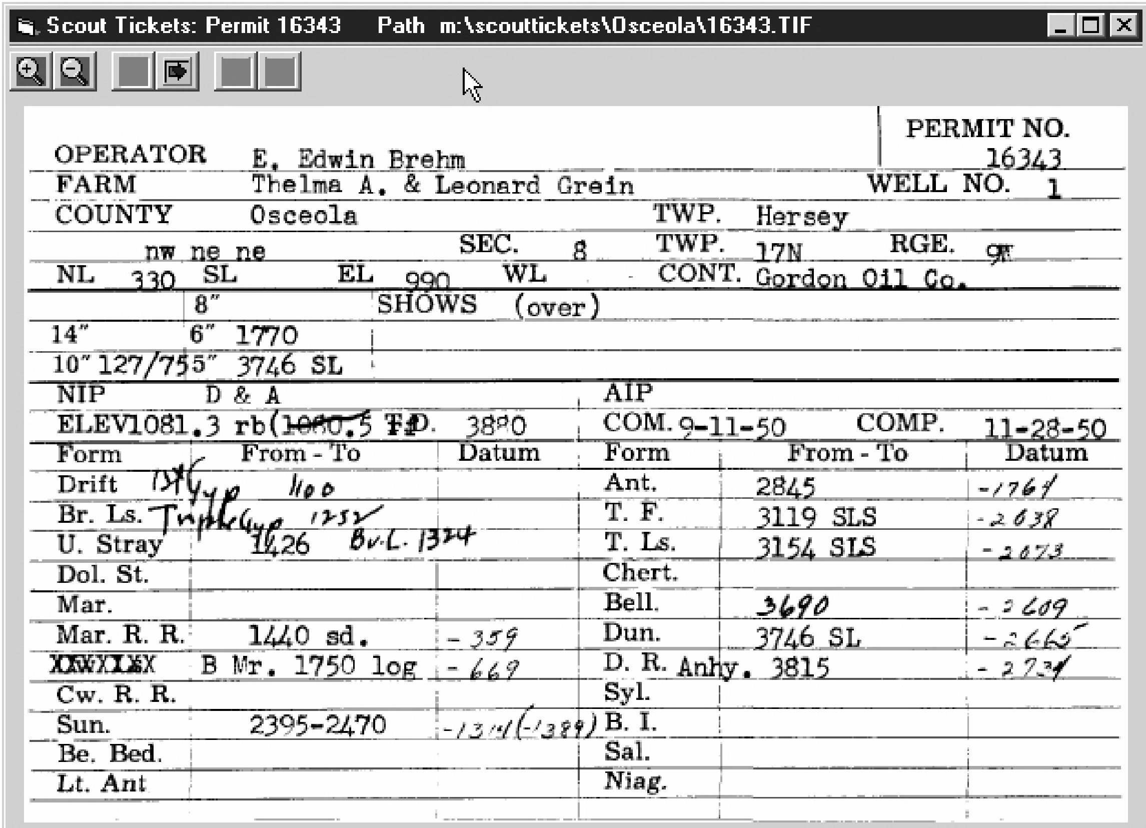


Figure 2.3. ATLAS Edit Screen for updating records and viewing Scout Tickets and Driller Reports.


Scout Tickets: Permit 16343 Path m:\scouttickets\Osceola\16343.TIF

PERMIT NO. 16343

OPERATOR E. Edwin Brehm

FARM Thelma A. & Leonard Grein WELL NO. 1

COUNTY Osceola TWP. Hersey

nw ne ne SEC. 8 TWP. 17N RGE. 9W

NL 330 SL EL 990 WL CONT. Gordon Oil Co.

8" SHOWS (over)

14" 6" 1770

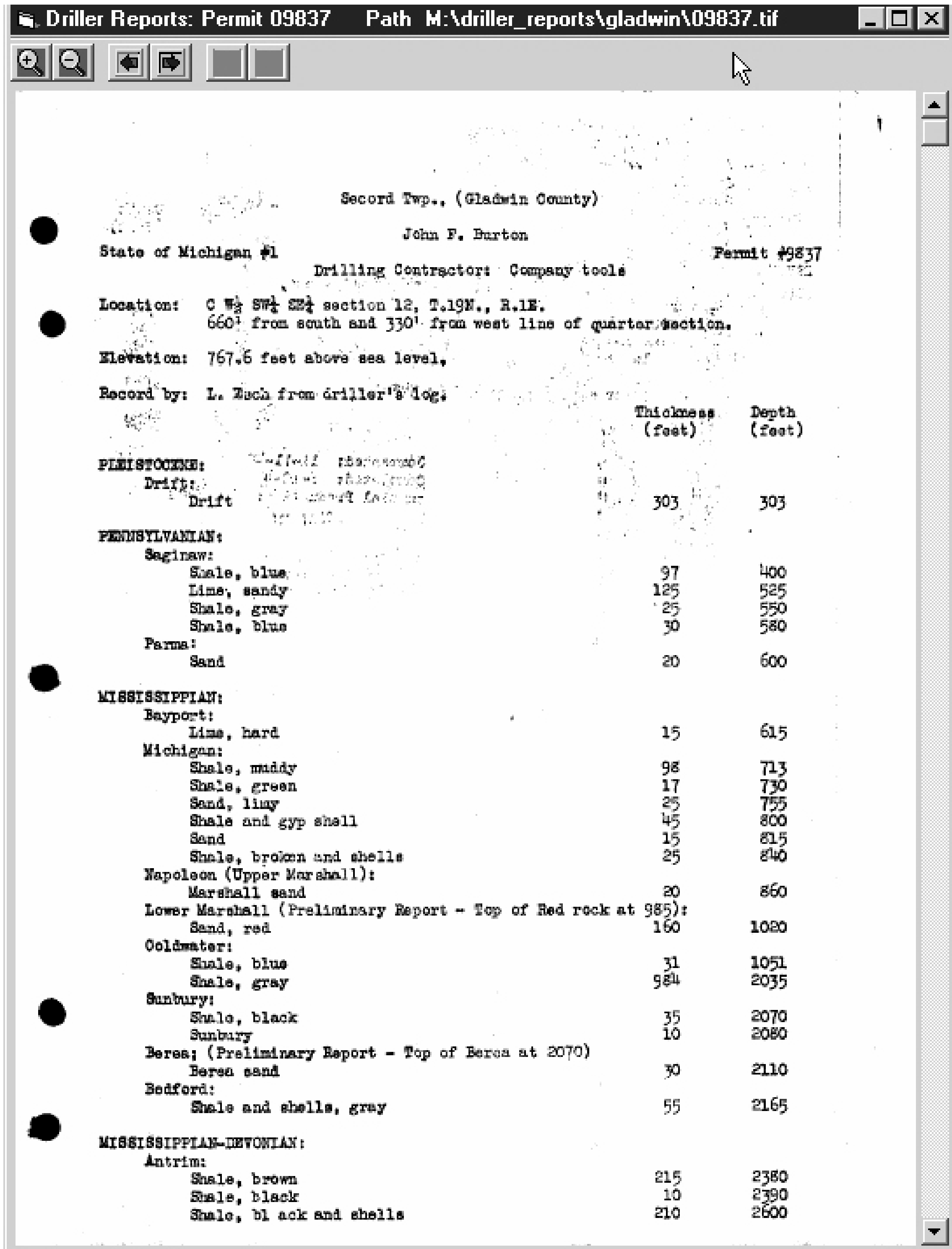
10" 127/755" 3746 SL

NIP D & A AIP

ELEV1081.3 rb(1080.5 TD. 3880 COM. 9-11-50 COMP. 11-28-50

Form	From - To	Datum	Form	From - To	Datum
Drift	1316 Gyp 1400		Ant.	2845	-1764
Br. Ls.	Triple Gyp 1252		T. F.	3119 SLS	-2038
U. Stray	1426 Br.L. 1324		T. Ls.	3154 SLS	-2073
Dol. St.			Chert.		
Mar.			Bell.	3690	-2609
Mar. R. R.	1440 sd.	-359	Dun.	3746 SL	-2665
XXXXXXX	B Mr. 1750 log	-669	D. R.	Anhy. 3815	-2734
Cw. R. R.			Syl.		
Sun.	2395-2470	-1314(-1389)	B. I.		
Be. Bed.			Sal.		
Lt. Ant			Niag.		

Figure 2.4. Sample Scout Ticket Display.



Secord Twp., (Gladwin County)

John F. Burton

State of Michigan #1 Permit #9837

Drilling Contractor: Company tools

Location: C W½ SW¼ SE¼ section 12, T.19N., R.1E.
660' from south and 330' from west line of quarter section.

Elevation: 767.6 feet above sea level.

Record by: L. Esch from driller's log.

	Thickness (feet)	Depth (feet)
PLEISTOCENE:		
Drift:		
Drift	303	303
PENNSYLVANIAN:		
Saginaw:		
Shale, blue	97	400
Lime, sandy	125	525
Shale, gray	25	550
Shale, blue	30	580
Parma:		
Sand	20	600
MISSISSIPPIAN:		
Bayport:		
Lime, hard	15	615
Michigan:		
Shale, muddy	98	713
Shale, green	17	730
Sand, limy	25	755
Shale and gyp shell	45	800
Sand	15	815
Shale, broken and shells	25	840
Napoleon (Upper Marshall):		
Marshall sand	20	860
Lower Marshall (Preliminary Report - Top of Red rock at 985):		
Sand, red	160	1020
Coldwater:		
Shale, blue	31	1051
Shale, gray	984	2035
Sunbury:		
Shale, black	35	2070
Sunbury	10	2080
Berea; (Preliminary Report - Top of Berea at 2070)		
Berea sand	30	2110
Bedford:		
Shale and shells, gray	55	2165
MISSISSIPPIAN-DEVONIAN:		
Antrim:		
Shale, brown	215	2380
Shale, black	10	2390
Shale, black and shells	210	2600

Figure 2.5. Sample Driller Report Display.

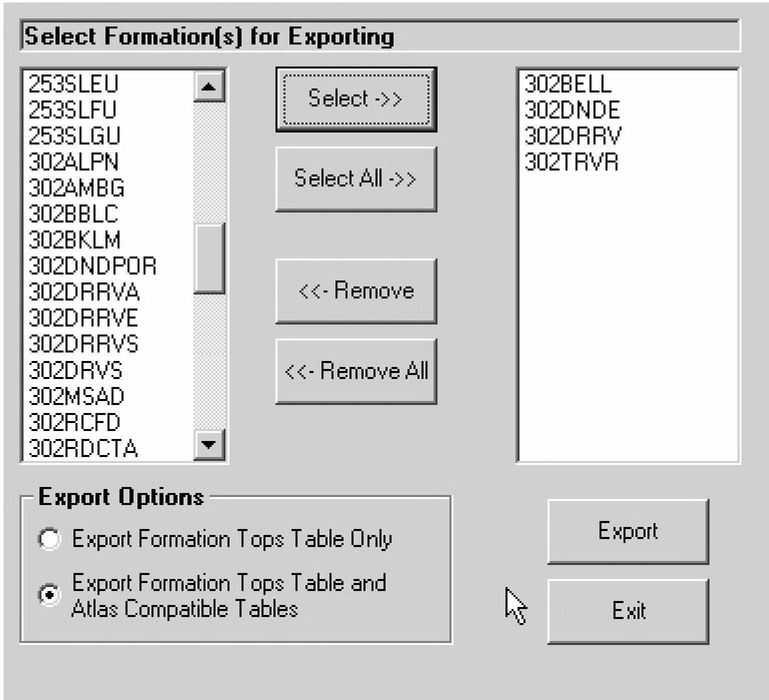
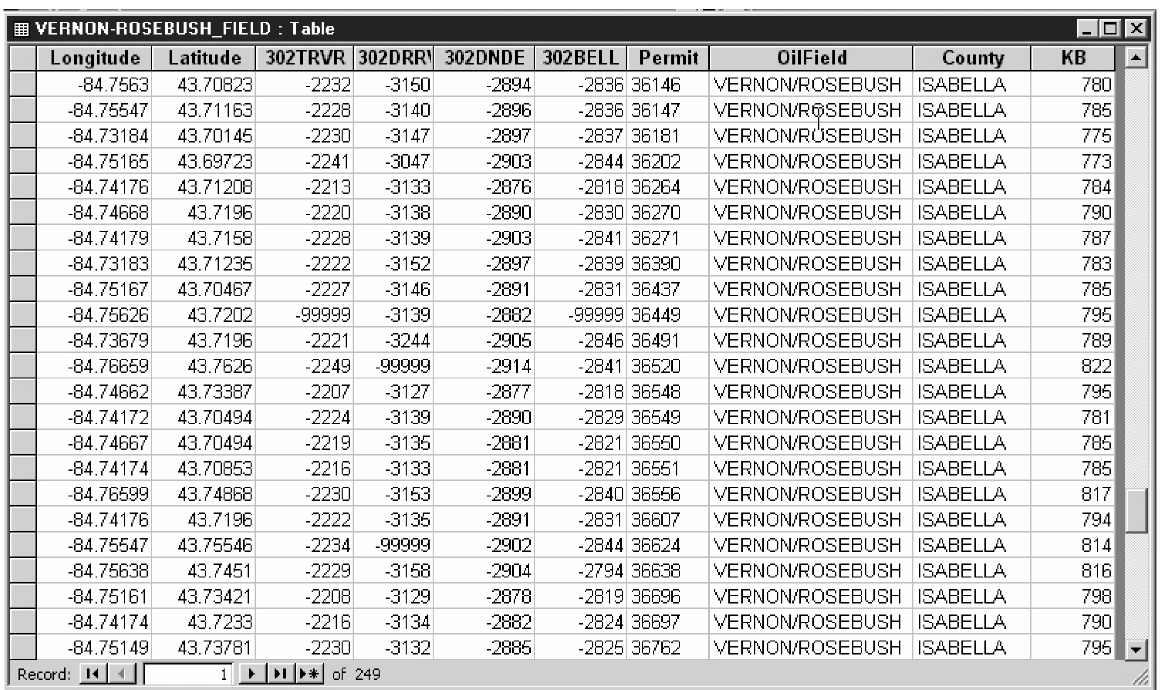


Figure 2.6. ATLAS Export Selection Screen.


VERNON-ROSEBUSH_FIELD : Table

Longitude	Latitude	302TRVR	302DRRV	302DNDE	302BELL	Permit	OilField	County	KB
-84.7563	43.70823	-2232	-3150	-2894	-2836	36146	VERNON/ROSEBUSH	ISABELLA	780
-84.75547	43.71163	-2228	-3140	-2896	-2836	36147	VERNON/ROSEBUSH	ISABELLA	785
-84.73184	43.70145	-2230	-3147	-2897	-2837	36181	VERNON/ROSEBUSH	ISABELLA	775
-84.75165	43.69723	-2241	-3047	-2903	-2844	36202	VERNON/ROSEBUSH	ISABELLA	773
-84.74176	43.71208	-2213	-3133	-2876	-2818	36264	VERNON/ROSEBUSH	ISABELLA	784
-84.74668	43.7196	-2220	-3138	-2890	-2830	36270	VERNON/ROSEBUSH	ISABELLA	790
-84.74179	43.7158	-2228	-3139	-2903	-2841	36271	VERNON/ROSEBUSH	ISABELLA	787
-84.73183	43.71235	-2222	-3152	-2897	-2839	36390	VERNON/ROSEBUSH	ISABELLA	783
-84.75167	43.70467	-2227	-3146	-2891	-2831	36437	VERNON/ROSEBUSH	ISABELLA	785
-84.75626	43.7202	-99999	-3139	-2882	-99999	36449	VERNON/ROSEBUSH	ISABELLA	795
-84.73679	43.7196	-2221	-3244	-2905	-2846	36491	VERNON/ROSEBUSH	ISABELLA	789
-84.76659	43.7626	-2249	-99999	-2914	-2841	36520	VERNON/ROSEBUSH	ISABELLA	822
-84.74662	43.73387	-2207	-3127	-2877	-2818	36548	VERNON/ROSEBUSH	ISABELLA	795
-84.74172	43.70494	-2224	-3139	-2890	-2829	36549	VERNON/ROSEBUSH	ISABELLA	781
-84.74667	43.70494	-2219	-3135	-2881	-2821	36550	VERNON/ROSEBUSH	ISABELLA	785
-84.74174	43.70853	-2216	-3133	-2881	-2821	36551	VERNON/ROSEBUSH	ISABELLA	785
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-84.75547	43.75546	-2234	-99999	-2902	-2844	36624	VERNON/ROSEBUSH	ISABELLA	814
-84.75638	43.7451	-2229	-3158	-2904	-2794	36638	VERNON/ROSEBUSH	ISABELLA	816
-84.75161	43.73421	-2208	-3129	-2878	-2819	36696	VERNON/ROSEBUSH	ISABELLA	798
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-84.75149	43.73781	-2230	-3132	-2885	-2825	36762	VERNON/ROSEBUSH	ISABELLA	795

Record: 1 of 249

Figure 2.7. Sample data from table exported from ATLAS.

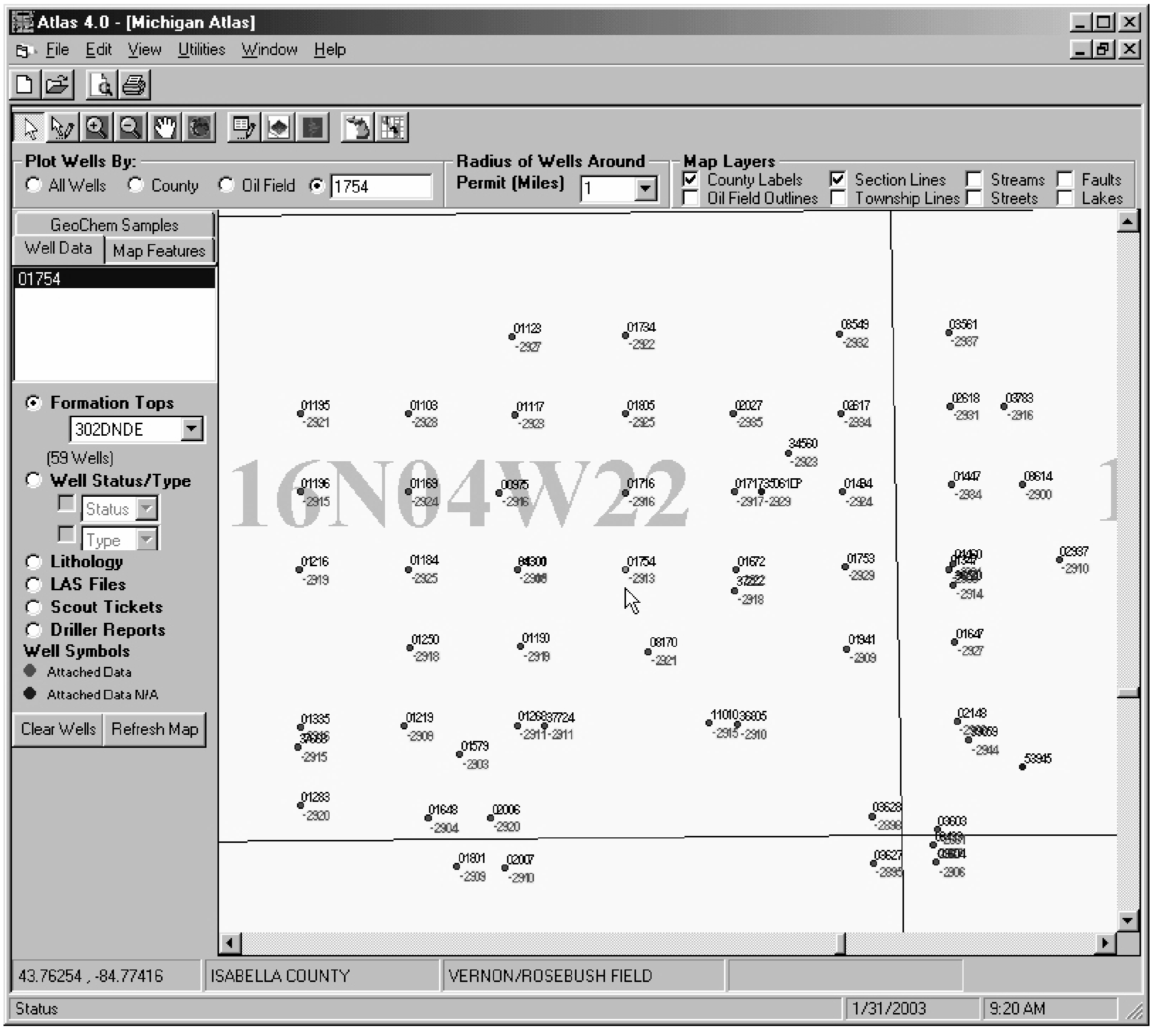

Figure 2.8. ATLAS display of wells within an approximate 1 mile radius of Permit 01754. The permit number is posted to the upper right of each well spot, and the subsea Dundee top depth is posted to the lower right of each well spot.

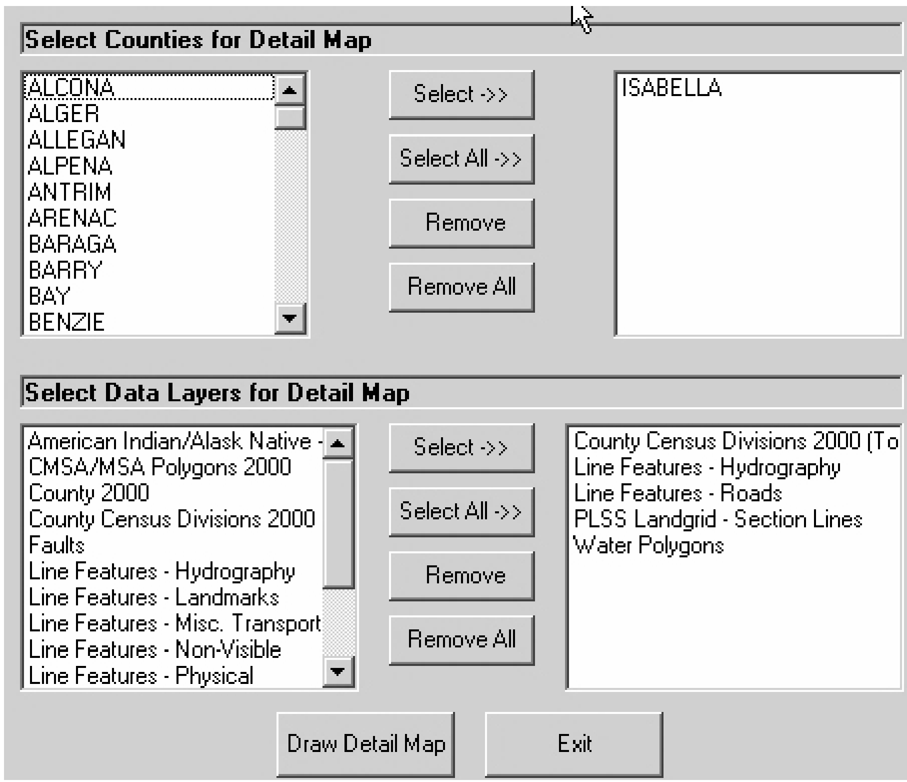

Figure 2.9. ATLAS selection screen for selecting counties and map features for enhancing the ATLAS display map.

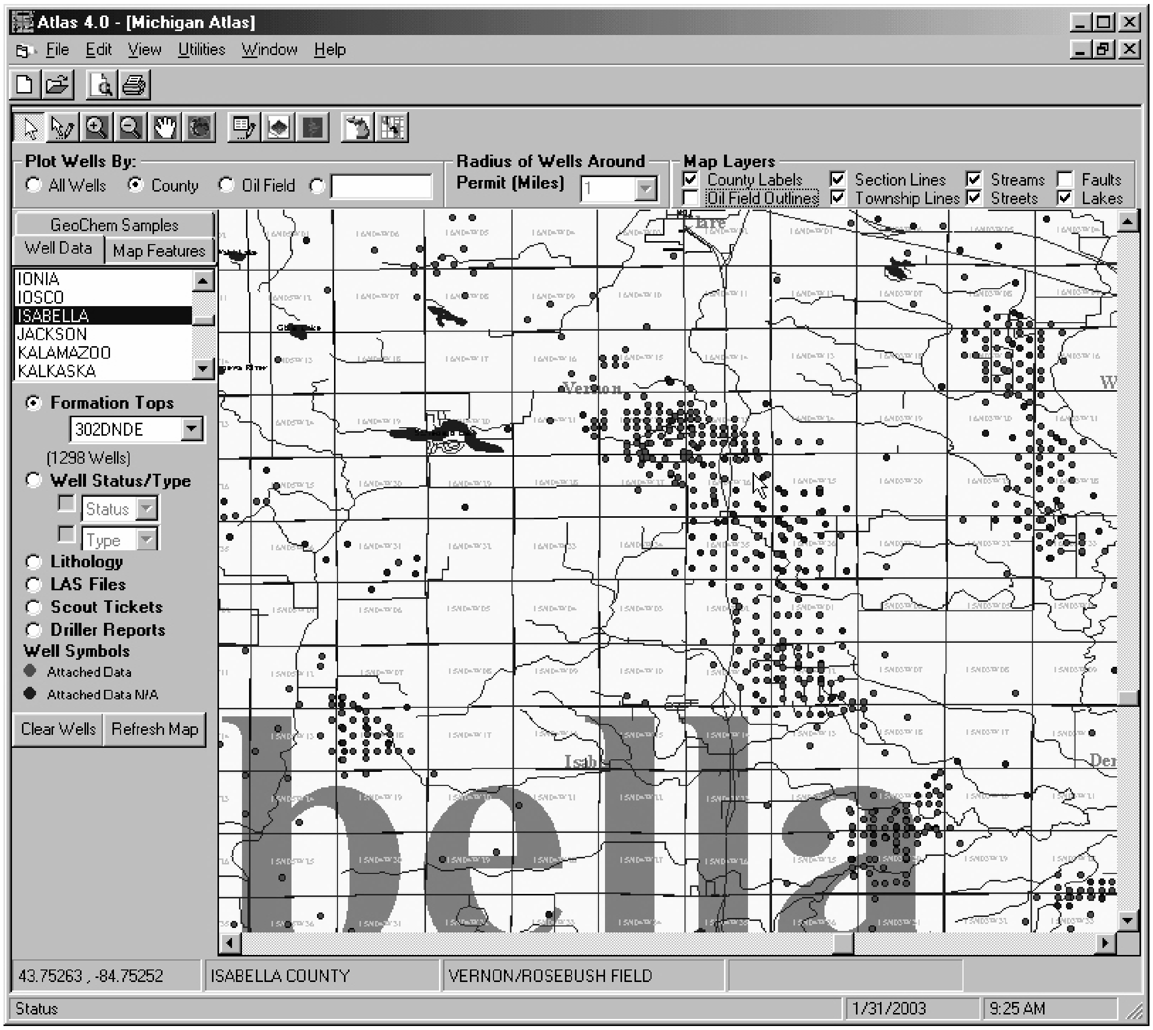

Figure 2.10. ATLAS map display showing lakes, rivers, roads, section lines, and township lines.

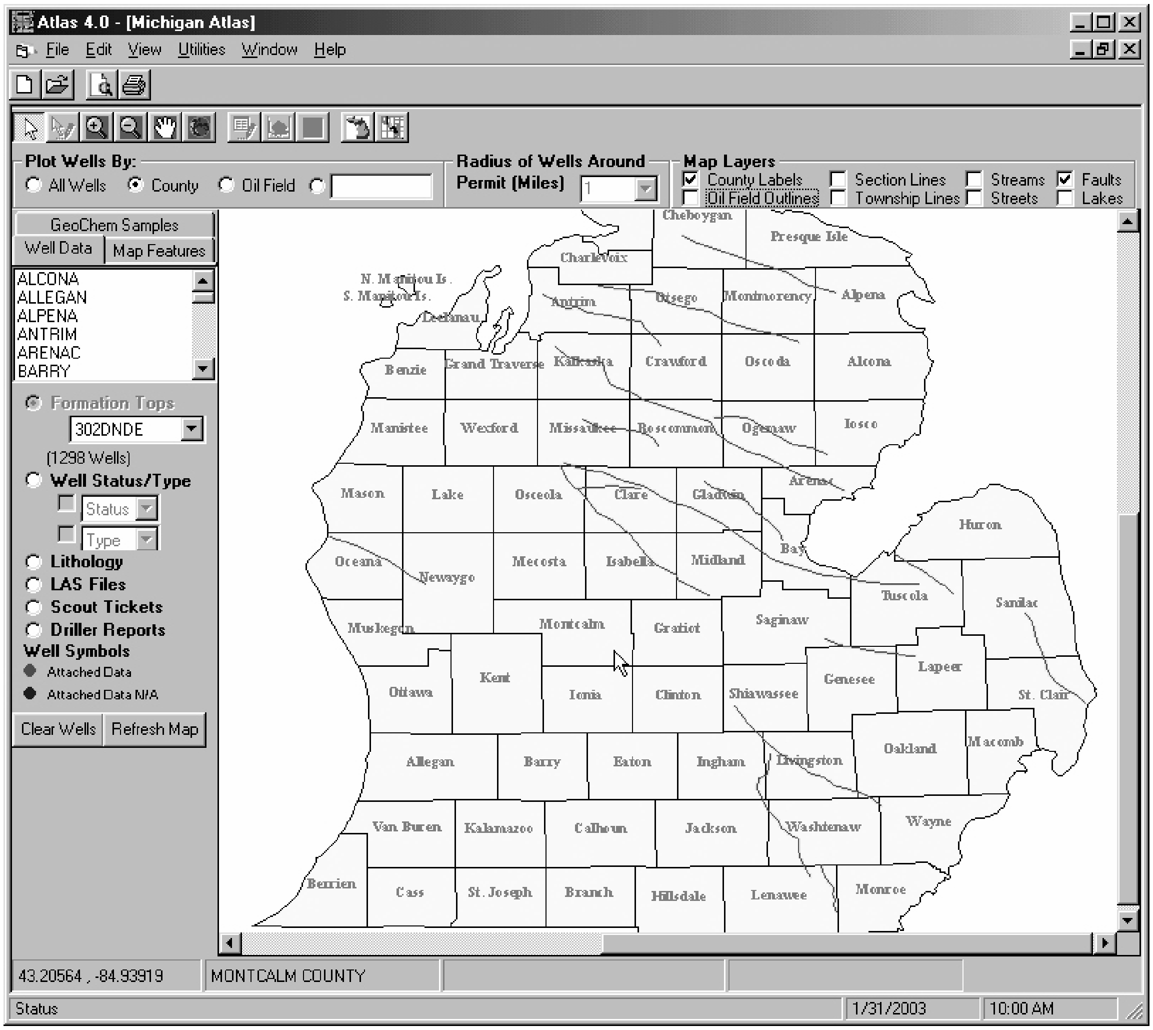

Figure 2.11. ATLAS map display of Michigan fault lines.

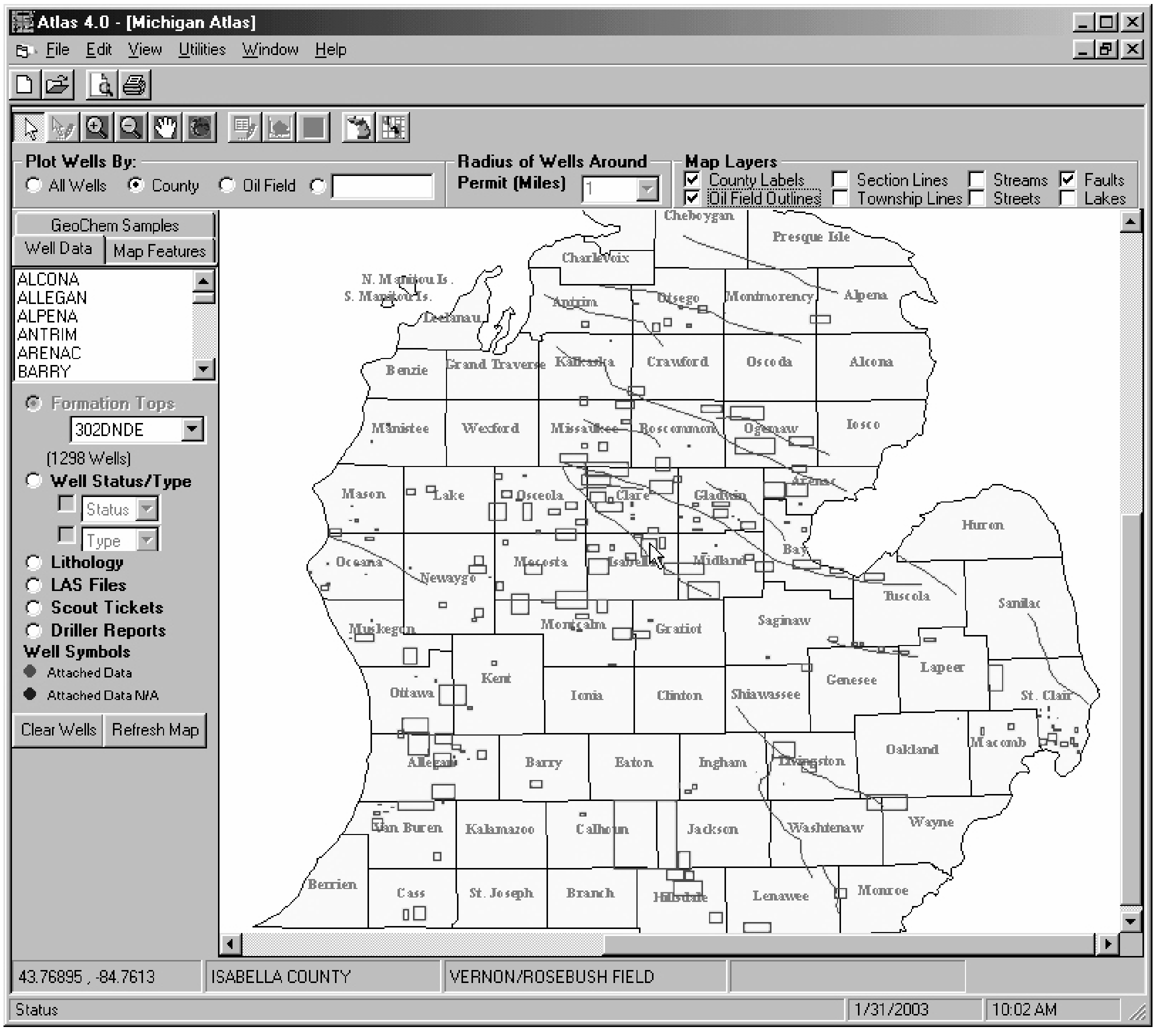

Figure 2.12. ATLAS map display of major oil fields in Michigan with fault lines.

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3.0 Faults & Deformation Bands

3.1 Introduction

A major finding of this project is the presence of a number of Northwest-Southeast trending faults or "lineations" or "deformation bands" (Figure 3.1) that cut the central Michigan Basin into a number of elongate sections. Although the fault-like nature of these lineations is problematical in some areas it is not in others (e.g. the Howell Anticline) and the lineations will be referred to as faults for convenience in this report. Readers should keep in mind that no lateral displacement has been demonstrated for these faults and the vertical displacements are gentle enough that some workers in the field prefer to map them as anticlinal and synclinal structures based on the rather gentle dips associated with the structures. Nevertheless, the continuity and vertical displacements that can be demonstrated for these features make a compelling case that they are fractured and displaced in some places and are therefore true faults. These faults are closely related to the hydrocarbon reservoirs and probably control both the locations of reservoirs as well as the fluid migrations that filled them with hydrocarbons and the late-stage hydrothermal dolomitization observed in many reservoirs.

3.2 Previous History of Faults in the Michigan Basin

Most geologic maps of the United States do not show the presence of any faults in Michigan (Figure 3.2) nor does the USGS fault file for the U.S. list any faults for Michigan Basin. The reason is not because people believe that faults are not present, but because it is difficult to map them because of the presence of glacial cover up to 600 feet thick over most of the State. This cover precludes directly mapping the bedrock geology of Michigan and effectively hides all faults and fault traces. Nevertheless, numerous publications show the presence of faults on a local scale, usually associated with producing gas and oil fields. This study basically built on that foundation by demonstrating the presence of basin-wide faults that essentially connect many of these earlier reported faults.

An increase in seismic data acquisition over the Michigan Basin has provided useful information regarding the Precambrian basement tectonics and its effect on younger basin structures because well control within the basement is limited. Seismic results indicate a vertically faulted basement, with the majority of faults terminating at or before Middle Devonian age rocks (Fisher and Barratt, 1985; Fisher and others, 1988). This fault movement was due to regional stresses and created a pattern parallel to that of the Canadian Shield as noted by Fisher and Barratt (1985). Dense well coverage within the Paleozoic stratigraphy of the southeastern region of the Michigan Basin reveals four major faults, from west to east: Albion-Scipio, Lucas Monroe, Howell, and Sanilac (Fisher and others, 1988).

The general trend for faults within the Michigan Basin is northwest-southeast. A majority of anticlines also trend this direction as their formation is controlled by the underlying faulted basement. As this trend does not follow recognized tectonics of Proterozoic time, Ryder (1996) suggests a connection between the faulted basement blocks and the similarly trending eastern arm of the Midcontinent rift system.

Ryder (1996) states the following regarding the origin of structures in the Michigan Basin:

> “According to Apotria and others (1993, 1994), the northwest-southeast fracture set is the oldest as shown by its continuity and abutting relationships. They suggest that fractures in this set formed as natural hydraulic fractures during northwest-southeast oriented Alleghanian compressive stress near peak burial and thermal maturation. Fracturing occurred preferentially in the black shales because of their low Poisson's ratio and their probable high fluid pressure owing to gas generation (Apotria and others, 1993, 1994). The northeast-southwest fracture set formed during post-Alleghanian uplift of the Michigan basin under a state of northeast-southwest oriented maximum horizontal compression. Cooling and unloading reduced the minimum horizontal stress to form extension fractures. This thermoelastic contraction mechanism is strongly influenced by Young's modulus
>
> Northwest-directed Alleghanian compression, as a primary cause of the regional northwest-southeast fracture set, is supported by regional petrofabric studies of Craddock and van der Pluijm (1989). Moreover, northwest-directed Alleghanian compression may have created the dominant, basement-cored, northwest-trending anticlines. One possible mechanism is that an unrecognized Proterozoic basement fabric--such as one formed during Grenvillian compression of Midcontinent rift structures (Cannon, 1994)--was reactivated by Alleghanian tectonics.”

3.3 History of Fault Interpretation and Identification in the Michigan Basin

Regional structural trend maps of the Michigan Basin show the presence of numerous northwest-southeast oriented fold or anticlinal trends but few, if any, fault trends or traces (Figures 3.3, 3.4) (Catacosinos et al., 1991, Figure 1; Fisher et al., 1988; Prouty, 1983, Figure 5; Ells, 1969, Figure 2). Many of these fold trends are asymmetric toward the north. Theories regarding the origin of these fold trends postulate the episodic reactivation of zones of basement weakness at one or more times during the Paleozoic (Prouty, 1983; Ells, 1969; Lockette, 1947; Newcombe 1932; Pirtle, 1932). The en echelon arrangement of some of these folds has been interpreted to be the result of shearing movement along deeply buried basement faults (Prouty, 1983).

The first published presentation of a fault on a subsurface map from the Michigan Basin was probably that of Newcombe (1932) on his structure map of the Berea sandstone over the Howell Anticline in southeast Michigan (refer to Figure 3.4). Cohee (1947) considered this fault to be normal while Paris (1977) concluded the fault to be largely lateral; today there is still controversy over the configuration of this fault. Ells (1969) presented a composite map of the Michigan Basin showing probable and possible faults (Figure 3.5). Most of the faults are located in the southeastern part of the basin and were interpreted to be related to dolomitization chimneys associated with Trenton-Black River oil fields. Four faults, however, are shown to be present in Dundee pools in the east, central part of the Michigan Basin. These Dundee fields are the Pinconning, North Adams, Deep River, and Skeels and the faults are shown to both parallel and to cross cut these anticlinal features. Various workers have shown faults on structure maps at the field scale (refer to Michigan Basin Geological Society Oil and Gas Fields Symposium publications), especially at deeper levels in the basin such as the Prairie du Chien. At shallower levels, however, most workers typically only show folded or anticlinal features on their field scale subsurface maps (e.g., Curren and Hurley, 1992).

Versical (1991, 1990) used vertical joint sets and strains calculated from twinned calcite grains in limestones to determine an overall southeast-northwest directed compressive stress orientation for the Michigan Basin due to Appalachian orogenesis. This direction of compression is approximately parallel with hydrocarbon producing anticlinal structures in the basin. Versical (1991) postulated the reactivation of basement faults with a strong component of left-lateral strike-slip movement to explain the low values of shortening strain determined in his study and interpreted riedel shear-related en echelon faults at the Dundee level in the West Branch, Clayton, Deerfield, and Northville fields. Veriscal (1991) also interpreted riedel shears as forming the conduits for later dolomitizing fluids in the Albion-Scipio and Stoney Point fields clarifying the en echelon anticline/syncline interpretations of Hurley and Budros (1990) and Ells (1962) for these fields.

Buthman (1995) illustrated several faults cutting the Ordovician Trenton Limestone in a regional Trenton structure map (Figure 3.6). This map is the only known publication showing interpreted fault trends at the basin scale for the Michigan Basin. The present study expands upon the foundation provided by previous workers by demonstrating that faulting is more pervasive and plays a more important role then previously believed in the location and productivity of oil and gas fields. This study also demonstrates that these faults extend to higher stratigraphic levels than previously interpreted and that many of the anticlinal trends in the basin may, in fact, be faulted anticlines.

3.4 Techniques for Mapping Large-Scale Faults

The faults depicted in Figure 3.1 were discovered by mapping the tops of formations, particularly the Dundee formation, using closely spaced contours (Figure 3.7) and then using specialized mapping software to further visualize and characterize these features. Only formation tops data were used to delineate these faults; seismic data would be useful to fill in areas of poor or no data as a next step in the characterization, but were not used here.

Although the technique for mapping these features is simple there are a number of considerations that need to be fulfilled in order to bring them out. First among these is a suitable density of data points; essentially subsea elevations of formation tops with latitude-longitude coordinates. A number of formations in the Michigan Basin have tops data associated with them, but only a few have the number required for high-density contouring. Among these, the Dundee Formation is rather uniquely suited. There are about 30,000 usable data points for this formation, covering most of the basin, and particularly covering the Central Michigan Basin, which is the focus of the investigation. These 30,000 data points were edited to remove bad or extraneous points, then fed into a contouring program (Surfer©) and gridded. It was found that a kriging algorithm produced the best results based on absence of “bulleyes” and general smoothness of the contours. High-resolution contour maps of the Dundee Formation are shown in Figures 3.7 and 3.8 for the entire data set covering most of the Michigan Basin and for the Central Michigan Basin respectively. These plots show a great deal more character than most published contour maps of the Dundee found in the literature. The reason is of course that the contour interval is much smaller, 10 to 20 feet as compared to the more usual 200 to 500 feet. This increased resolution in turn shows structures that are either not apparent at lower resolutions or are not as well defined. The close spacing of the contour bands trending Northwest-Southeast stands out in particular. It is these features that first drew attention to the presence of previously unmapped faults in the basin.

In addition to the standard contour maps of structure, several new techniques have been developed for terrain analysis and were used to further characterize and locate the faults. In general terrain analysis utilizes algorithms to compute parameters for a surface that are related to fluid flow, including algorithms that will compute strike and dip from a digital model of a surface. Surfer© uses algorithms called “terrain aspect” and “terrain slope” to compute these attributes. Terrain Aspect, calculates the downhill direction of the steepest slope (i.e. dip direction) at each grid node. It is the direction that is perpendicular to the contour lines on the surface, and is exactly opposite the gradient direction. Terrain Aspect values are reported in azimuth, where 0 degrees points due North, and 90 degrees points due East. Terrain Slope calculates the slope at any grid node on the surface and is reported in degrees from zero (horizontal) to 90 (vertical). For a particular point on the surface, the Terrain Slope is based on the direction of steepest descent or ascent at that point. This means that across the surface, the gradient direction can change. Grid files of the Terrain Slope can produce contour maps that show isolines of constant steepest slope. This operation is similar to the way the first directional derivative defines the slope at any point on the surface but is more powerful in that it automatically defines the gradient direction at each point on the map.

In this study it was found that terrain aspect produced a useful map of the faults (Figure 3.9). This algorithm basically plots the direction of steepest descent on the surface and thus shows the direction a fault would face as it crosses the basin. This map basically confirms the results obtained from analysis of the stacked contours on the structure map, but does so in a more rigorous manner. Attempts to use the terrain slope function did not produce useful results, probably because the surface representation of the top of the Dundee Formation was too rough. Smoothing the surface digitally may improve this situation, but remains to be demonstrated.

3.5 Relation to Hydrocarbons

The significance of these large-scale faults in the Michigan Basin is that they are closely related to hydrocarbons and to regional dolomitization trends. The relationship to hydrocarbons is obvious when the producing reservoirs in the basin are plotted with the faults

(Figure 3.10). Most of the major reservoirs in the Dundee Formation, for example, are located in low-amplitude anticlines on the up-thrown sides of these faults. It appears likely that the same geologic processes that produced the faults also produced the anticlines. Thus the faults and anticlines could be contemporaneous. It should be noted that some fields, mostly minor ones, do occur in small anticlinal structures on the downthrown side of the faults (Figure 3.10). However, these fields tend to be located further away from the faults, often several miles, while the large fields on the upthrown sides are usually located within 200-300 feet of the fault.

In terms of the late, hydrothermal dolomitization, the faults could have been the fluid conduits for the diagenetic fluids. Evidence for this is the same as for the reservoirs, proximity to the fault of altered reservoirs (e.g. Vernon-Rosebush Fields, Figure 3.11).

3.6 Origin

The origin of these deformation bands is unknown. The fact that they run for hundreds of miles uninterrupted across the basin indicates that the process was not a local phenomenon. Circumstantial evidence suggests that the bands are related to the tectonic process that operated on the Eastern seaboard of the U. S. during the Paleozoic, specifically the Taconic, Arcadian and Appalachian orogenies. A plot of the Devonian (Dundee-age) rocks in the Eastern U. S. (Figure 3.12) shows that these rocks are progressively more deformed going West to East. The Devonian and earlier rocks in the Appalachian Mountains are severely deformed, the same rocks in the Appalachian Basin less so and the same age rocks in the Michigan Basin apparently undeformed except for deformation bands reported here. If this scenario is true, then it suggests that the tectonic stresses that deformed the Eastern seaboard in the Middle-to-Late Paleozoic also reached the Michigan Basin, albeit with greatly reduced intensity.

3.7 Summary

It appears that the Michigan Basin suffered some moderate deformation during the Paleozoic orogenies that so strongly deformed the Eastern U. S. and that this deformation is recorded in more or less continuous NW-SE trending deformation bands that cut the basin into a number of structural provinces. The deformation was not severe enough to cause noticeable displacement of the Paleozoic sediments, but it did fold them into a number of gentle anticlines that parallel the deformation bands and which trend in the same direction. It some locations (e.g. the Howell Anticline) it is almost certain that the deformation produced (vertical) displacement of the sediments and it appears likely that at least moderate rupturing and fracturing occurred along most of the length of the deformation. The presence of hydrocarbons in the anticlines adjacent to the deformation bands, as well as extensive hydrothermal dolomitization of some reservoirs, suggests that they served as fluid conduits as well.

More work is needed to fully characterize these deformation bands, but this study has definitely established that they are present and that they are mappable by at least two techniques. It is likely that existing seismic could further elucidate these deformation zones now that we know almost exactly where they are located. A number of questions regarding the migration and reservoiring of the hydrocarbons in the basin can be answered by the presence of the deformation bands: (1) the likely flow paths for fluids that altered and later filled the reservoirs; and (2) why the fields in Michigan have such pronounced Northwest-Southeast trends. The Northwest-Southeast trends appear to be related to distant tectonics in the Appalachian Orogen that only marginally effected the Michigan Basin. The effects generated anticlinal reservoirs and opened the rocks sufficiently to provide fluid conduits and rock alteration (dolomitization) resulting in the creation of reservoir quality porosity and permeability in otherwise tight limestones.

3.8 Figures

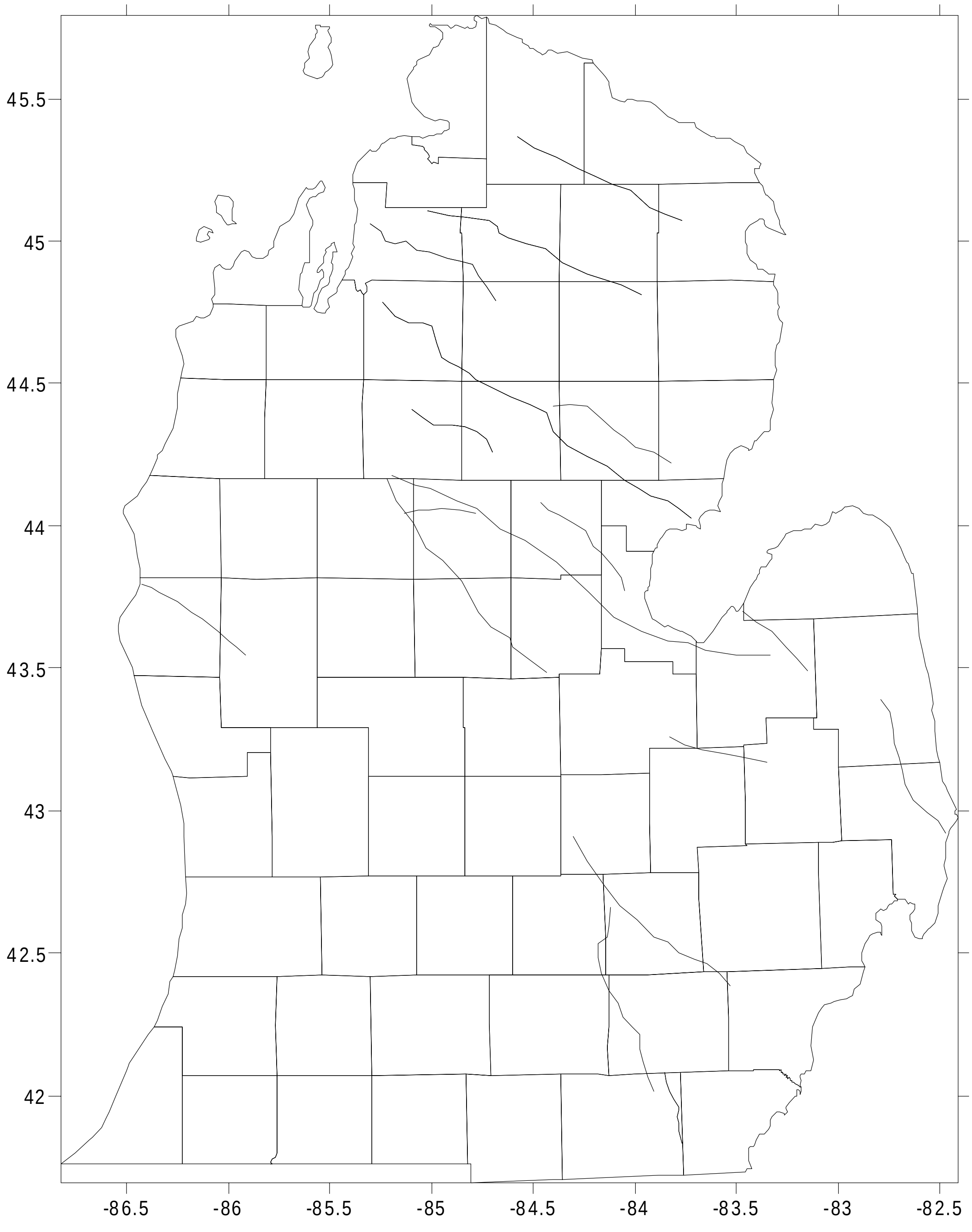

Figure 3.1. Location map showing trends of major basin-scale faults in Michigan Basin.

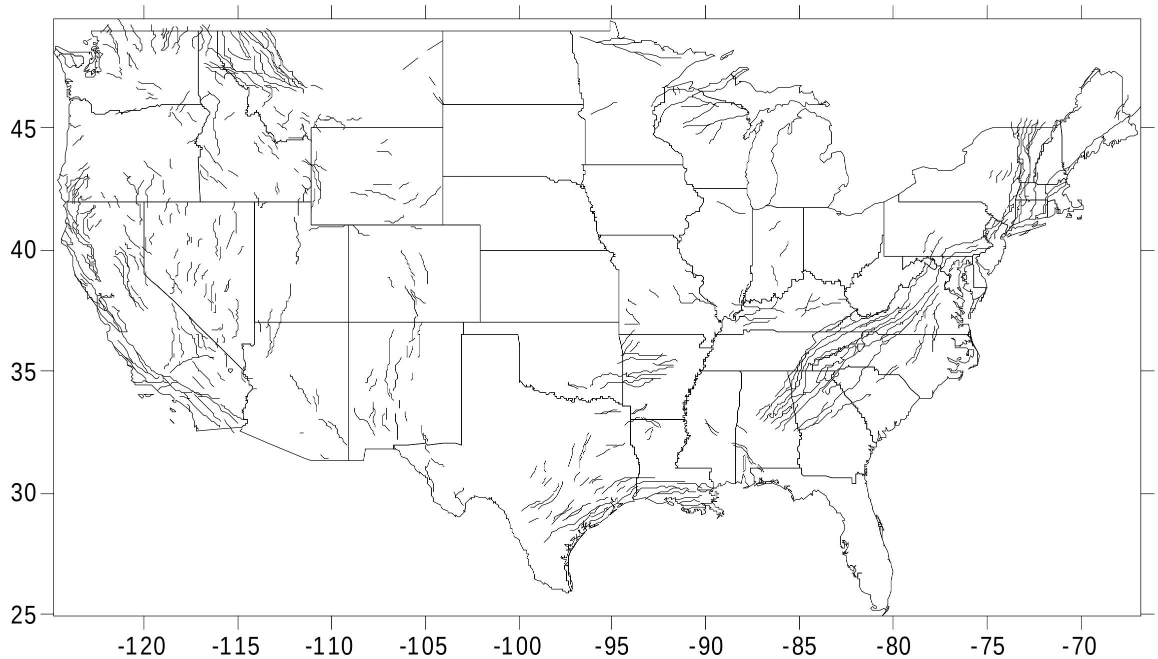

Figure 3.2. Map of United States showing major faults mapped by USGS. Note absence of any faults in Michigan.

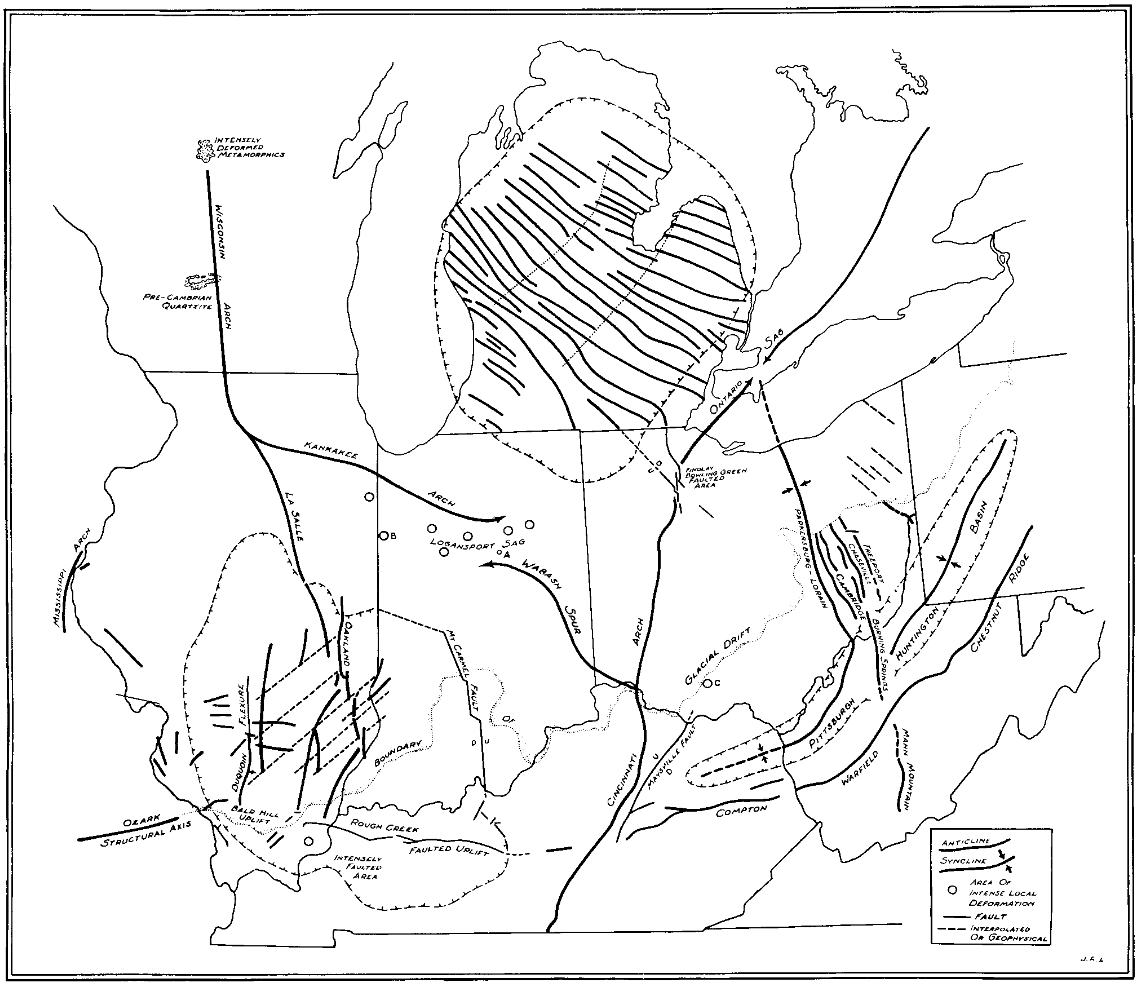

Figure 3.3. Structural trends in the Michigan Basin from Ells (1969).

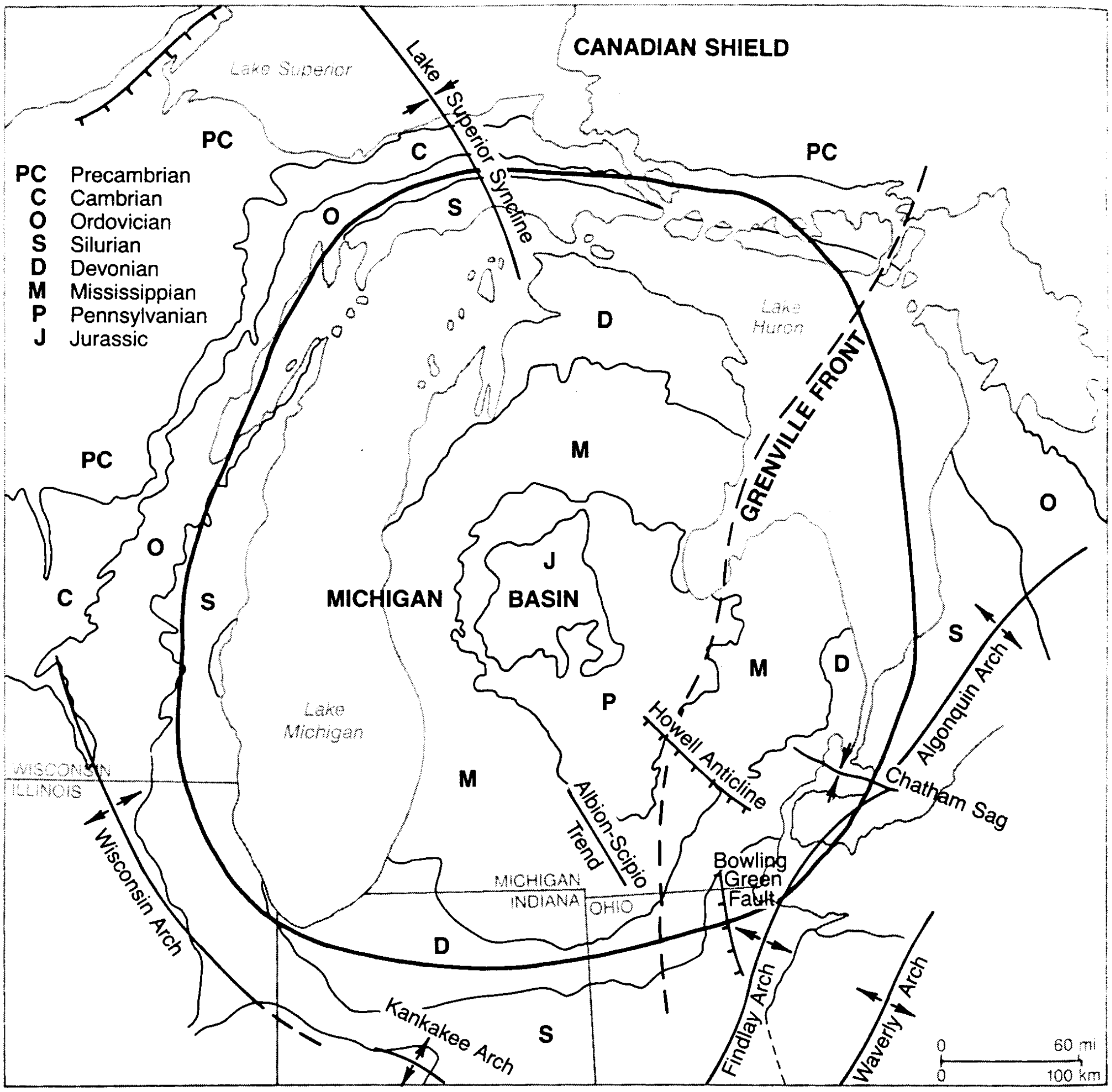

Figure 3.4. Structural trends in the Michigan Basin from Catacosinos (1991).

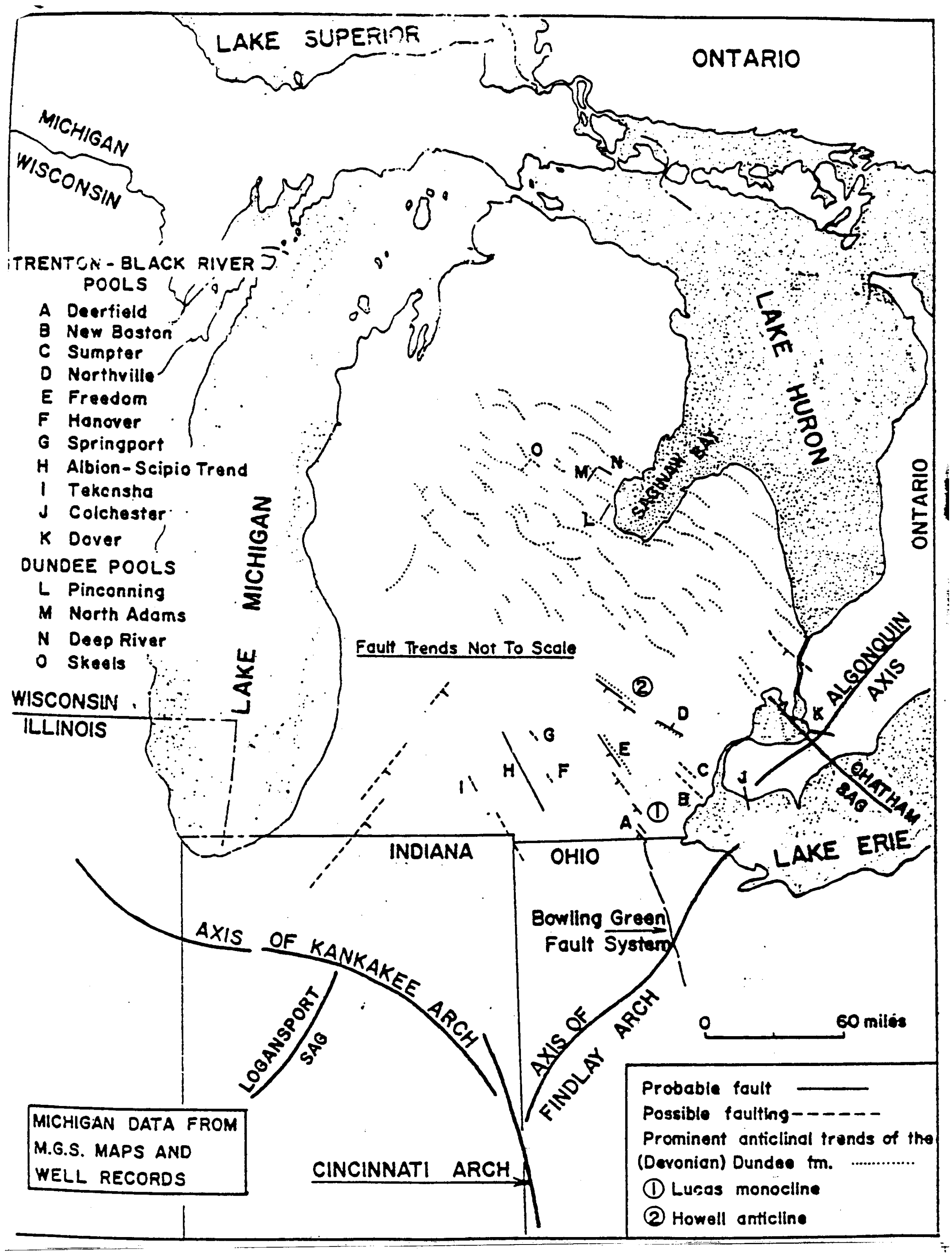

Figure 3.5. Anticlinal and probable and possible faults in the Michigan Basin (Ells, 1962).

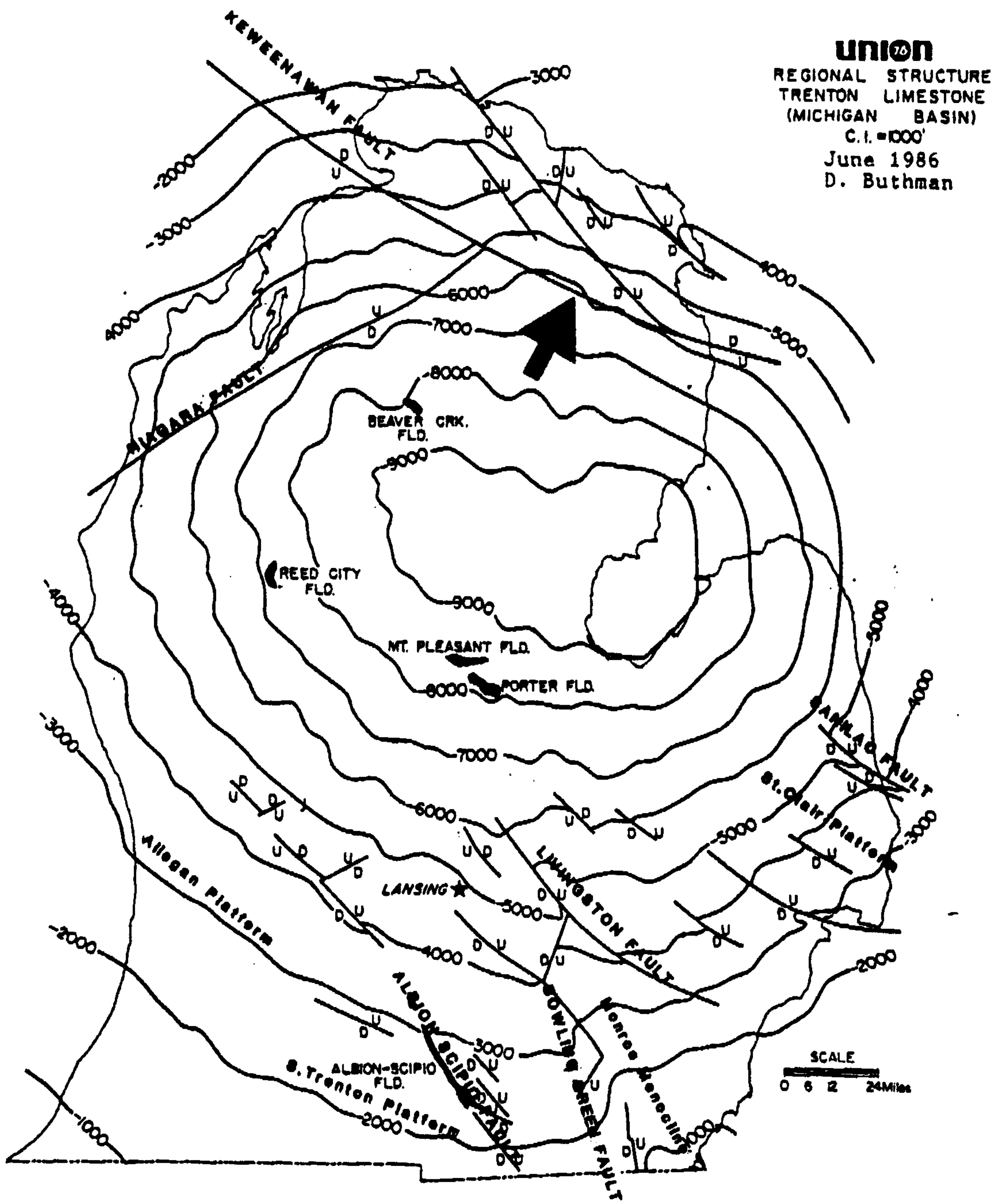

Figure 3.6. Regional Trenton structure of the Michigan Basin illustrating major fault lineations (Buthman, 1995).

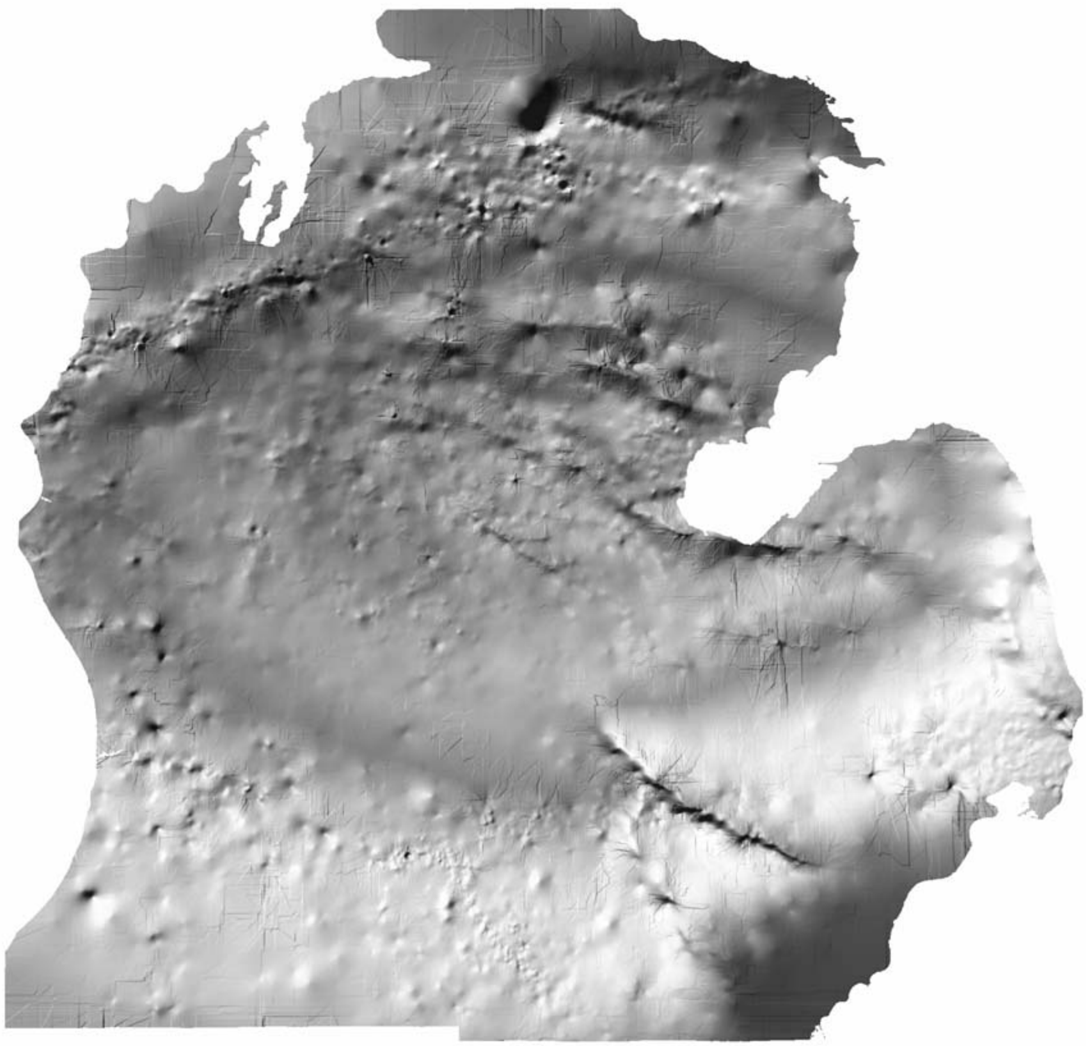

Figure 3.7. Structure map of top of the Dundee Formation in Michigan that suggests the presence of a basin-wide system of subparallel faults/lineations.

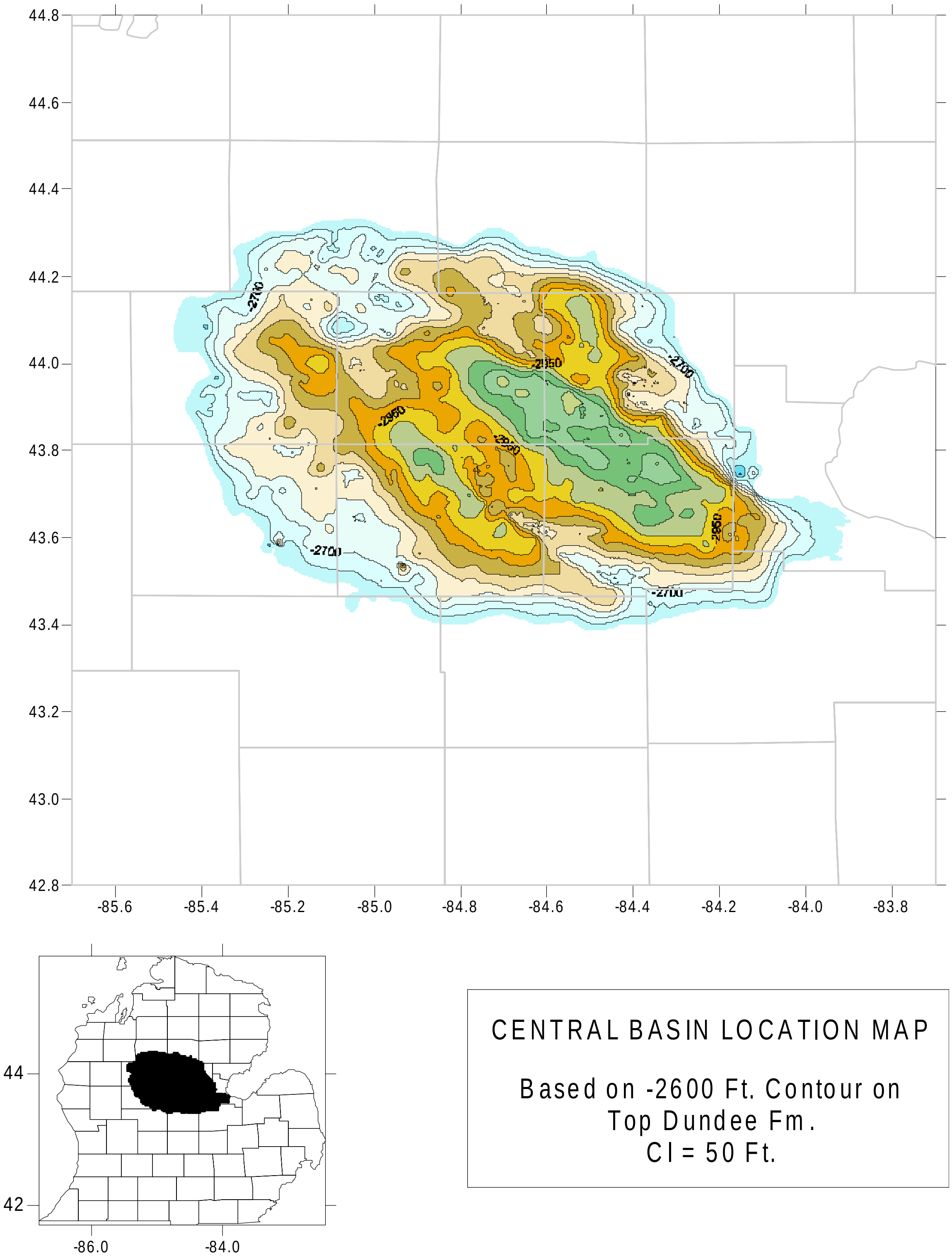

Figure 3.8. High resolution structure contour map on top of the Dundee Formation in the Central Michigan Basin showing the presence of the large-scale faults.

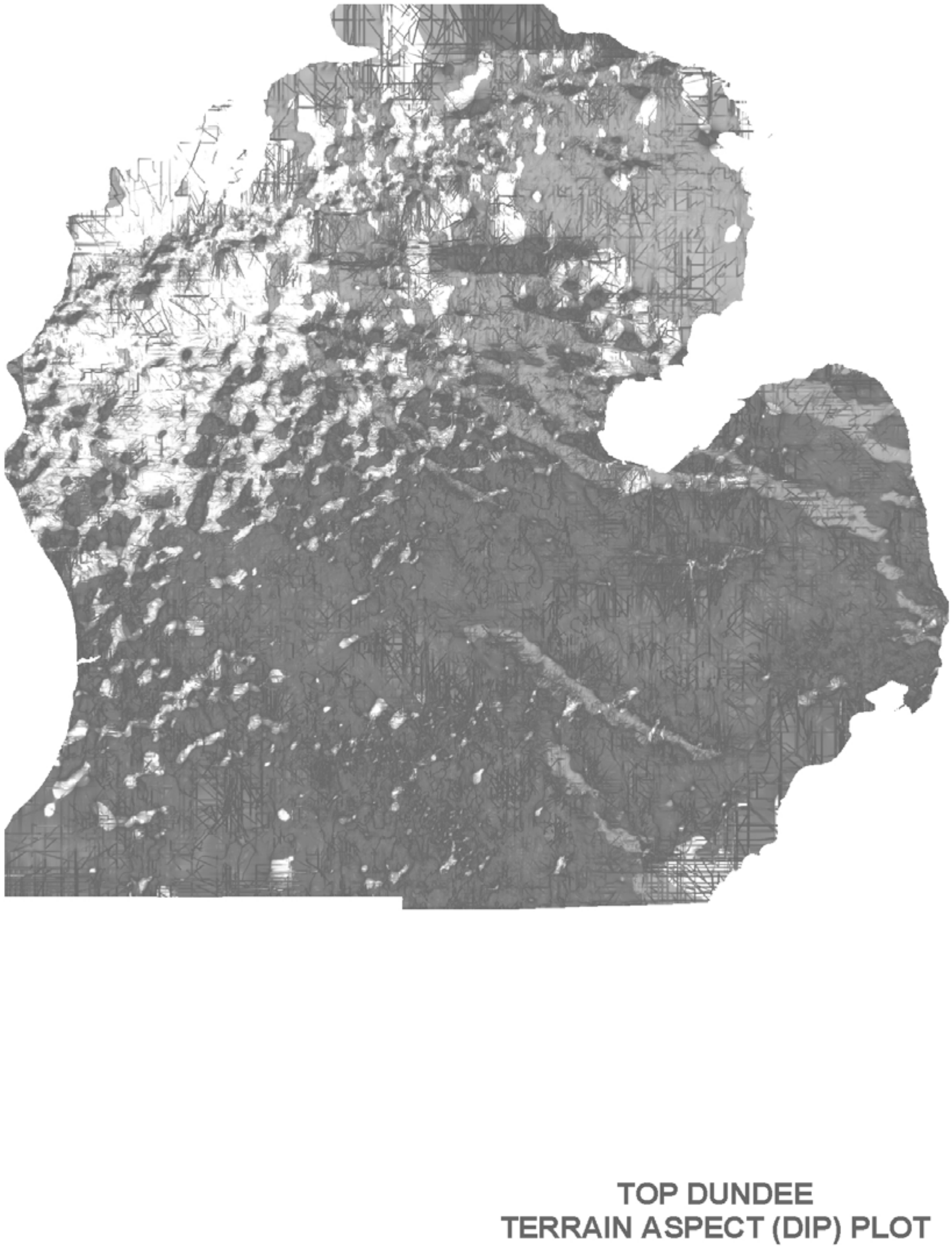

Figure 3.9. Terrain aspect map of the Central Michigan Basin delineating the large-scale faults.

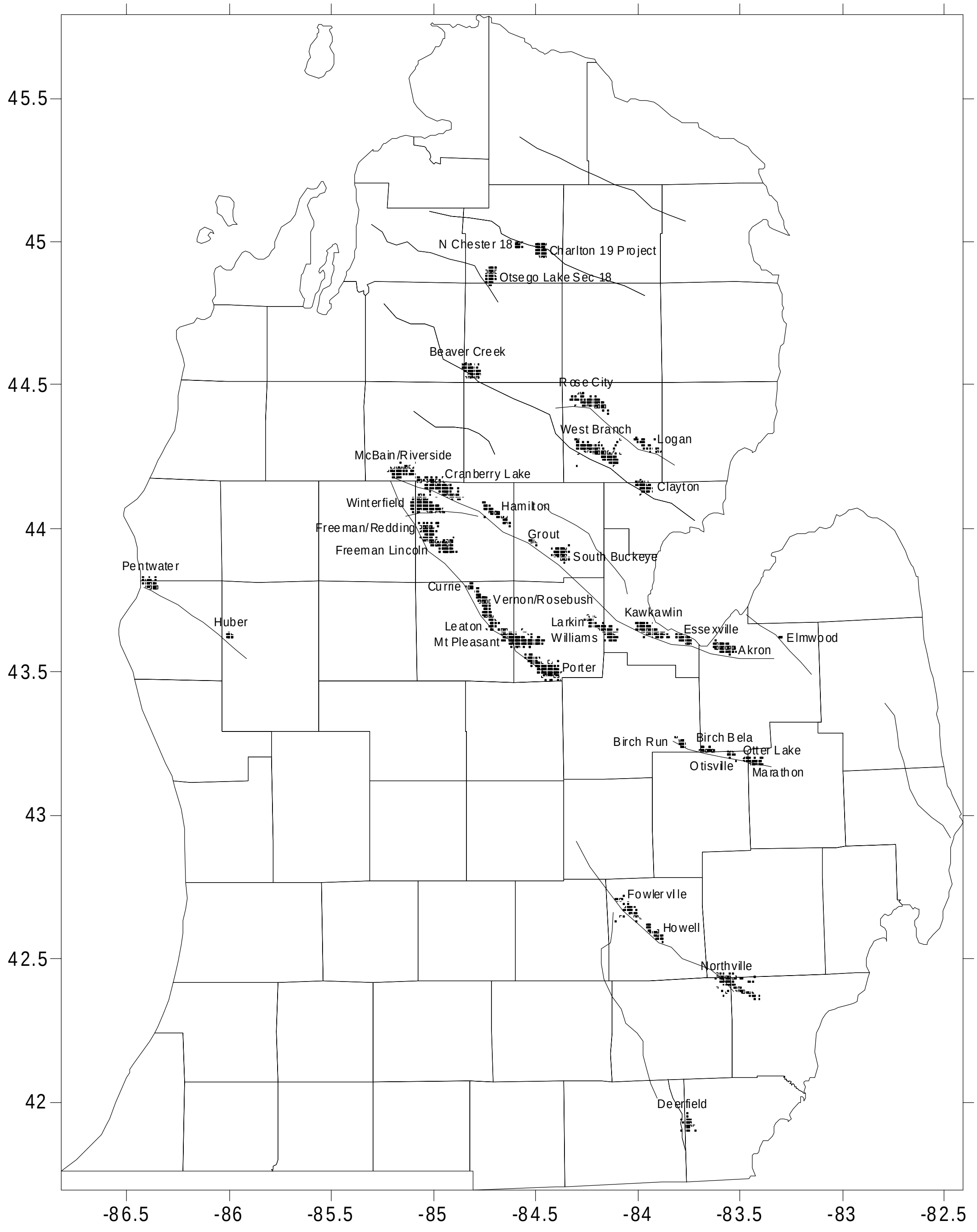

Figure 3.10. Map showing the relationship between the large-scale fault system and major gas and oil fields in Michigan.

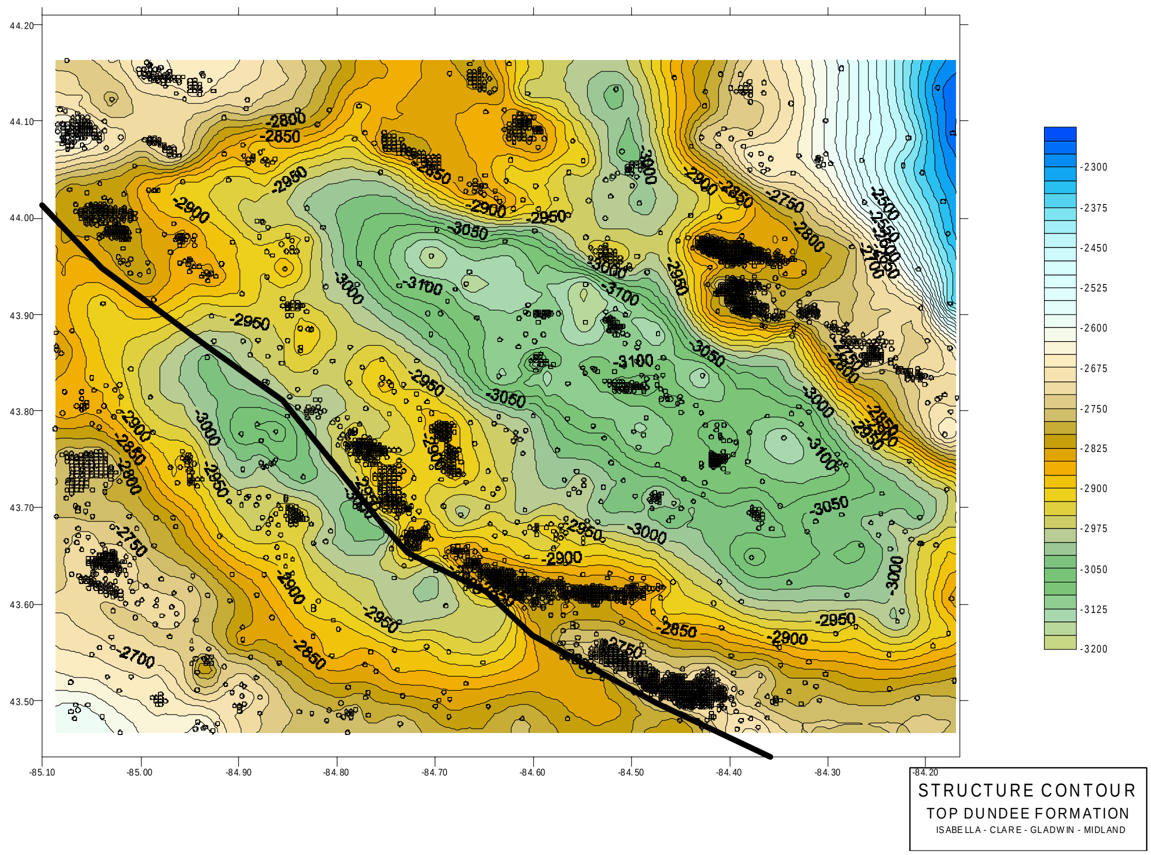

Figure 3.11. Structure map of the Top of the Dundee Formation at Vernon-Rosebush fields showing the relationship between these fields and the fault.

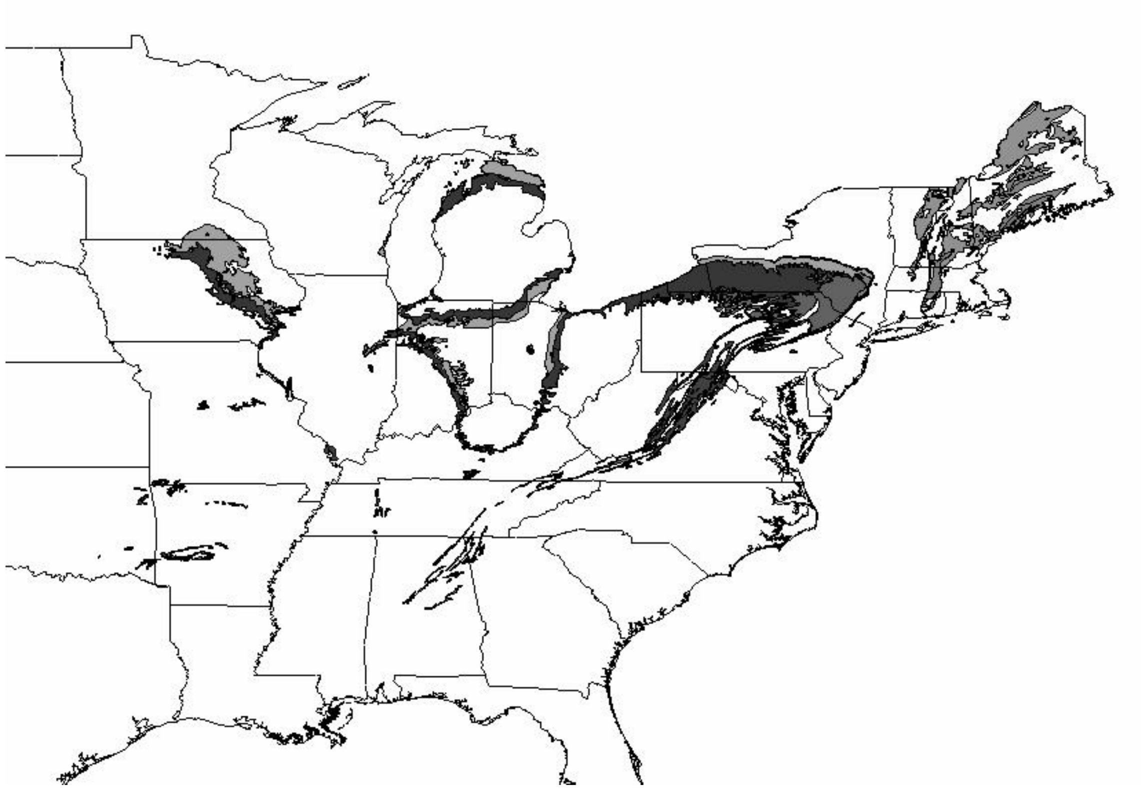

Figure 3.12. Plot of the Devonian age rocks for the Eastern United States showing progressive deformation from west (least deformed) to east (most deformed).

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4.0 Fractures

4.1 Introduction

Numerous studies, including some done in the course of this study, have established that the Michigan Basin is extensively fractured in some places, including many of the more prolific gas and oil reservoirs. The fracturing is revealed in both logs and core and is often associated with diagenetic cements, such as hydrothermal “saddle” dolomite. The larger fields associated with fracturing include Crystal, Vernon, Fork, Cat Creek and exploratory wells not associated with producing fields. In general, the fracturing occurs in carbonate rock and may be either numerous, closely spaced, healed fractures, or more open vug or cavity-filling fractures lined with authigentic cements. They often have a preferred orientation and provide good fracture porosity and permeability.

Some examples of fractures from the fields cited above include:

1. Tow 1-3 HD: Crystal Field, Montcalm County, MI, Permit #50047
2. Thelma Rousseau 1-12: Fork Field, Mecosta County, MI Permit #35426
3. Paul Rieman #1: Cat Creek Field, Osceola County, MI, Permit #27191
4. Bessie & Fernon Lee #1: Exploratory, Montcalm County, MI, Permit #24011
5. Shuttleworth #1: Exploratory, Gratiot, MI, Permit 26779 (near Crystal Field)

4.1.1 Tow 1-3 HD: Crystal Field, Montcalm County, MI,

Figure 4.1 (Tow 1-3-1) Photograph of slabbed core from Tow 1-3 HD showing coarse white saddle dolomite-filled fractures in Dundee limestone. Note cavities filled with euhedral dolomite. 3195 ft.

4.1.2 Paul Rieman #1: Cat Creek Field, Osceola County, MI Permit #27191

Figure 4.2 (Rieman 1-1) Medium-grained euhedral dolomite (2 types) filling vugs. 3749 ft.

4.1.3 Bessie& Fernon Lee #1: Exploratory, Montcalm County, MI. Permit # 24011

Figure 4.3 (Lee 1-1) Coarse, white saddle dolomite in abundant fracture in Dundee Limestone. 3466.5 ft.

4.1.4 Shuttleworth #1: Exploratory, Gratiot County, MI. Permit #26779 (near Crystal Field)

Figure 4.4 (Shuttle 1-5) Photo of core segment 1-10-2 showing fracture and vug-filling saddle dolomite in Dundee Limestone.

4.2 Figures

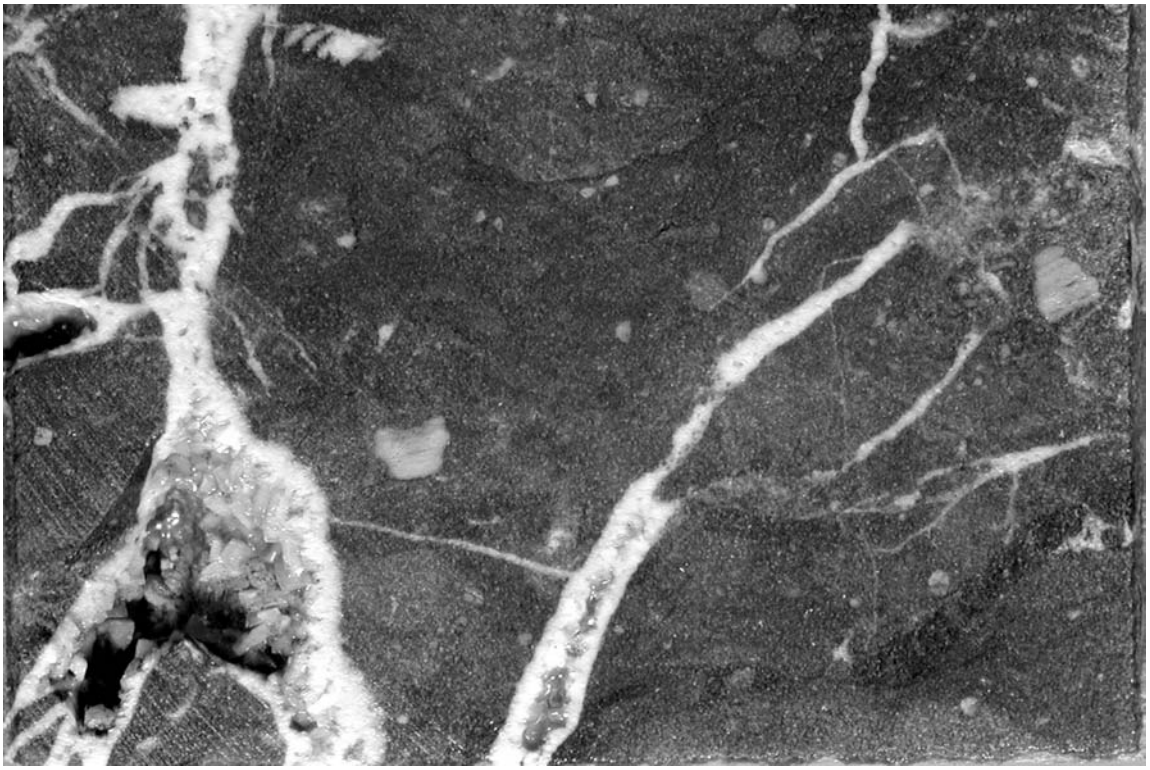

Figure 4.1. (Tow 1-3-1) Photograph of slabbed core from Tow 1-3 HD showing coarse white saddle dolomite-filled fractures in Dundee limestone. Note cavities filled with euhedral dolomite. 3195 ft.

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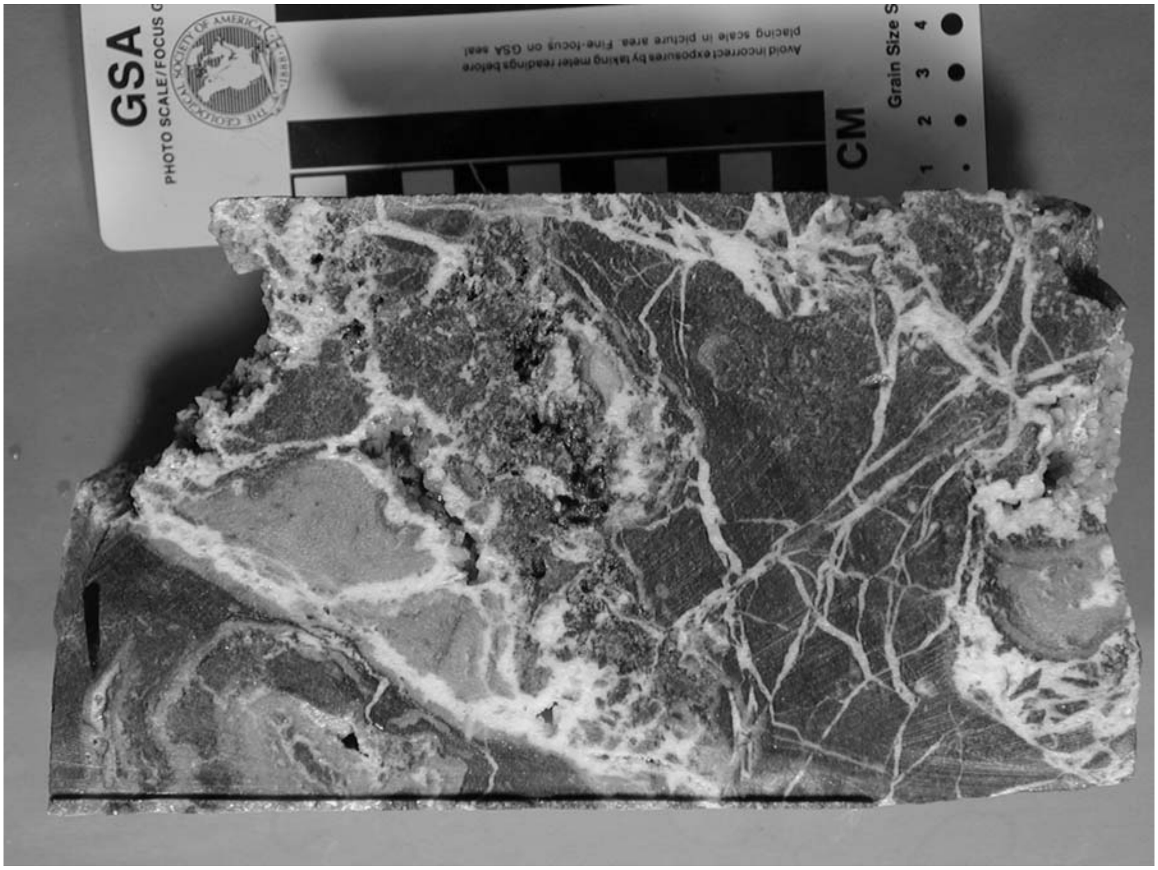

Figure 4.4. (Shuttle 1-5) Photo of core segment 1-10-2 showing fracture and vug-filling saddle dolomite in Dundee Limestone.

5.0 Diagenesis

5.1 Introduction

Several stages of diagenesis have occurred in the Michigan Basin, including sabbka-type dolomitization and a late Paleozoic hydrothermal dolomitization. The Paleozoic diagenesis is associated with hydrocarbon reservoirs, particularly in Devonian rocks, and is considered a necessary condition for a good reservoir. In addition to the late-stage dolomite, the early sabbka dolomite is mostly associated with the Late Silurian to Mid-Devonian carbonates but does not form good reservoirs. In this study data was collected on all known reported occurrences of dolomite in Paleozoic reservoirs. This is usually the hydrothermal “saddle” dolomite reported in Chapter.

5.2 “Top Porosity” / Late-stage Dolomite

The presence of dolomite has been recorded over by drillers as “top of porosity” and is given in drillers reports as such, much the same as a formation top pick. This is a generally reliable pick, either by log or by cuttings. It is reported in the Dundee (Middle-Late Devonian) Formation either at the very top of the formation, at the contact with the Bell Shale, or several tens of feet below the top of the Dundee (Figure 5.1). The dolomite likely forms through the circulation of Mg-rich brines derived from underlying evaporites on the tight (“tombstone”) limestone that comprises the Dundee Limestone. Thus, although the Bell Shale overlies the Dundee and could be a cap rock, the unaltered Dundee Limestone itself often serves as the seal. Dundee plays are typically complex combinations of structural, diagenetic and stratigraphic/facies-change traps. Several of the giant fields in Michigan, such as Albion-Scipio and Deep River, have a significant stratigraphic aspect and a minor structural aspect, and are both heavily dolomitized by late-stage hydrothermal fluids.

Figure 5.1 also shows the faults mapped in this project superimposed on the dolomite occurrences. In some cases, there is close proximity between the dolomite and a fault, suggesting a genetic relationship. In others, there is no relationship to the mapped faults, but the dolomite trends and the shapes of some of the fields suggest further examination of those areas for evidence of faults. This could be done using a more local scale rather than the basin scale used to map the larger faults.

5.3 Summary

The main accomplishment regarding diagenesis in the Michigan Basin during the course of this study was examining the driller’s reports for reported occurrences of dolomite and building a digital database. Most of these data are shown in Figure 5.1. It is obvious that further work could be done with these data, including looking at the relationship between top of dolomite and the top of the Dundee Formation. Further work needs to be done looking for evidence of smaller faults than those reported in Chapter 3 and their relationship to the dolomitization.

5.4 Figures

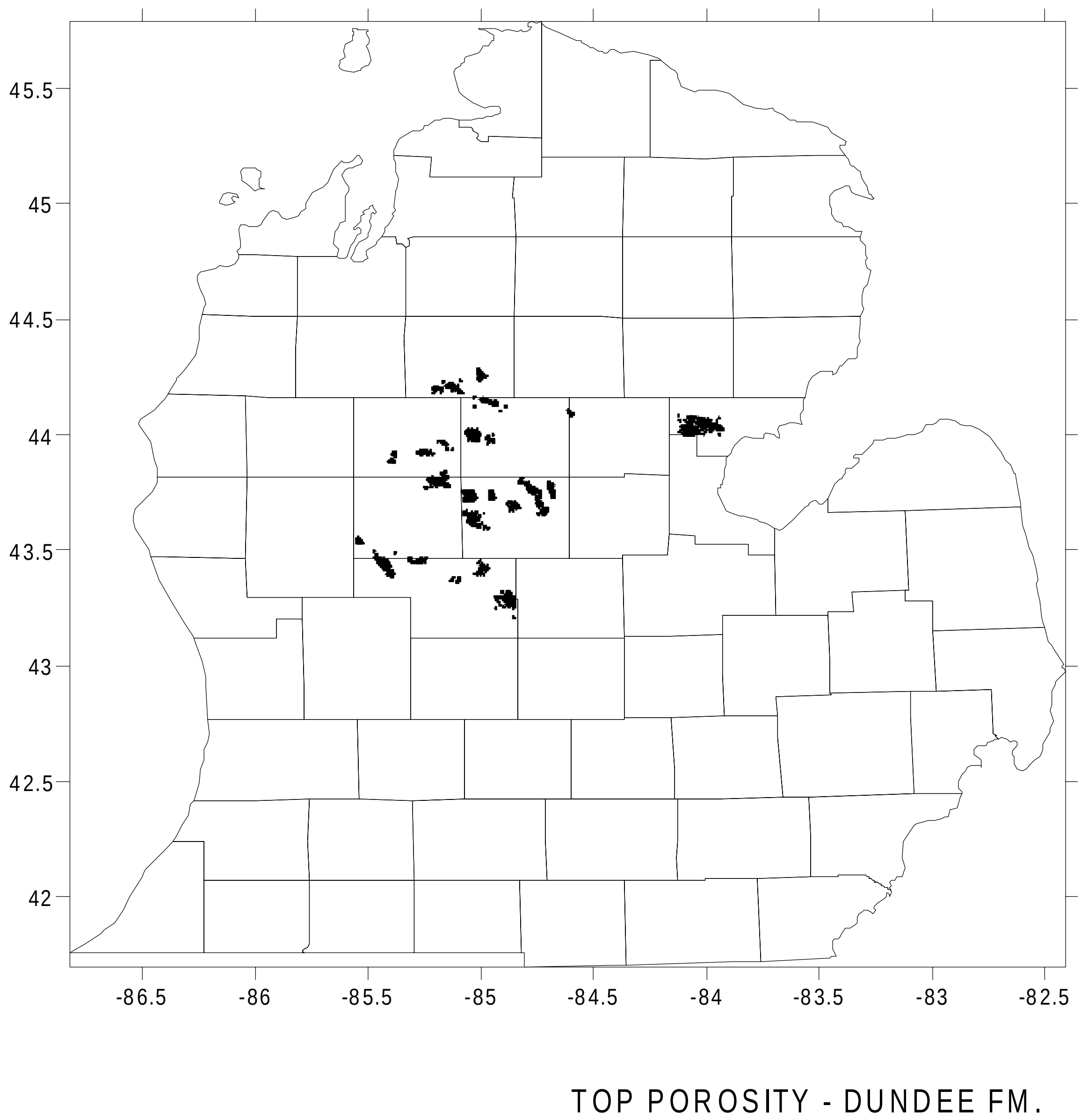

Figure 5.1. Map showing location of dolomitized Dundee Fields. The large faults reported elsewhere in this report are superimposed on the dolomite occurrences.