Oil & Natural Gas Technology

An Approach to Recover Hydrocarbons from Currently Off-Limit Areas of the Antrim Formation, MI Using Low-Impact Technologies

Final Report

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Authors: *Dr. James R. Wood and William C. Quinlan*

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Submitted by:
Michigan Technological University
1400 Townsend Drive
Houghton, MI 49931

Jordan Development Company, L.L.C.
1503 Garfield Road North
Traverse City, MI 49686

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ABSTRACT

The goal of this project was to develop and execute a novel drilling and completion program in the Antrim Shale near the western shoreline of Northern Michigan. The target was the gas in the Lower Antrim Formation (Upper Devonian). Another goal was to see if drilling permits could be obtained from the Michigan DNR that would allow exploitation of reserves currently off-limits to exploration.

This project met both of these goals: the DNR (Michigan Department of Natural Resources) issued permits that allow drilling the shallow subsurface for exploration and production. This project obtained drilling permits for the original demonstration well AG-A-MING 4-12 HD (API: 21-009-58153-0000) and AG-A-MING 4-12 HD1 (API: 21-009-58153-0100) as well as for similar Antrim wells in Benzie County, MI, the Colfax 3-28 HD and nearby Colfax 2-28 HD which were substituted for the AG-A-MING well.

This project also developed successful techniques and strategies for producing the shallow gas. In addition to the project demonstration well over 20 wells have been drilled to date into the shallow Antrim as a result of this project's findings. Further, fracture stimulation has proven to be a vital step in improving the deliverability of wells to deem them commercial. Our initial plan was very simple; the "J-well" design. We proposed to drill a vertical or slant well 30.48 meters (100 feet) below the glacial drift, set required casing, then angle back up to tap the resource lying between the base to the drift and the conventional vertical well. The "J"-well design was tested at Mancelona Township in Antrim County in February of 2007 with the St. Mancelona 2-12 HD 3.

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1. EXECUTIVE SUMMARY

The goal of this project was to develop and execute a novel drilling and completion program in the Antrim Shale near the western shoreline of Northern Michigan (Figure 1). The target formation was the gas in the Lower Antrim Formation which is a widespread Upper Devonian (Figure 2) shale that has been a very prolific unconventional (shallow gas) producing horizon (Walter, 1996; Coleman, Liu and Riley, 1988; Dellapenna, 1991), having yielded over 2,000,000,000 MCF to date (Figure 3), about one-third of Michigan's total gas production (Wollensak, 1991). Another goal was to see if drilling permits could be obtained from the Michigan DNR that would allow exploitation of reserves currently off-limits to exploration.

This project was successful in meeting both of these goals: the DNR (Michigan Department of Natural Resources) issued permits starting in January 2007 that opened up the shallow subsurface for exploration and production, in this case shallow gas from the Antrim Formation. We succeeded in obtaining drilling permits from MI-DEQ for two wells, the demonstration well AG-A-MING 4-12 HD (API: 21-009-58153-0000) and AG-A-MING 4-12 HD1 (API: 21-009-58153-0100). These permits were approved in January, 2007 for the location cited above (Antrim County, Michigan, Torch Lake Township, Section 12, T30N-R09W, Figure 4). Due to right-of-way delays for gathering lines in the Torch Lake Field, we obtained permits for similar Antrim wells in Benzie County, MI, the Colfax 3-28 HD and nearby Colfax 2-28 HD wells and shifted the project demonstration well to that area (Figure 5).

This project also developed successful techniques and strategies for producing the shallow gas. In addition to the project demonstration well over 20 wells have been drilled to date into the shallow Antrim as a result of this project's findings. The well schematics and production histories to Sept. 2008 are included in this report.

Statement of Permitting Problem

The central problem in obtaining a DNR permit to drill the shallow Antrim is that a great deal of potentially productive shale lies within areas that are off-limits to gas development due to surface constraints such topography, wetlands, or housing. In addition to these constraints, the Michigan Department of Environmental Quality (MDEQ) requires that 30.48 meters (100 feet) of surface casing be set into bedrock below the glacial drift for all drilling (see Appendix I. State Casing Statute Instruction 1-94). The actual requirement is that casing be set through and 30.48 meters (100 feet) below the lowest aquifer penetrated. This requirement is in effect to protect groundwater resources, and since the glacial drift is everywhere regarded as a potential aquifer, MDEQ routinely requires 30.48 meters (100 feet) of casing below the glacial drift. Further, fracture stimulation cannot be conducted within 15.24 meters (100 feet) of the base of the surface casing string. Fracture stimulations (Apotria, Kaiser and Cain, 1994; Decker, Coates and Wicks, 1992; Briggs and Elmore, 1980) to date have been a vital step in improving the deliverability of wells to deem them commercial. As a result of the permits issued to this project the door has been opened to exploring and producing a large amount of productive Antrim shale can neither be accessed nor completed in a conventional sense due to State regulations. This opens up a vast resource of domestic gas for conventional development at a very opportune time.

Statement of well design

Our initial plan was very simple and was referred to as the "J-well" design. We proposed to drill a vertical or slant well 30.48 meters (100 feet) below the glacial drift, set required casing, then angle back up to tap the resource lying between the base to the drift and the conventional vertical well (Figure 6). The Drilling Prognosis is detailed in the project handbook (*Lingo Antrim Play: Handbook*). Figure 7 is the planned well bore schematic for the demonstration well while Figure 8 is a bedrock subcrop map from the Michigan DEQ map (Bedrock Well Study of Northwest Michigan, 2007) that shows the Antrim subcrop in gray. The "J"-well design was tested at Mancelona Township in Antrim County in February of 2007 with the St. Mancelona 2-12 HD 3. Figures 9a – 9d show the well trajectory with no vertical exaggeration. Approximate acreage that will become available as a result of this project's success is shown in Figure 10. The areas north of the heavy black line that indicates the cutoff line of where production is limited because of the 1-94 drilling restriction (Appendix I).

2. REPORT DETAILS

2.1 Experimental Methods

2.1.1 Data Collection (Task 1.0)

Data for the Lower Peninsula Antrim Trend has been collected from the Michigan DEQ, the Michigan Core Repository at Kalamazoo and from MTU files. These data consist of formation top picks (~629,000), well logs, well locations and production histories.

Well data was collected from our industry partner, Jordan Development Company, L.L.C., from wells in the three areas of interest to this project: Milton-Bradley field (22 vertical wells) in western Antrim County, Deward Cleaver field (2 horizontal and 3 vertical wells) in eastern Antrim County, and the Colfax 29 field (2 horizontal wells) in western Benzie County.

The project database also includes data from the Michigan Department of Environmental Quality (MI-DEQ), Michigan Public Service Commission, and the Census 2000 TIGER/Line data. The data consists of well locations, formation tops and elevations, oil, gas and CO_2 production data, scanned log images, LAS files (266 LAS files in Northern Michigan; 220 with Antrim formation picks), roads, hydrology, and political boundaries, and water well data in Antrim, Charlevoix and Cheboygan Counties.

Digital Oil and Gas Permit Well Files are available through the Michigan DEQ and have been added to our data archives. Oil and Gas Permit Well Files (PWF) are the documents that are generated over the life of a well – from application to plugging. These are the files that were previously on microfilm, and have been scanned in as multiple page tif image files. Currently the files for permits 1 to 47,999 are available.

Project databases have been organized and documented for the Project Handbook. The three databases for well locations, formation tops, and production are available online on the Michigan DEQ website and are updated periodically. A project database has been created that will link to these databases. A set of queries has been developed that will extract the information needed to reproduce the datasets used in the Project Handbook. This will allow future users of the data to include information from new wells for updated mapping. In particular, the formation tops data needs selective queries performed before mapping can take place.

Measured depths (MD) and true vertical depths (TVD) of formation tops (glacial drift base) are stored in a table by API number, formation code, and method obtained. There are multiple records for some formation tops because top picks from multiple sources are stored in the database. When creating structure and isopach maps, gridding algorithms should be used with one value for each x-y coordinate. A set of instructions and database queries will be included in the Project Handbook that will explain how the formation tops are chosen from the database. For example, when a TVD depth is present in a slanted well, it is chosen over MD. Also, we

have developed a sequence of choices for the method obtained. We have also encountered inconsistent data when formation tops are obtained from different sources.

Data Sources

Data Category	Source
Well Locations	Michigan DEQ
Formation Tops	Michigan DEQ
Production Data	Michigan DEQ (Oil-Gas-Water, 1982 – present) Michigan Public Service Commission (Gas, Water, CO_2, 1990 – present) Michigan Tech Historic Production (Oil-Gas-Water, Annual by Field 1925-1986)
Gravity Data	Jordan Development Company, LLC
Michigan Bouguer Anomaly Data	University of Texas at El Paso GeoNet - United States Gravity Data Repository System
Digital Well Logs	LAS files – MTU
Raster Logs	Michigan DEQ
Permit Well Files	Michigan DEQ
Base map shape files	Census 2000 TIGER/Line data Michigan Resource Information System (MIRIS)

2.1.2 Mapping (Task 2.0)

The scope of this project focused on the Northern section of the Lower Peninsula of Michigan. When reference is made to "Northern Michigan" in this report, the maps have been prepared from data located north of the 400,000 meter line in the Michigan GeoRef coordinate system.

The maps of Northern Michigan contain some common features. The Antrim subcrop is symbolized on the maps in two ways. Some of the maps indicate the Antrim subcrop with a filled gray shade, and the color contour maps indicate the subcrop with a bright pick outline. The heavy black line that runs through the center of the subcrop indicates the northern border of where Antrim gas wells can be drilled following the State of Michigan regulations requiring 30.48 meters (100 feet) of casing below the glacial drift or any fresh water aquifers. The subcrop area above this line shows the additional Antrim acreage that will become available for exploration and production as a result of the interpretation of the 1-94 Instruction for this project.

Images of the maps and cross sections described below have all been included in the *LINGO Antrim Play: Handbook,* a deliverable of this LINGO project, but representative figures have been chosen and are included in this.

1. **Log Curve Profile**
   A stratigraphic log curve profile has been prepared for the Bargy #16-14 vertical well (Figure 11), which is located in eastern Antrim County, Michigan in the vicinity of the project demonstration area. This profile shows the gamma ray (GR) and density curves (ZDEN) with formation tops to illustrate the signature of the gamma ray as it passes through the Lachine, Paxton and Norwood members of the Antrim Shale.

   Several more profiles of Antrim wells across Northern Michigan are included in the project handbook. The project horizontal wells show the gamma ray signature along the directional survey line of the well.

2. **Cross Sections: Northern Michigan (Lachine, Paxton, Norwood formations)**
   a. Cross Section A-A' (Figure 12): Antrim County to Alpena County, North (West to East)
   b. Cross Section B-B': Antrim County to Alpena County, South (West to East)
   c. Cross Section C-C': Manistee County to Otsego County (Southwest to Northeast)

3. **Cross Sections: Northern Michigan (Lachine, Paxton, Norwood formations)**
   a. Cross Section D-D': Milton Bradley field, Antrim County (North to South)
   b. Cross Section E-E': Colfax 29 Field, Benzie County (West to East)

4. **Structure contour maps: Northern Michigan**
   a. Lachine (Figure 13), Paxton, and Norwood members of the Antrim Shale
   b. Top of Antrim Formation

5. **Structure contour maps: Michigan Counties**
   a. Antrim: Lachine, Paxton, and Norwood members of the Antrim Shale
   b. Benzie: Lachine, Paxton, and Norwood members of the Antrim Shale

6. **Isopach contour maps: Northern Michigan**
   a. Lachine (Figure 14), Paxton, and Norwood intervals of the Antrim Shale
   b. Ellsworth Shale to Antrim Formation
   c. Antrim Shale to Lachine member of Antrim Shale
   d. Glacial Drift

7. **Isopach contour maps: Michigan Counties**
   a. Antrim: Lachine, Paxton, and Norwood intervals of the Antrim Shale
   b. Benzie: Lachine, Paxton, and Norwood members of the Antrim Shale

8. **Symbolized map of bedrock: Northern Michigan**
   For each well with formation tops picked, the depth of the Base of the Glacial Drift is equal

to the top of the formation that lies directly beneath the Glacial Drift. This formation was extracted to create a symbolized map that shows the trends of which formation characterizes the bedrock.

9. **Bouguer Gravity Anomaly maps**
   The Michigan Bouguer Anomaly maps were created from data obtained from the University of Texas at El Paso website for GeoNet – United States Gravity Data Repository System. (http://paces.geo.utep.edu/research/gravmag/gravmag.shtml). The original data has been converted from NAD27 latitude/longitude coordinates to Michigan GeoRef.

   a. Northern Michigan (Figure 15)
   b. Antrim County, Michigan
   c. Benzie County, Michigan

10. **Antrim Production History maps: Northern Michigan**
    The Antrim production history maps show cumulative gas (Figure 9), water, and CO_2 production in 5-year intervals. Production data is recorded monthly by production units (PRUs), which may consist of one or more wells connected to a gas line. Production unit locations were determined by assigning each PRU to the section number where most of its wells are located. Then summation queries were used to sum the cumulative production by Section starting with 1990, in 5-year increments. Symbolized maps were then created to show the trends in Antrim production of gas and co-produced carbon dioxide and water over time.

    The following maps have been inserted into the Project Handbook, and the Excel spreadsheets used in the creation of the maps have been archived as part of the project deliverables.

    a. Gas (1990-1994, 1990-1999, 1990-2004, 1990-2007)

    b. CO_2 (2000-2003, 2000-2007 [Figure 17])

    c. Water (1990-1994, 1990-1999, 1990-2004, 1990-2007)

2.1.3 Regulatory (Task 3.0)

This task was satisfactorily resolved when the Michigan DEQ decided to permit the AG-A-MING demonstration well without modification of the instruction 1-94. The permit was issued on December 14, 2006 for the AG-A-MING well (see map, Figure 4). Under this Permit (58153) the Michigan DEQ, accepted the concept of the "J" well (Figure 7).

2.1.4 CO_2 Mitigation (Task 4.0)

CO_2 production data, reported by the Michigan Public Service Commission, is recorded as a percentage of gas produced by month and by producing field. Production data recorded prior to the year 2000 is a combination of **Produced gas** (includes CO_2 volumes) and **Sales Gas** (volumes after CO_2 has been separated) totals. Between 1998 and 2000, the production reporting

was converted to report only **Sales Gas**. Figure 16 is a timeline showing when the standard criterion for reporting CO_2 was switched over. We provide charts and maps showing trends in the data in northern Michigan (Figure 3 and Figure 17), and in each of the three producing fields of interest to this project, the Milton Bradley, the Deward Cleaver, and the Colfax 29.

2.1.5 Synthesis (Task 5.0 Year 2)

The *LINGO Antrim Play: Handbook* is a deliverable of this project, and is a documentary of the maps, charts, and well diagrams and histories that have been compiled for this LINGO project. The handbook table of contents is shown below.

LINGO Antrim Play: Handbook

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Data Deliverables
The data used to create the maps and charts in the handbook was downloaded from public domain data. The project handbook and our project website http://www.geo.mtu.edu/svl/LINGO/ contain links to these sites and will also contain detailed documentation of how the data was used to prepare the project handbook.

2.1.6 Demonstration Wells (Task 6.0)

As mentioned above (Executive Summary) we petitioned DOE for permission to switch the project demonstration well to an equivalent Antrim site in Benzie County, MI due to some unforeseen right-of-way issues that did not seem resolvable in the timeframe of this project. For completeness and continuity in this report, we have included descriptions of the work done in the three areas which pertain to this project (Figure 1): the final project demonstration well site, Colfax 29 in Benzie County; the Deward Cleaver area of Antrim County where experimental "J" wells were drilled; and the original demonstration site in the Milton Bradley area of Antrim County.

2.1.6.1 Final Demonstration Site: Colfax 29

In December 2007, a request was sent to the DOE to substitute the State Colfax #3-28 HD in Benzie County (Figure 5) for the AG-A-Ming 4-12 HD well since right-of-way problems precluded timely drilling of the AG-A Ming 4-12 HD.

There were two main objectives for this project. One involved compliance with Michigan well site regulation embodied in Instruction 1-94 (Appendix I) and a second involving using a new horizontal "J" well design (Figure 7) to recover gas from previously off-limit acreage in the Antrim Formation. Both objectives have essentially been achieved in this past year: the Regulatory task has been completely resolved and the originally proposed design of the "J" well has been tested in the field, although not at the proposed demonstration site.

The Colfax #3-28 HD and nearby Colfax #2-28 HD were drilled with the revised configuration (Figure 18). The method employed in the Colfax wells, which is likely to be used in future drilling in the Milton Bradley area (original project demonstration site), was a cased hole drilled

to near horizontal (75 to 85 degrees) and carried through the Antrim section in a slightly downward inclination. Perforated completion intervals were then shot through the pipe and individually fracture treated. Figure 19 is the record of completion for the project demonstration well, St. Colfax 3-28 HD. The gamma ray log is plotted with the perforation intervals along the deviated well path in Figure 20. Increasing gamma ray signatures indicate high gas content, and these intervals in the Lachine and Paxton formations along the horizontal well path provided more locations for the perforation zones. Daily production data for the St. Colfax 3-28 HD (Figure 21) and for the St. Colfax 2-28 HD (Figure 22) are averaging 90 and 70 mcf per day, respectively, as of September 30, 2008.

2.1.6.2 Experimental Demonstration Site: Deward Cleaver Project

While the AG-A-MING #4-12 HD well was put on hold, Jordan Development Company, LLC drilled several wells in the Deward Cleaver project area in southeast Antrim County, MI with the "J" well project design. The State Mancelona #2-12 HD3, the State Mancelona #15-13 HD2, and the State Mancelona #15-13A HD1 & HD2 (Figures 23 and 24) began production in June 2007.

These wells revealed problems with the original design of the "J" well (Figure 25), mainly in terms of disappointing production relative to ordinary vertical wells (Figures 26 and 27). However, these wells provided us with an opportunity to redesign and modify the demonstration well before it was drilled. From what was have learned at the Deward Cleaver wells, it was necessary to reduce the ascent angle into the Antrim productive zones as well as case and perforate the well.

Problems and Solution to the original "J" well design

Jordan Energy had the opportunity to use the "J" well design proposed for this project in three wells drilled in the Deward Cleaver project in eastern Antrim County, before the project demonstration well could be drilled. The open hole upward slanting configuration of the Lachine and Norwood laterals are shown in the mud log and well bore cross section in the State Mancelona 15-13 HD2 (Figures 28a-28f) and HD1 (Figures 29a-29f). These wells did not produce as well as expected; in fact they performed worse than simple vertical wells drilled nearby. Figure 26 is an updated plot of average daily production from the State Mancelona 2-12 and State Hayes 4-18 vertical wells compared with average daily production from the State Mancelona #2-12 HD, #15-13 HD, and the #15-13A HD "J" wells. Figure 27 shows actual daily gas production from June 2007 through September 2008 for these same Antrim wells.

Earlier it was reported that the basic problem with the "J" well design appeared to be the development of blockages along the horizontal leg. Two possibilities had been put forward: one, fluids are trapped in undulations in the well bore, resulting in a fluid lock, and two, material sloughs off the well, eventually blocking the gas flow. We suggested it was possible that both mechanisms operated at the same time and reinforced flow restriction. Subsequently Jordan determined that cavings from the hole were really not an issue, but that accumulated debris within the perceived undulations of an open hole well bore was the most likely cause of poor production and that this could be alleviated through the use of a downward sloping cased hole.

Subsequently, while wells were drilled at Deward Cleaver (State Mancelona #2-12 HD, #15-13 HD, and the #15-13A HD) with the "J" well approach, the State Colfax 3-28 HD and 2-28 HD have been drilled with a new design, a high- angle cased hole that will be perforated. Figure 7 shows the original configuration of the demonstration well, Figures 9a-9d show the "J" well trajectory for the St. Mancelona 2-12 HD3 with no vertical exaggeration, while Figure 18 shows the current modification. The Colfax wells were completed in mid February 2008 and production began in April and May of 2008, respectively. Daily production data has been collected from the Deward Cleaver and the State Colfax wells (shown in Figures 21, 22, and 27).

Lessons Learned – Bill Quinlan
Deward Cleaver Horizontal Drilling Experience using the "J" well design

Jordan Development Company, LLC (Jordan) drilled three open hole lateral Antrim Shale tests in the Deward Cleaver Field within Mancelona East Township of Antrim County between June of 2006 to July of 2007. The approach used to drill these three wells is identical to the well design originally proposed for the AG-A-Ming #4-12 HD demonstration well.

The Deward Cleaver wells consisted of directionally drilled pilot holes which were cased, from which open hole laterals were drilled at a 90 degree or greater inclination. The open hole laterals were oriented to allow fluids to drain back out of the laterals and into the pilot holes. An electric submersible pump was then set below the open hole windows within the pilot holes to enable produced water to be removed from the well.

The resultant production from these open hole laterals did not meet anticipated production expectations. Upon review, Jordan has gained a great deal of insight as to improvements in the drilling and completion approach going forward to improve well production.

The first potential weakness in the drilling approach taken in the Deward Cleaver is that the exit for each lateral creates a "lip" at the casing window. This "lip" results in a point of fluid back-up, whereby the produced water draining back to the pilot hole must rise up before entering the casing and being pumped from the hole. The result is a pressure drop which adversely effects production.

The open hole laterals were designed to gradually rise over their length to allow all produced water to drain back to the pilot hole. Jordan and its drilling contractors were very diligent in the effort to accomplish a smooth and gradual incline to the lateral placement. However, it is nearly impossible to avoid slight dips and valleys within the well path. As such, several sumps are formed within the lateral which trap produced fluid, hamper production, and potentially render portions of the lateral unproductive.

Another potential issue with the original design is in the effect of drilling damage within the open hole laterals. During lateral drilling, the ability to efficiently remove cuttings becomes increasingly difficult as the hole extends further out. As a result, cuttings begin to accumulate along the hole and are finely ground to a paste as drilling progresses. This shaley paste causes

formation damage which is very difficult to remove as the clay fines are inert to stimulation treatments such as acid.

As formation pressure depletes, the total effect of these drilling and design inefficiencies can greatly hamper gas deliverability. Jordan is now employing a new design which incorporates drilling a 75 to 80 degrees angle hole through the Antrim. This high angle hole is then cased and completed through pipe with eight to fourteen perforated and fracture stimulated zones. A pump is then run in below all zones to lift produced water from the well.

The main advantage of the new design is that fluids drain directly and efficiently into the production casing. In this way, the well is produced in a more conventional means through perforations with no fluid back-ups or traps. In addition, by discretely stimulating multiple zones utilizing fracture treatments, the effect of any drilling damage is completely removed. Jordan views this new drilling and completion approach far superior to the original design for future Antrim Shale development.

2.1.6.3 Original Demonstration Site: Milton Bradley Project

The original demonstration well, A-GA-MING #4-12HD and #4-12HD1, is part of the Milton Bradley Project in west Antrim County (Figure 1) developed by Jordan Development Company, LLC. In addition to the LINGO demonstration well, Jordan Development is developing the prospect with a series of vertical wells, and one disposal well (see Figure 4). The horizontal section of the demonstration well must remain within the 240 acre boundary set up in the PRU (PRoduction Unit). The vertical wells will be part of one production unit (PRU), and the demonstration well will be the only well in its PRU. (Since the demonstration well will be producing from its lateral, it will have access to as much or more pay as the vertical wells and will drain a similar area. This is an additional benefit of the LINGO well: it will in some cases replace as many as 4-6 wells with consequent economies and less disruption to the environment. The complete specifications for the A-GA-MING 4-12 as provided by Jordan will be included in the final project handbook.

The AG-A-MING #4-12 HD well was not drilled within the scope of this project because right-of-way negotiations have put this well on hold. Jordan Development Company, LLC still has plans to drill this well, but the demonstration site for this project was changed to the Colfax #3-28 HD well in southeast Benzie County. As of September 2008, twenty-two vertical wells have been drilled in the Milton Bradley project area. Average daily production for this set of wells has risen to 2,000 mcf per day (Figure 30).

2.1.7 Well Logging (Task 7.0)

A collection of well logs have been put together into cross sections to show the trends of the gamma ray logs through the Lachine, Paxton, and Norwood formations. Cross Section A – A' displays the gamma ray logs from West to East across the northern line of Antrim producing wells from Antrim County to Alpena County (Figure 12). A second Cross Section B – B' displays wells to the south of line A–A', and Cross Section C–C' displays wells in southwest to northeast direction from Manistee County to Otsego County. We have also created localized

cross sections D–D' showing the trends in the Milton Bradley project, and E–E' showing the two horizontal wells in the project demonstration area, Colfax 29. These cross sections are included in the project handbook.

Mud logs, Gamma Ray and Casing Collar logs were run in the Colfax 2-28 and 3-28 wells. The well logs are displayed in a cross section format with the directional survey and formation tops defined as in Figure 20.

2.2 Results and Discussion

In this section we will provide a preliminary discussion of the maps promised as deliverables in this project. Several of these maps are key products in that they outline the additional prospective area that will become available for exploration and production as a result of the novel permitting and drilling undertaken here. We will also provide a preliminary discussion of the maps promised as deliverables in this project. Several of these maps are key products in that they outline the additional prospective area that will become available for exploration and production as a result of the novel permitting and drilling undertaken here. The map images will all be presented in the project deliverable, *LINGO Antrim Play: Handbook*.

The Antrim Formation is mainly a gray to black shale with dominantly black, high gamma-ray facies in the lower sections. These lower sections can be distinguished by gamma-ray and have been termed, the Lachine, Paxton, and Norwood members of the Antrim Formation. In general these facies are high in organic matter (3-12 %) and represent anoxic facies deposited in stagnant bottom waters in closed or nearly closed Devonian seaway. They are thus marine sediments and have sufficient organic content to qualify as high-grade source rock. Some sample will burn if exposed to a flame. These are the sought after sections as they are thought to be the source of the Antrim gas, which has been reported to be biogenic (Walter, et. al, 1996). Consequently, it is of interest to map these facies in terms of how they are impacted by the J-well technology. The history and characteristics of the Antrim Shale Gas Play are outlined in a section of the project handbook.

Structure and isopach maps for the Lachine, Paxton, and Norwood formations in the Northern Michigan Antrim Trend (Figures 13 and 14), and also localized to Antrim County, are presented in the *LINGO Antrim Play: Handbook*. Figure 31 is a spot map showing the identity of the formation immediately under the glacial till (Glacial Till in the Michigan Stratigraphic Code). It is apparent that the sub-till facies distribution is complex and not easily generalized or mapped. At present we feel the spot map as depicted in Figure 31 is the best representation. It is clear to us that prospect development will have to proceed at a very small map scale in the area of interest if the Antrim is to be mapped at the Member level.

Other interpretations are possible but it appears that these erosional edges of the Antrim are "ragged" and unpredictable, possibly due to glacial process in the waning stages of the last glacial retreat. In such cases, detailed information can perhaps be obtained by micro-gravity techniques which have been reported to allow mapping of the till-Antrim contact. We have a detailed map (Figure 10) of the additional Antrim acreage that will become available for exploration and production as a result of the interpretation of the 1-94 Instruction for this project.

All project tasks have been completed. The initial benchmark for the demonstration well was met in December 2006 when the Michigan DEQ issued a permit for the well. The main obstacle in the drilling of the original project demonstration well was in obtaining right-of-way for facilities. A second group had tied up acreage in the vicinity of the proposed demonstration well which prevented access to the gathering facilities and hence delays in drilling. It became clear that the AG-A-Ming well could not be drilled within the timeframe of this project. Our December 2007 request to substitute the St. Colfax 3-28 HD in Benzie County was approved by the DOE. This

well and the nearby St. Colfax 2-28 HD, drilled in the same configuration, have been drilled and well data (i.e., well bore diagrams, mud log, Gamma Ray log, perforation records, and detailed well completion documents, and current production records) have been gathered into a complete well history and analysis.

2.3 Conclusion

There were two main goals of this project: (1) to structure or revise permit requests so that the Michigan DEQ would approve drilling in areas of the Antrim that were to shallow to allow access by vertical wells, and (2) to design a well or system to wells to produce gas economically from these shallow reservoirs. A final goal was to produce a "handbook" reporting the details of the project experiences as well as a map of the potential acreage opened up as a result of this project.

Well permit for access to shallow Antrim

We were successful in arguments to the DEQ that the approach to tapping Antrim gas reserves by drilling a lateral through the required casing zone and then angling back up met regulatory requirements. After listening to our presentation, the DEQ had no objections and was favorably impressed by the further advantage of the approach in lessening environmental impact as a result of requiring fewer wells and (potentially) providing more efficient drainage. DOE required this approval as a critical milestone that had to be met in the first year of the project since the viability of the entire project depended on a favorable result. This was accomplished.

Gas production from the shallow Antrim

This objective was more difficult to achieve: our initial design for the so-called "J-well" did not produce effectively and had to be redesigned (details in handbook). After a series of changes and modifications, we were able to produce the shallow Antrim in three areas of interest: Milton Bradley (original demonstration site), Deward Cleaver (site where "J" design was tested), and Colfax 29 (new demonstration site). Our experiences here will serve as a template for similar development and will provide lessons in "what not to do". This will also be the first time to our knowledge that a lateral has been used to produce Antrim gas. This project has the potential to be another Crystal Field demonstration that convinces the Michigan gas and oil industry to use laterals to develop Antrim production. (Crystal Field was a DOE-sponsored demonstration project in the 1990's that was influential in converting the Michigan Oil and Gas Industry to shift to lateral wells for conventional oil production. See DOE Contract No. DE-FC22-94BC14983).

All of the project tasks were completed on schedule. Promised deliverable maps are complete and the last task, drilling of the demonstration well at State Colfax 3-28 HD was completed in April, 2008. The *LINGO Antrim Play: Handbook* contains details of well design, maps of potential Antrim reservoir opened up, and production histories of the shallow Antrim wells that went on-line during the duration of this project.

3. GRAPHICAL MATERIALS

3.1 List of Figure Captions

3.2 FIGURES

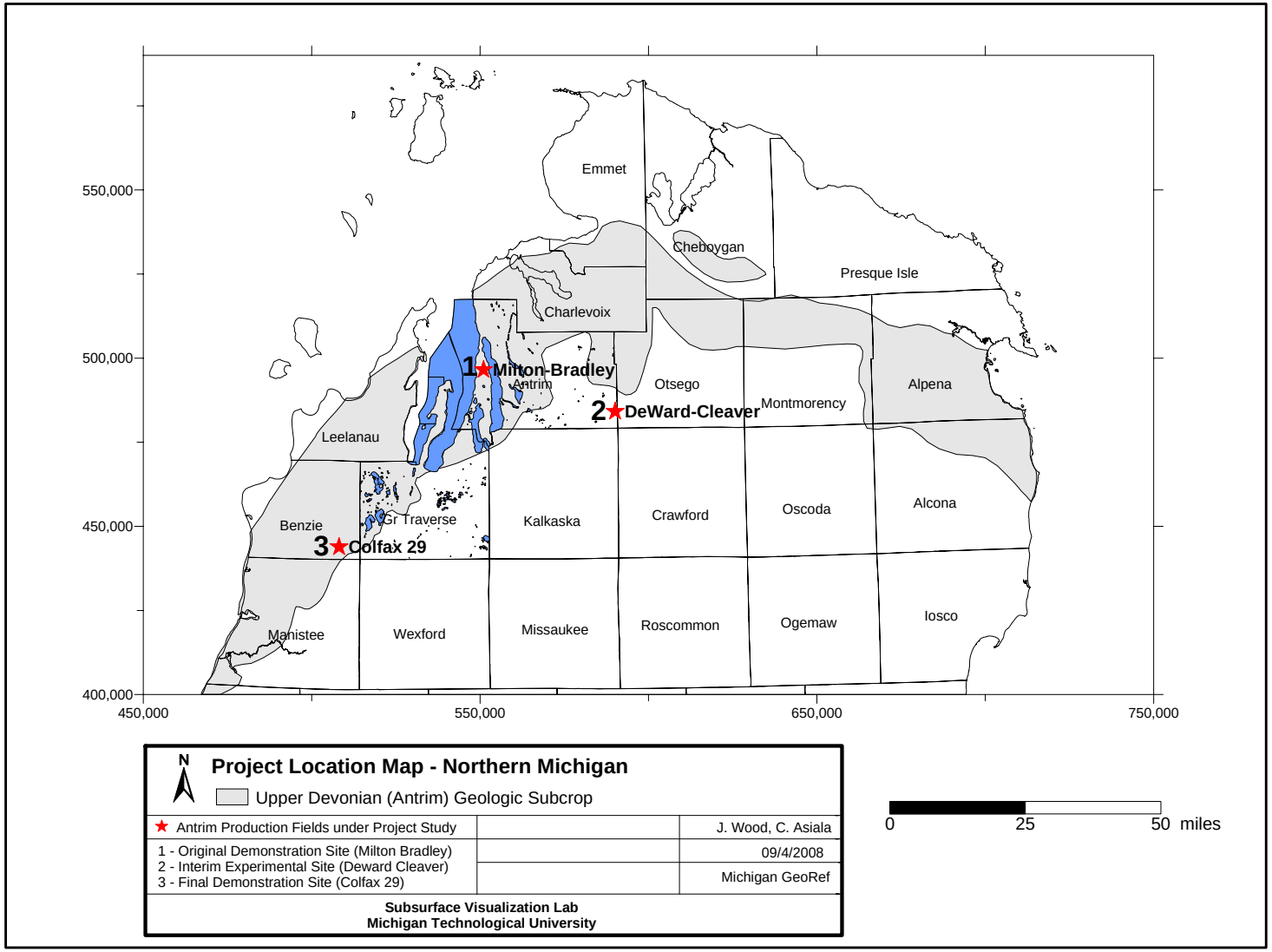


Figure 1. Location map of Northern Michigan. The original project demonstration well, AG-A-MING 4-12HD was planned to be drilled in the Milton-Bradley (1) project in Antrim County; the "J" well configuration was tested in the Deward Cleaver (2) project in Antrim County, and the final site of the project demonstration well is the Colfax 29 field (3) in Benzie County. The gray area is the geologic subcrop of the Upper Devonian which contains the Antrim.

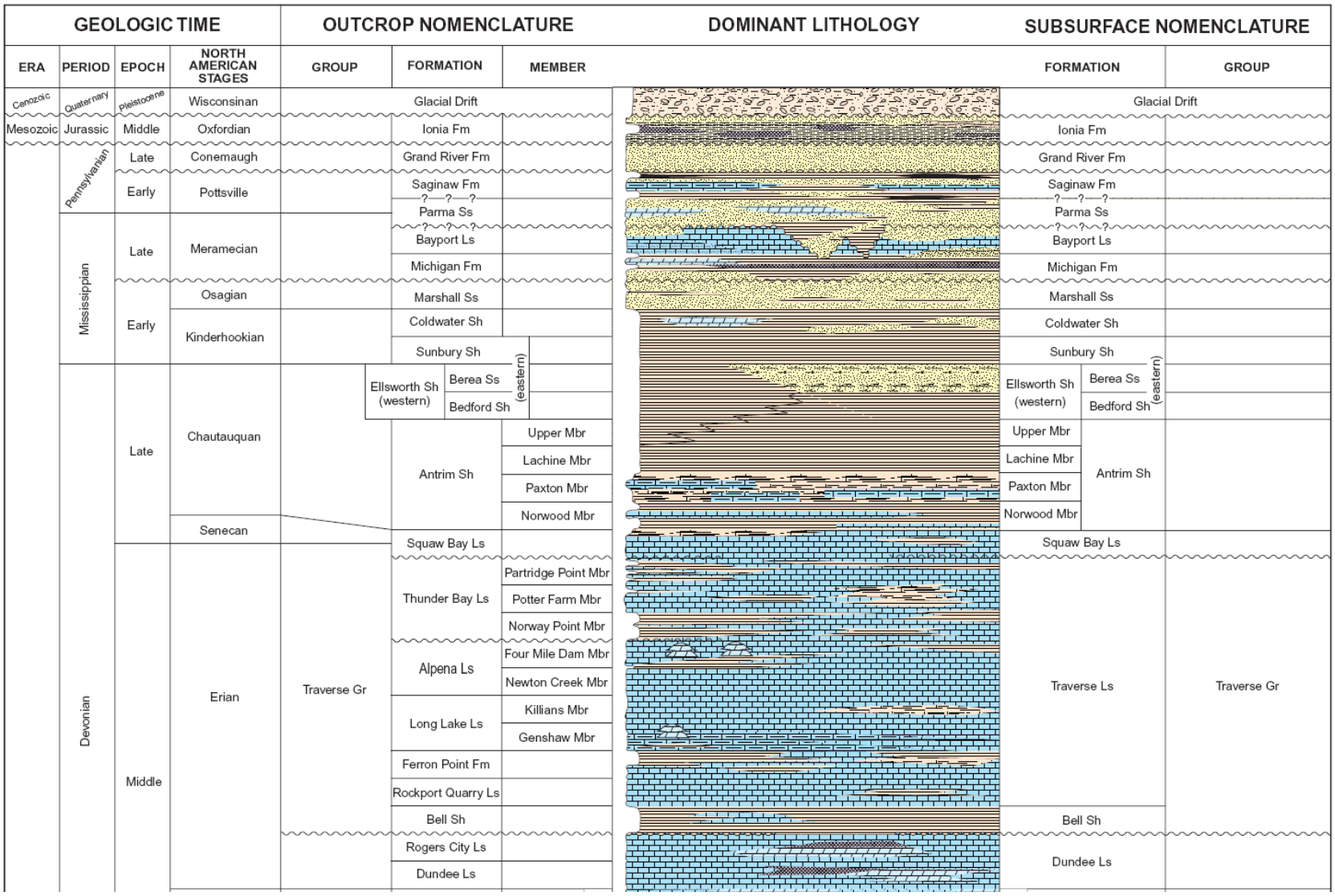


Figure 2. Subset of Michigan stratigraphic column from the Glacial Drift through the Dundee formation (Stratigraphic Nomenclature for Michigan, MI-DEQ).

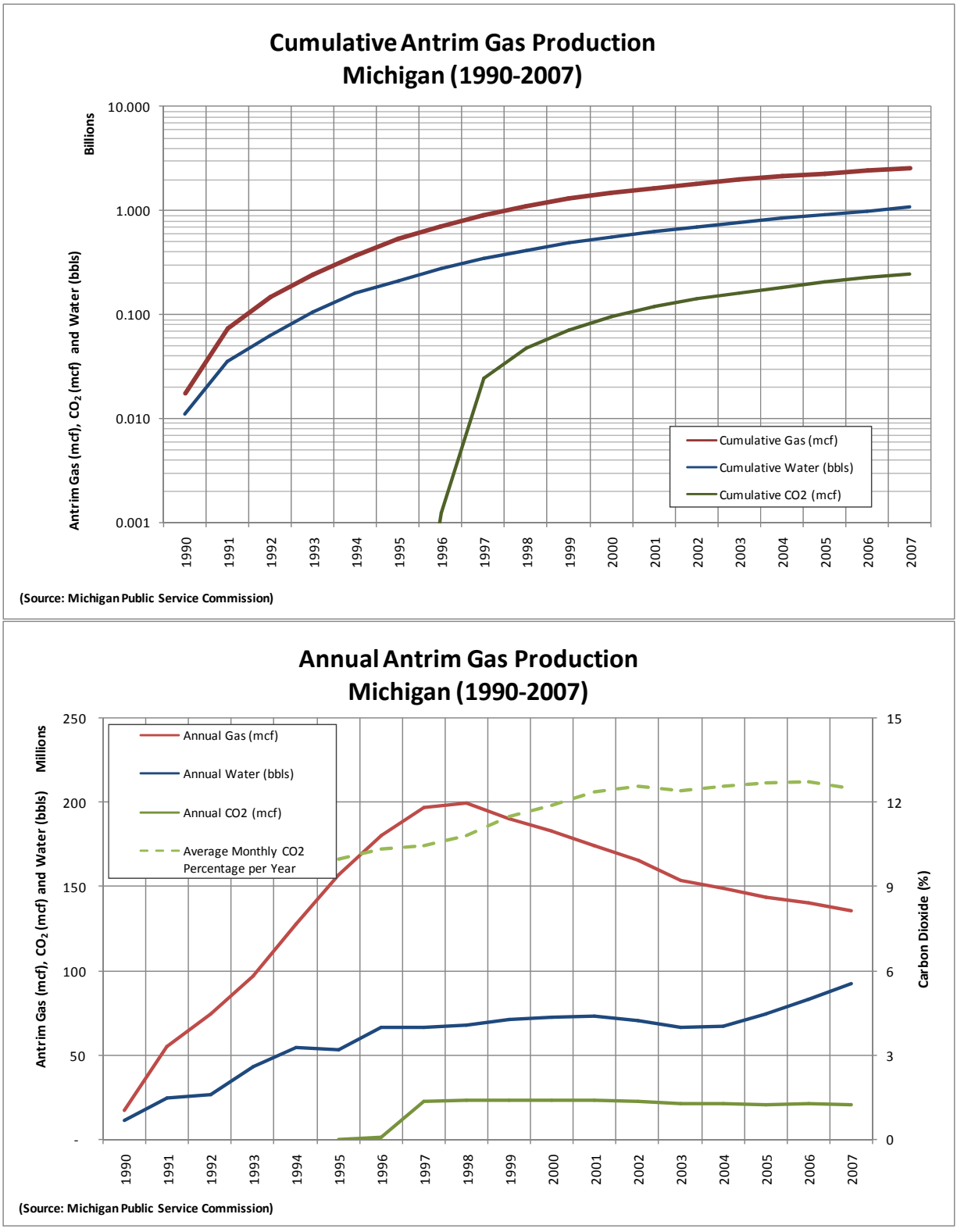


Figure 3. Top chart shows Cumulative Antrim Gas (mcf), along with co-produced water (bbls) and CO_2 from 1990 through 2007. Bottom chart shows Annual Antrim gas, water, and CO_2 production along with an annual average CO_2 percentage.

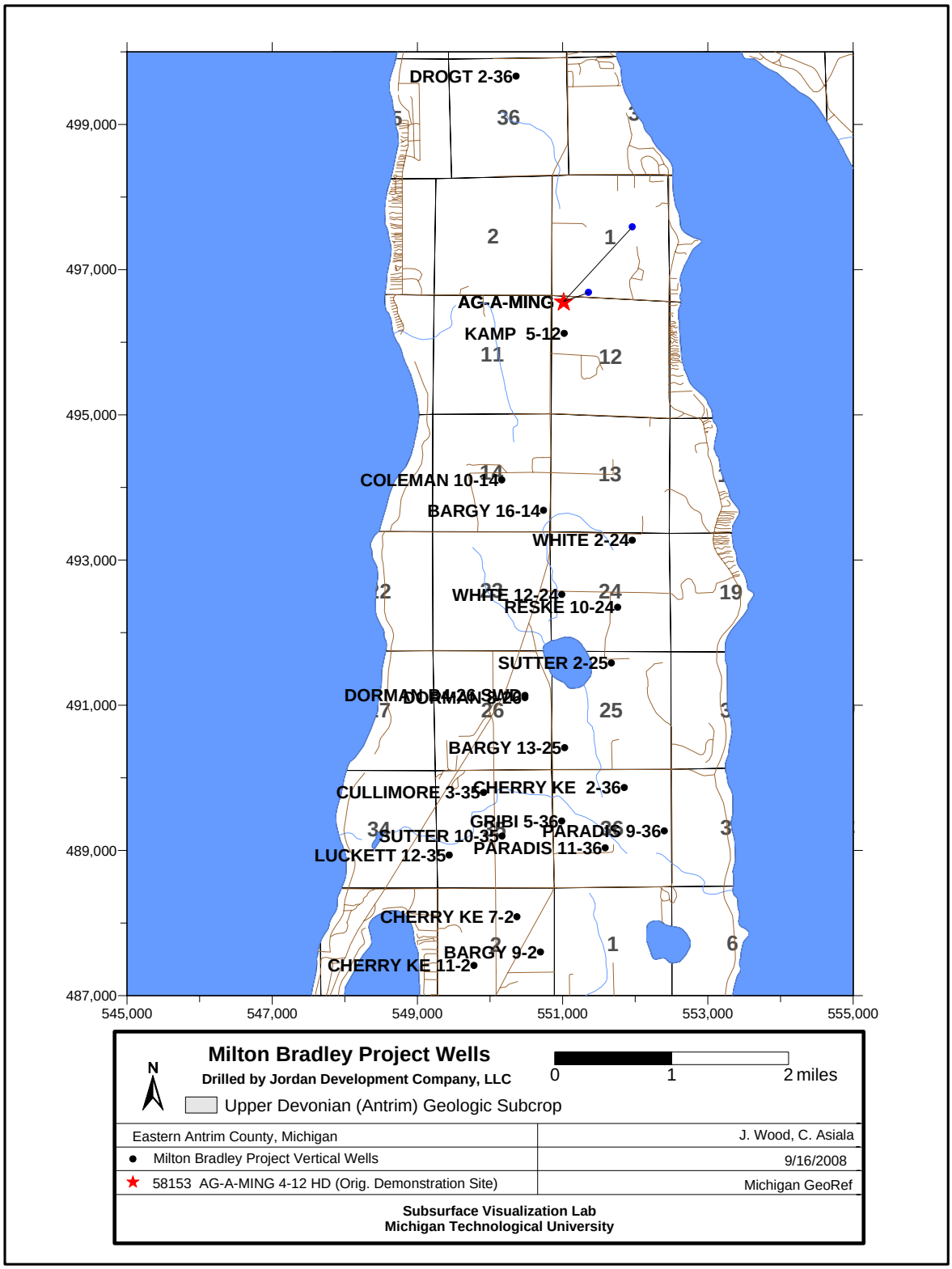


Figure 4. Location map showing planned horizontal laterals of the originally planned demonstration well, AG-A-Ming 4-12HD. Other well locations are vertical gas wells and one brine disposal well drilled during the timeframe of this project.

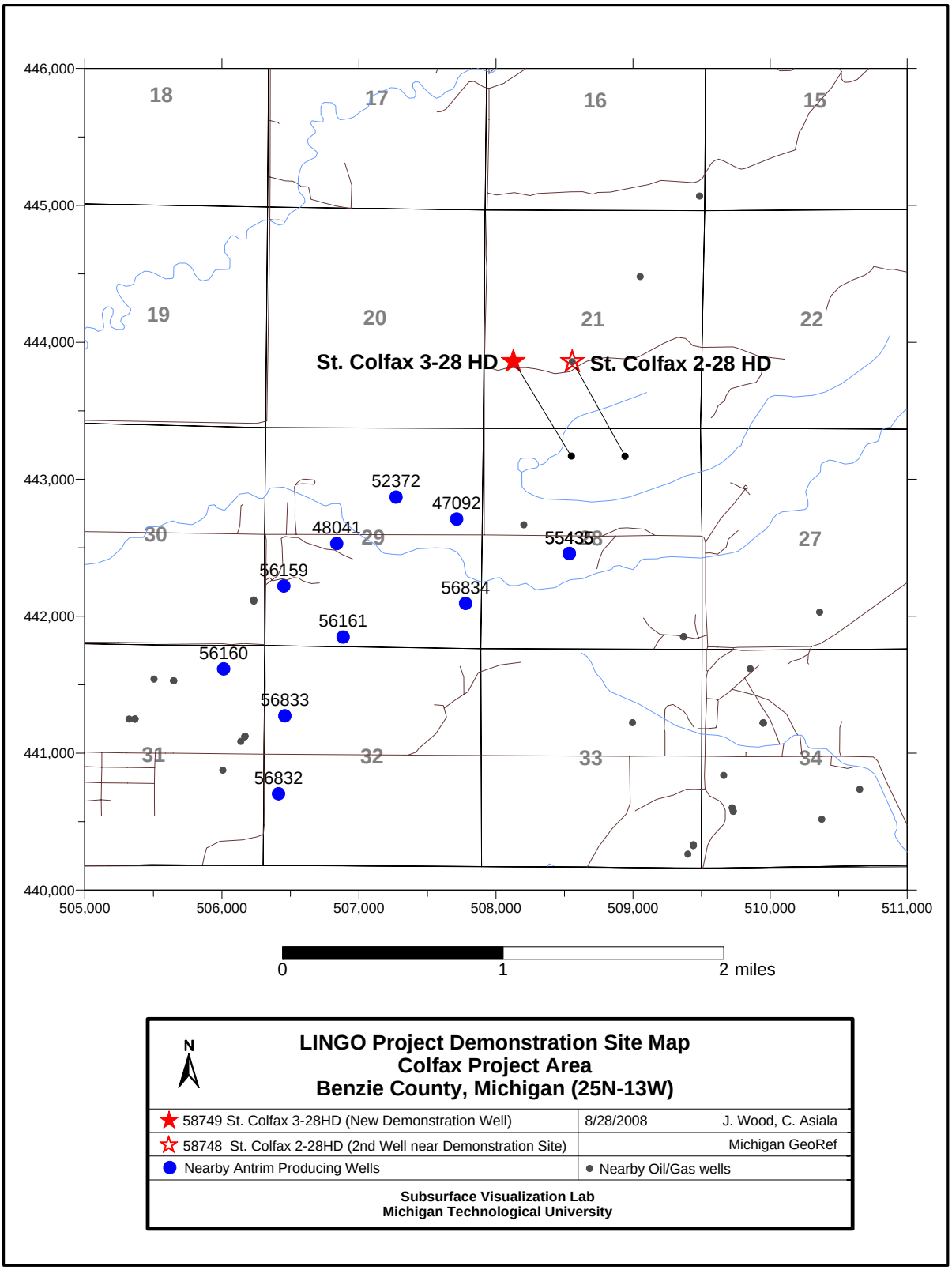


Figure 5. Location map of site change in project demonstration well. St. Colfax 3-28 HD in Benzie County, MI is the new demonstration well, and data from the similar and adjacent well, St. Colfax 2-28 HD, is available to the project.

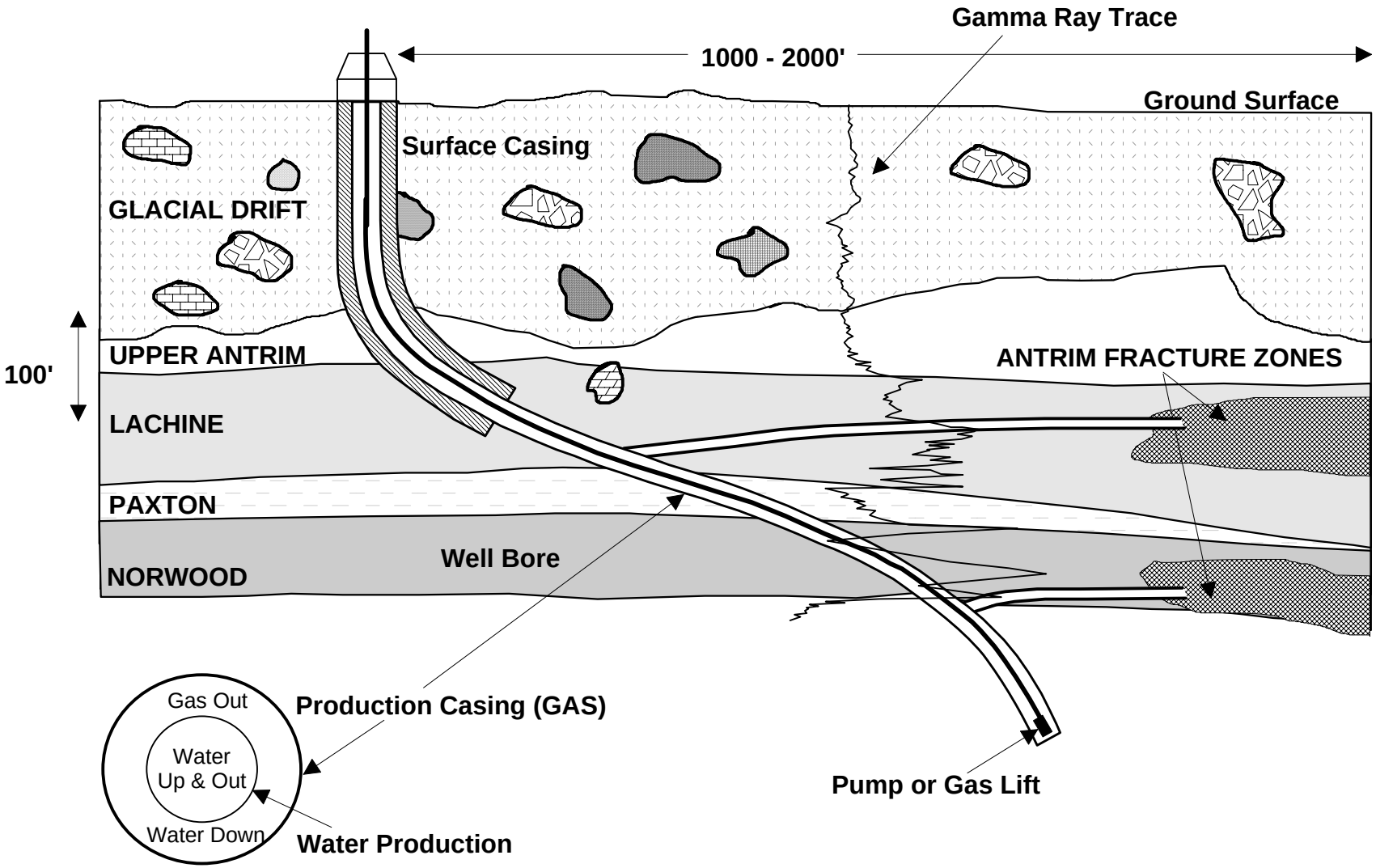
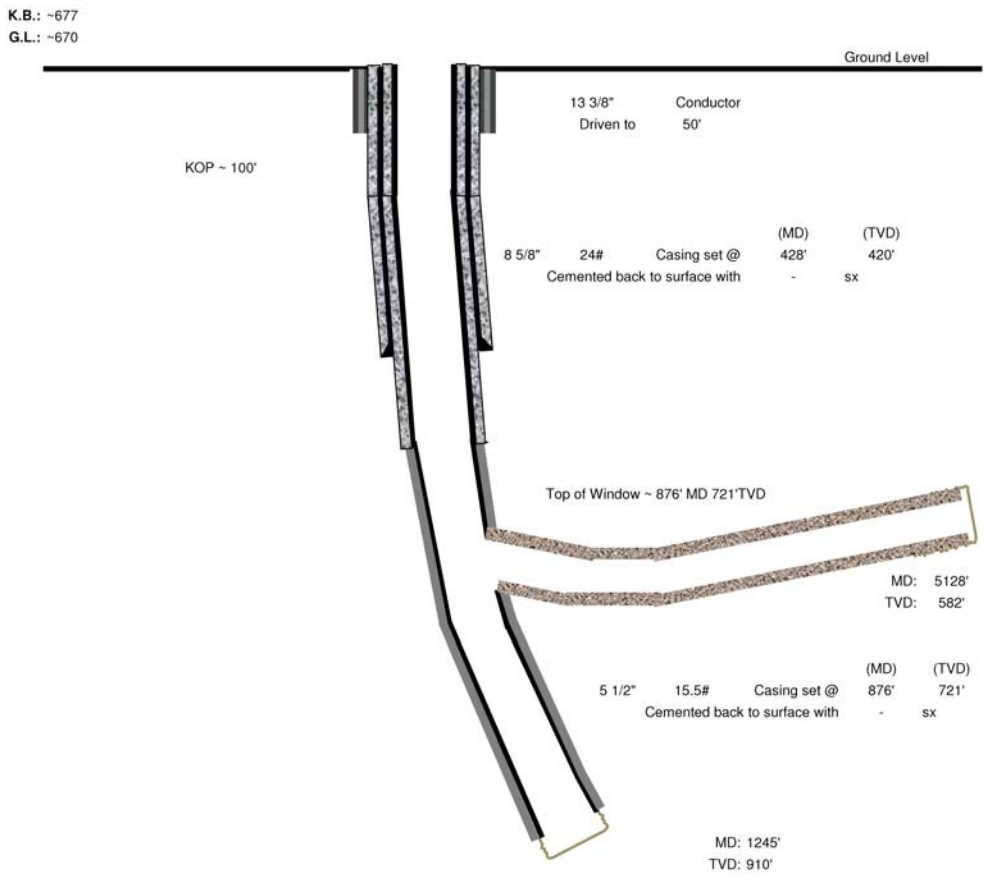


Figure 6. Schematic diagram illustrating the drilling plan to tap the shallow Antrim gas reserves using a slant well in place of a vertical well and casing it so that it satisfies Michigan regulatory statutes. Horizontal wells will branch out to the pay zones of the slant well. Note that the laterals can slope upward to drain water to the pump at the bottom of the slant well. Gas is produced in the outer tubing and goes directly to the surface. Water is drained to the bottom of the slant well and pumped up the inner annulus. The gamma ray log illustrates the highly variable nature of the radioactivity in the Antrim which can be used to locate and guide the drill bit using MWD (Measurement While Drilling) technology.

A-GA-MING #4-12HD & HD1



Well Name & Number:	A-GA-MING #4-12HD & HD1			**MDEQ#**	58153		
Section:	12 & 1	**Township:**	T30N	**Range:**	R9W	**Surface Hole Location:**	NW NW NW
County:	Antrim			**State:**	Michigan	**Bottom Hole Location:**	SE SW NE
Township:	Mancelona			**Country:**	United States		
Spud Date:	-						
Prepared By:	Benjamin J. Nieto			**Last Revision Date:**	08/08/07		

Figure 7. Well bore schematic of the A-GA-MING demonstration well located in the Milton-Bradley project in western Antrim County, MI.

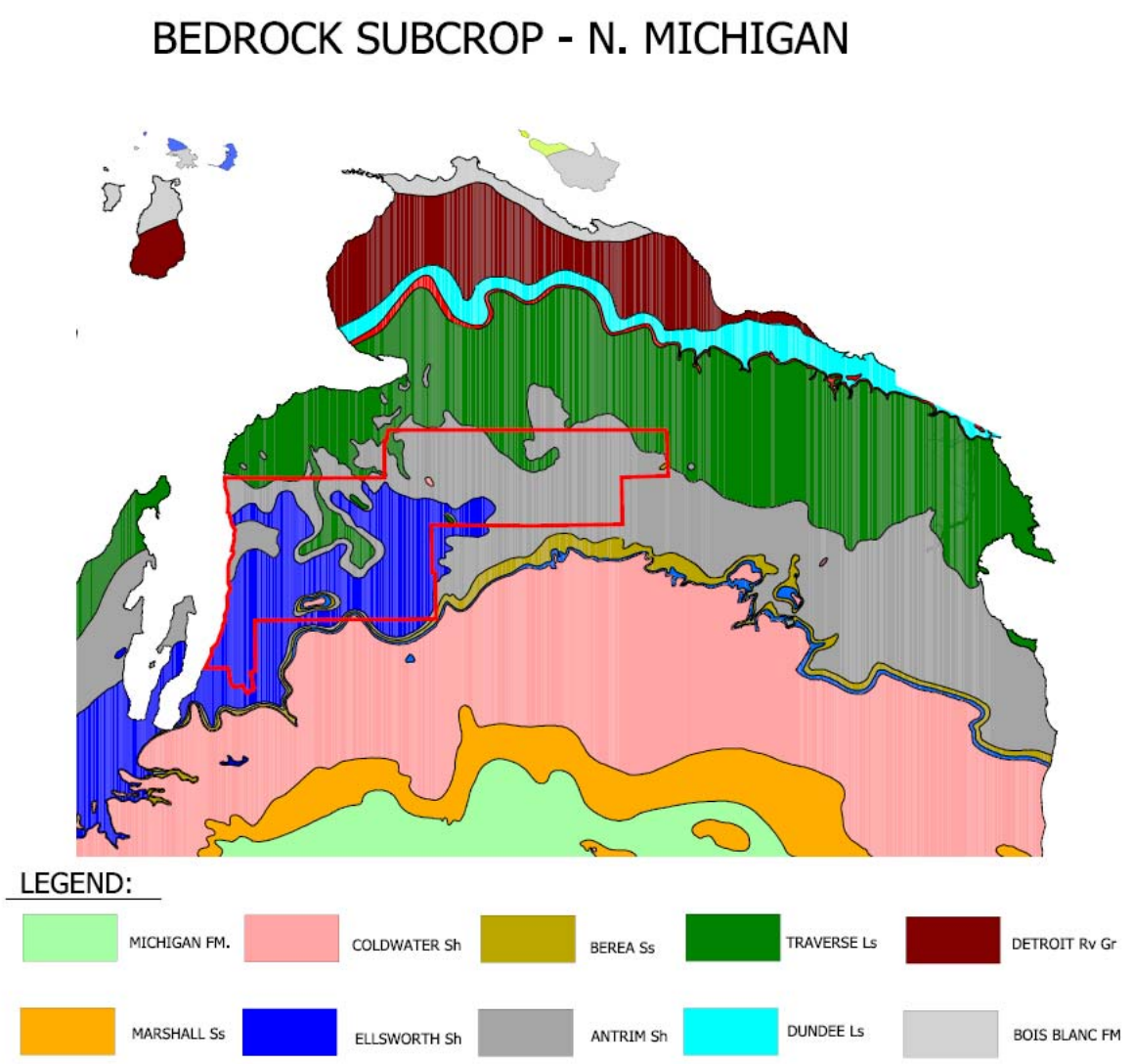


Figure 8. Bedrock subcrop map of Northern Michigan developed by the Michigan Department of Environmental Quality. The gray area depicting the Antrim Shale is an indication of the area which could be expanded for gas exploration upon the success of this project.

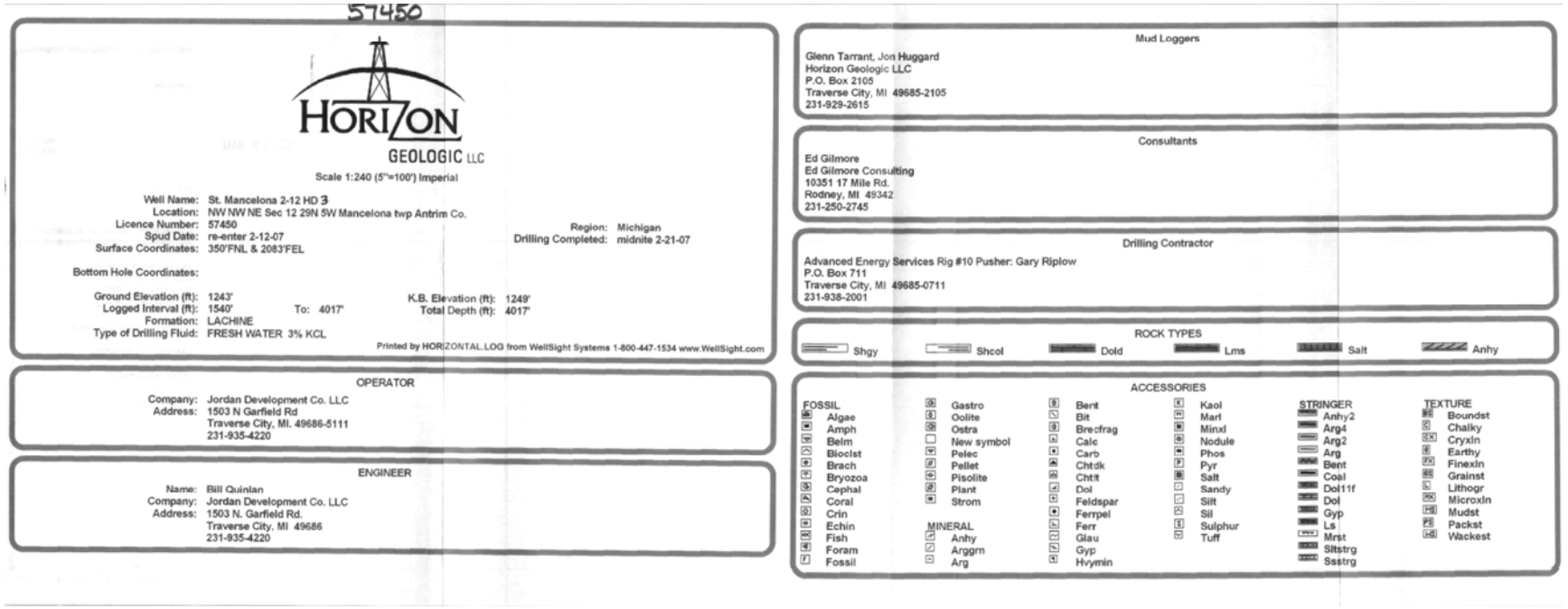


Figure 9a. Mud log and well bore cross section of the Lachine lateral in the State Mancelona 2-12 HD3 (API: 21-009-57450-0300) well in the Deward Cleaver project area in east Antrim County, MI. The lateral was drilled with an upward slope in an open uncased hole with no fracturing or perforating. The measured depth of the well ranges from 1470 – 4030 feet and the true vertical depth of the lateral slopes upward on a scale from 1420 to 1380 feet.

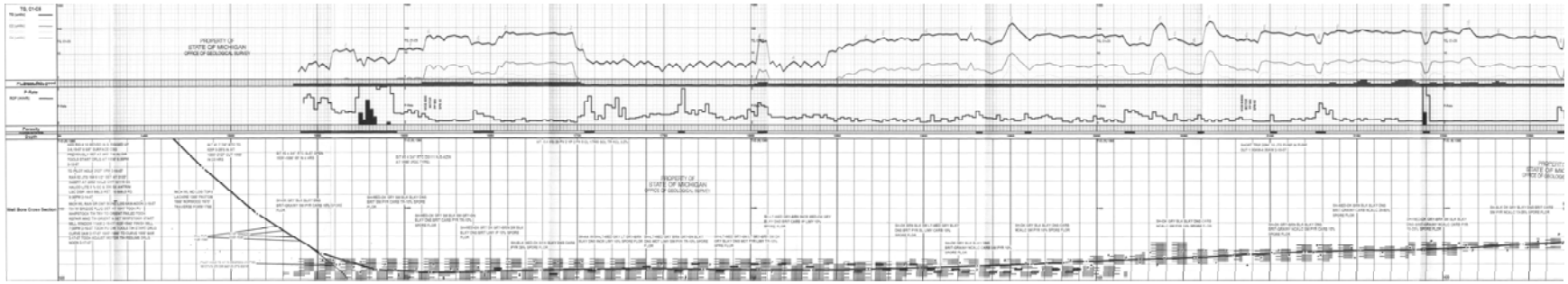


Figure 9b. State Mancelona 2-12 HD: Horizontal leg through the Lachine member, measured depth scale is from 1400 - 2270 feet, well bore on bottom track, vertical scale is 1380-1420 feet, true vertical depth.

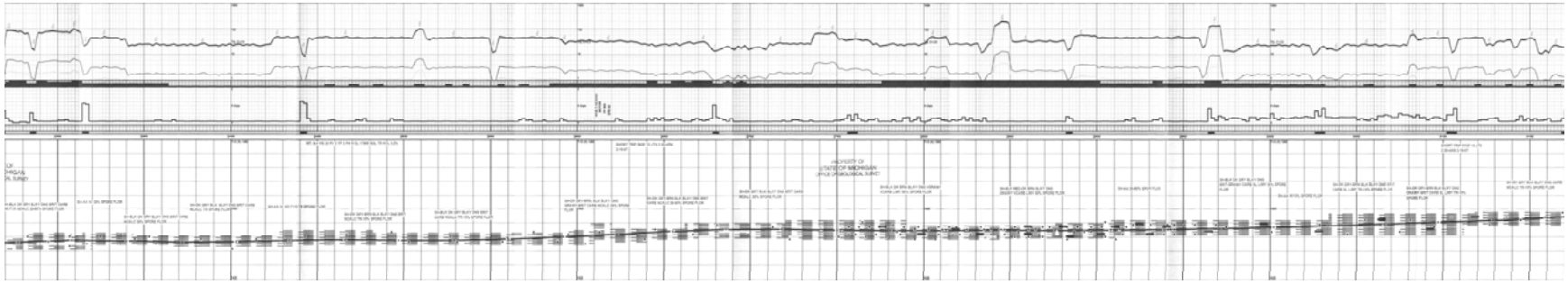


Figure 9c. State Mancelona 2-12 HD: Horizontal leg through the Lachine member, measured depth scale is from 2270 - 3170 feet, well bore on bottom track, vertical scale is 1380-1420 feet, true vertical depth.

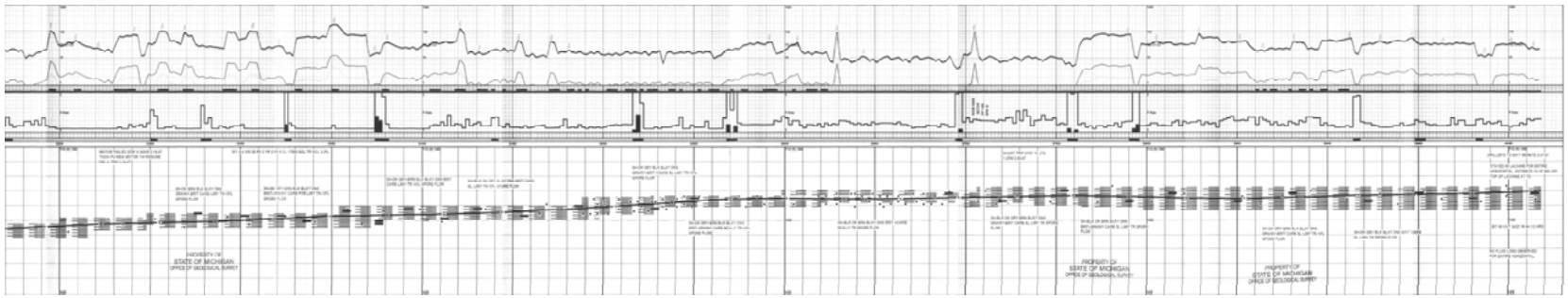


Figure 9d. State Mancelona 2-12 HD: Horizontal leg through the Lachine member, measured depth scale is from 3170 - 4030 feet, well bore on bottom track, vertical scale is 1380-1420 feet, true vertical depth.

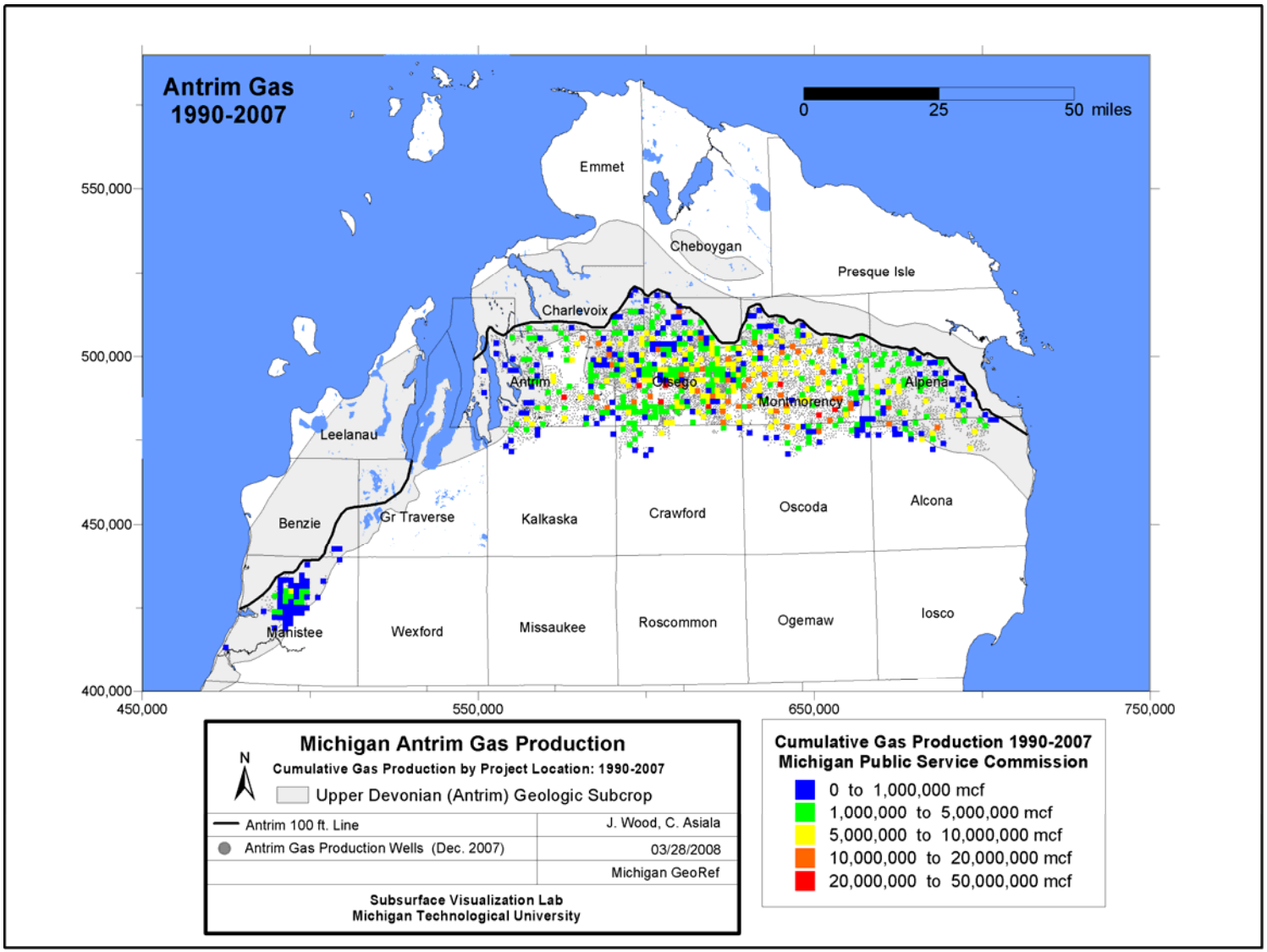


Figure 10. Cumulative Antrim gas production map of Northern Michigan. The gray shaded area is the Antrim subcrop and the black line indicates the cutoff line of where production is limited because of the 1-94 drilling restriction (Appendix I). The gray area above this line shows the area of the Antrim that could be opened up for Antrim gas production through the efforts of this DOE project.

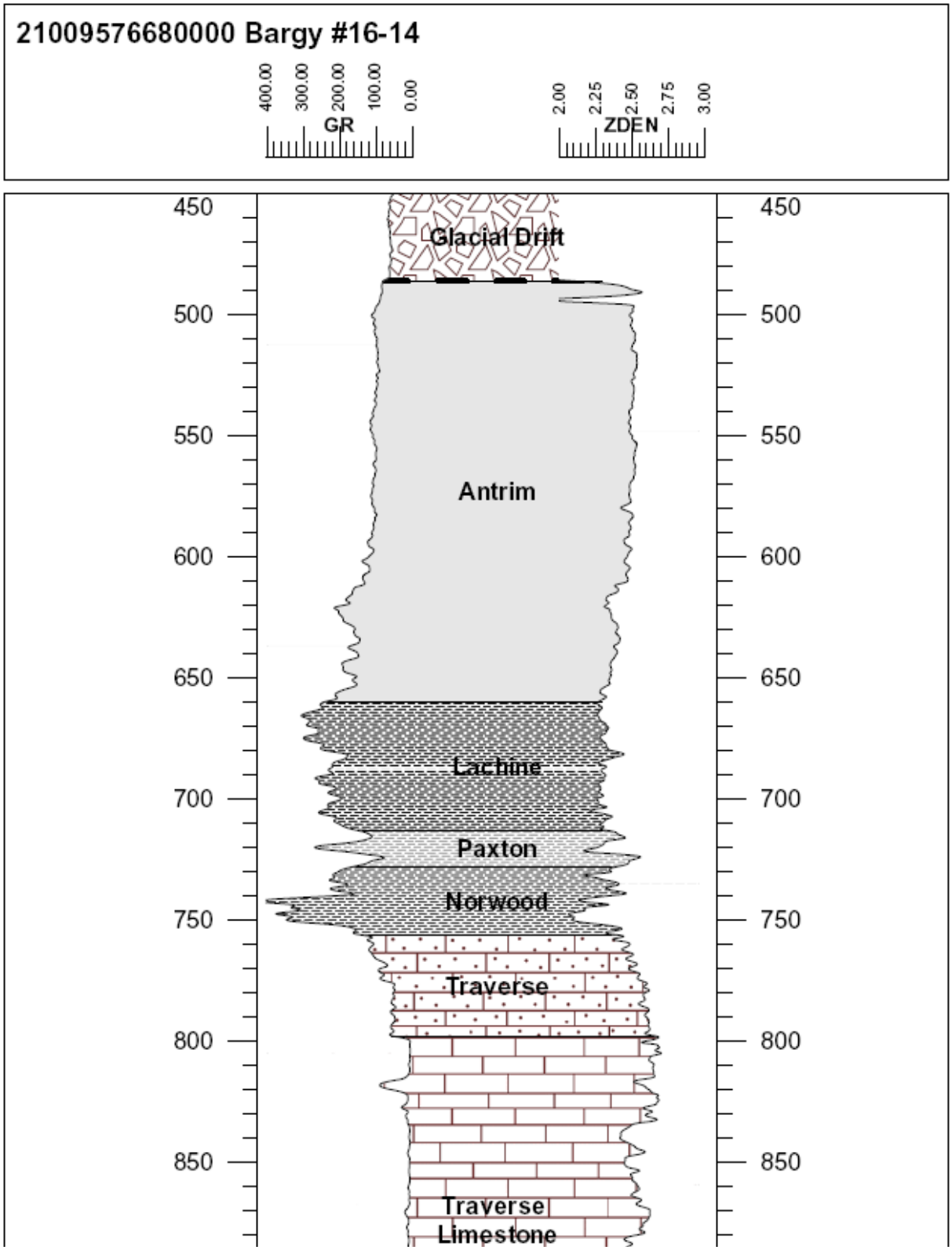


Figure 11. The Bargy #16-14 is located in the same project area as the demonstration well. This log display shows the typical signature of the Gamma Ray for the three Antrim Shale members, the Lachine, Paxton, and Norwood.

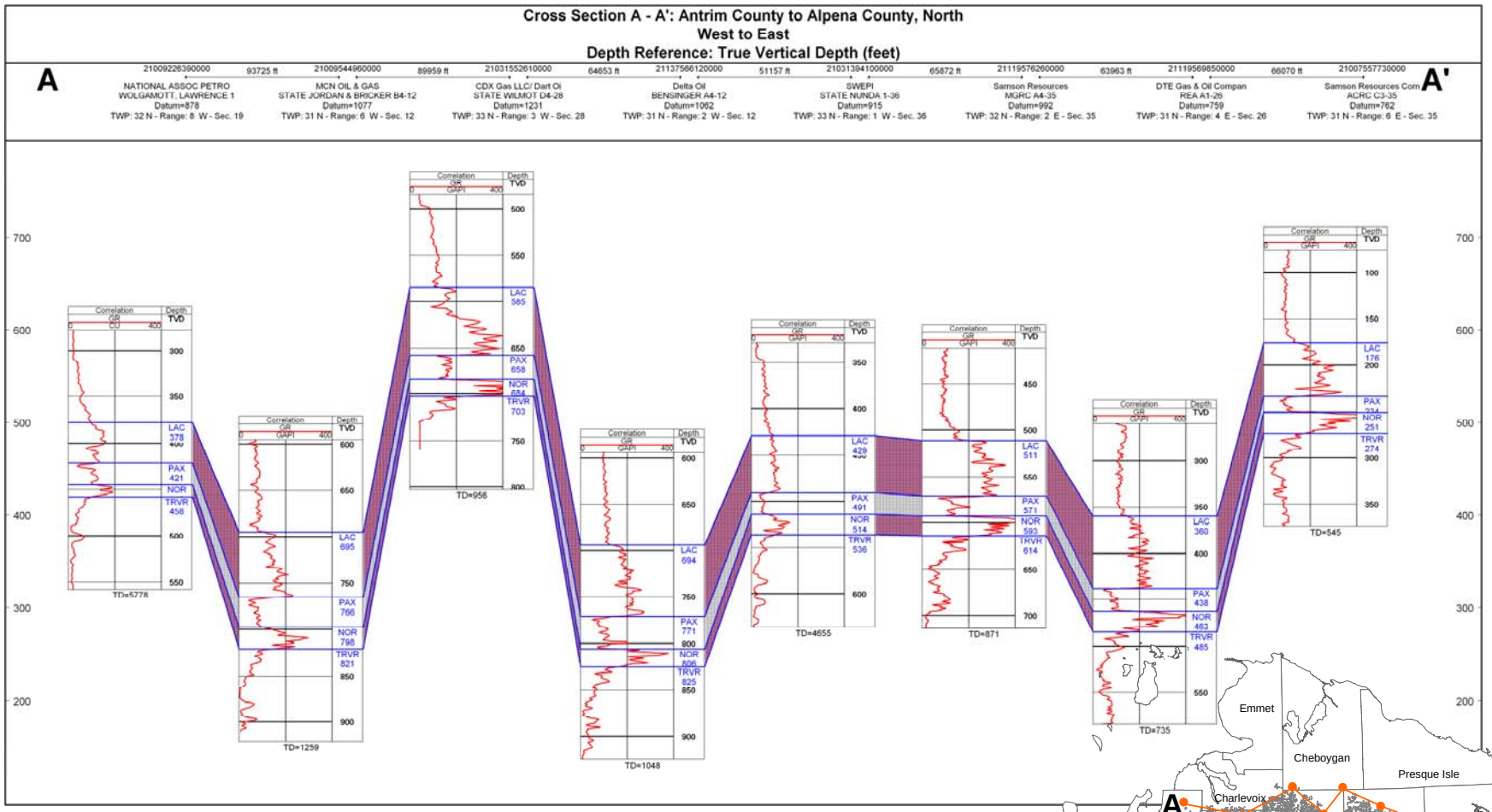


Figure 12. West – East Cross Section A-A' across the northern Lower Peninsula of Michigan along the current northern line of Antrim production wells, showing the subsea depths of the Lachine, Paxton, and Norwood formations.

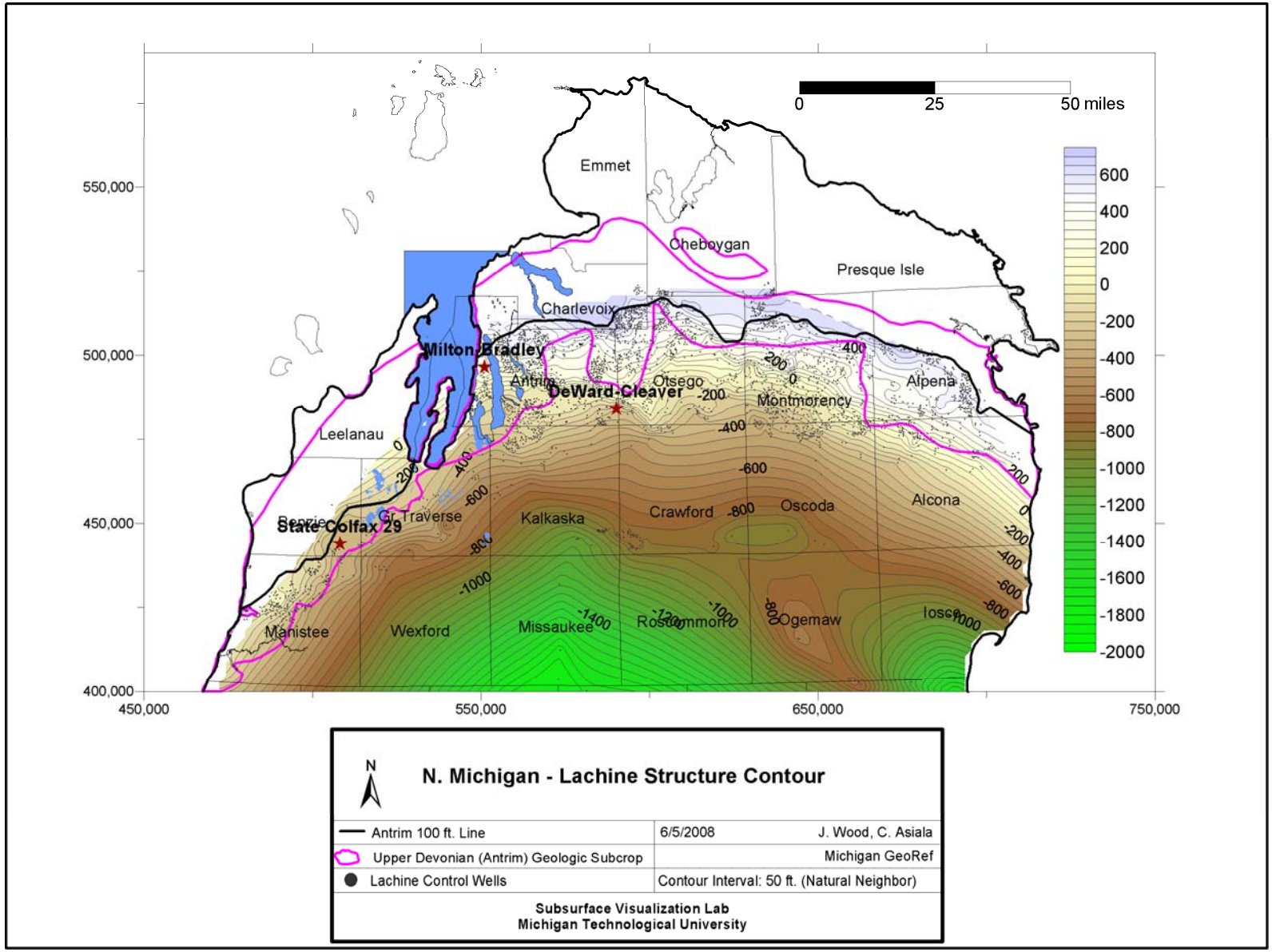


Figure 13. Structure map of the Lachine member of the Antrim formation in Northern Michigan. Contour Interval is 50 feet.

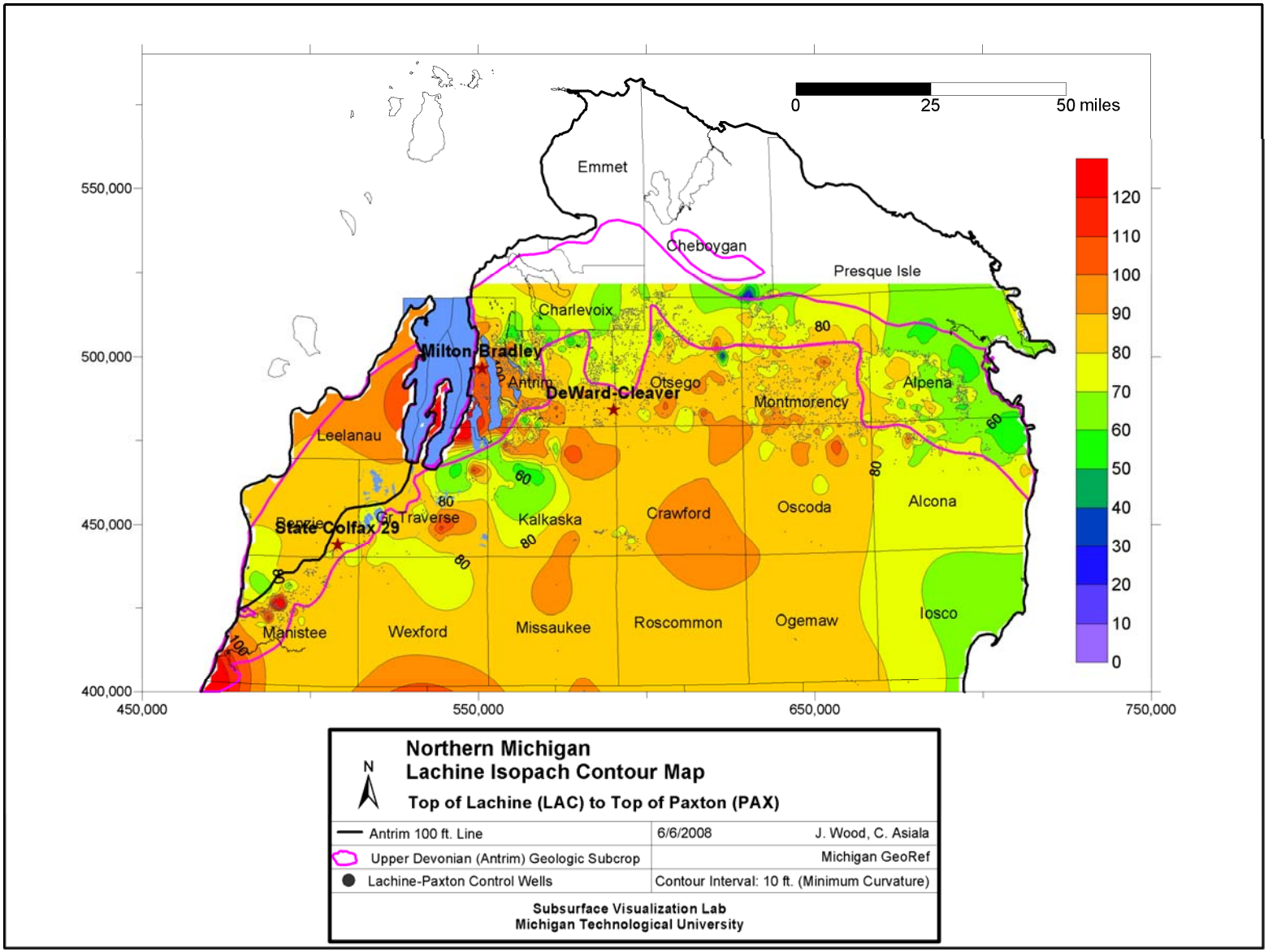


Figure 14. Isopach thickness map of the Lachine member of the Antrim formation over northern Michigan, contour interval is 10 feet.

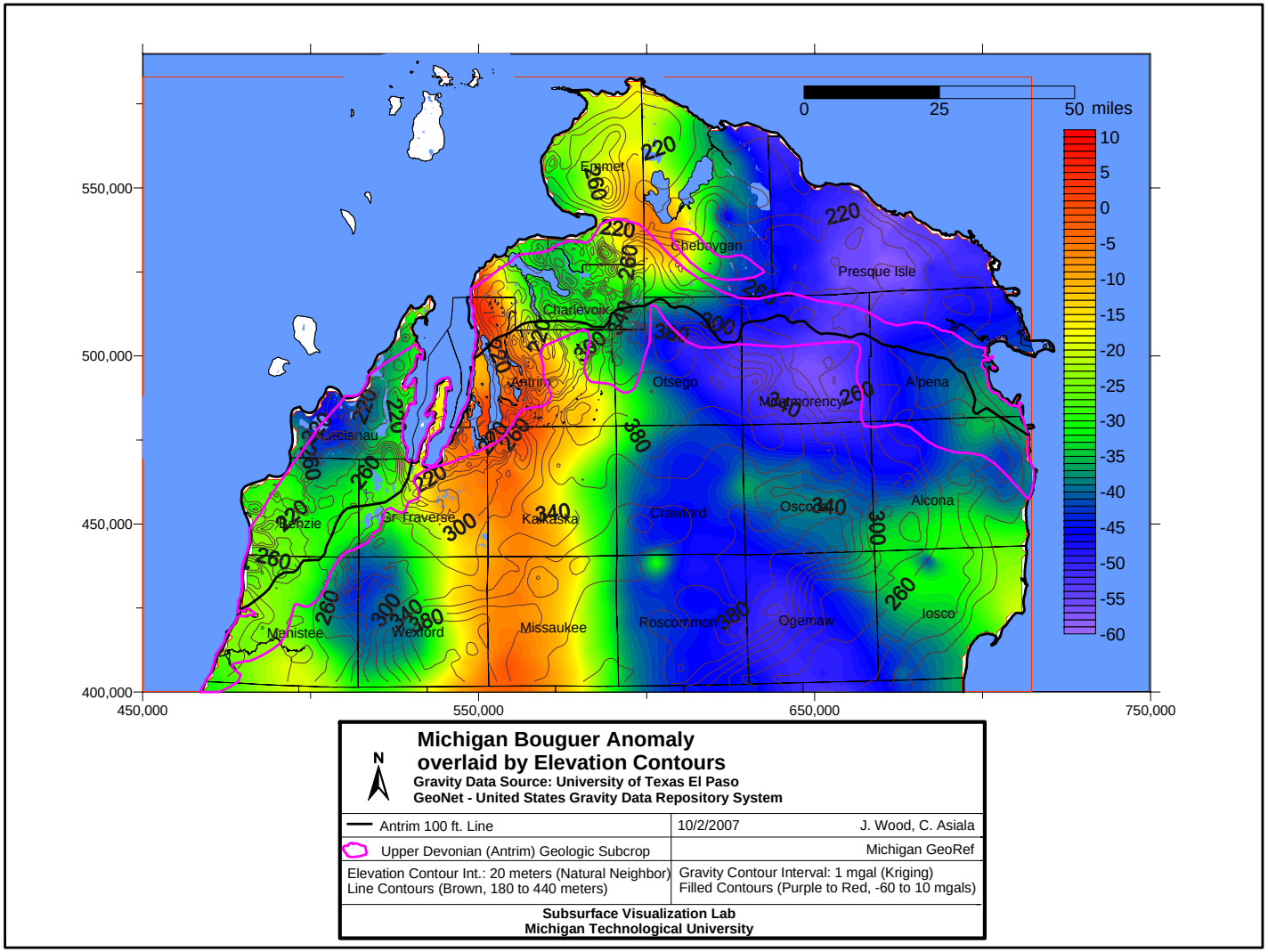


Figure 15. Michigan Bouguer Anomaly map created from data obtained from the University of Texas El Paso website for GeoNet –Gravity and Magnetic Dataset Repository. (http://irpsrvgis00.utep.edu/repositorywebsite/). Color-filled contours are shown from -60 to 10 mgals with a contour interval of 1 mgal. The elevation contours overlaid on the Bouger Anomaly ranges from 180 to 440 meters and were contoured at a 20 meter interval.

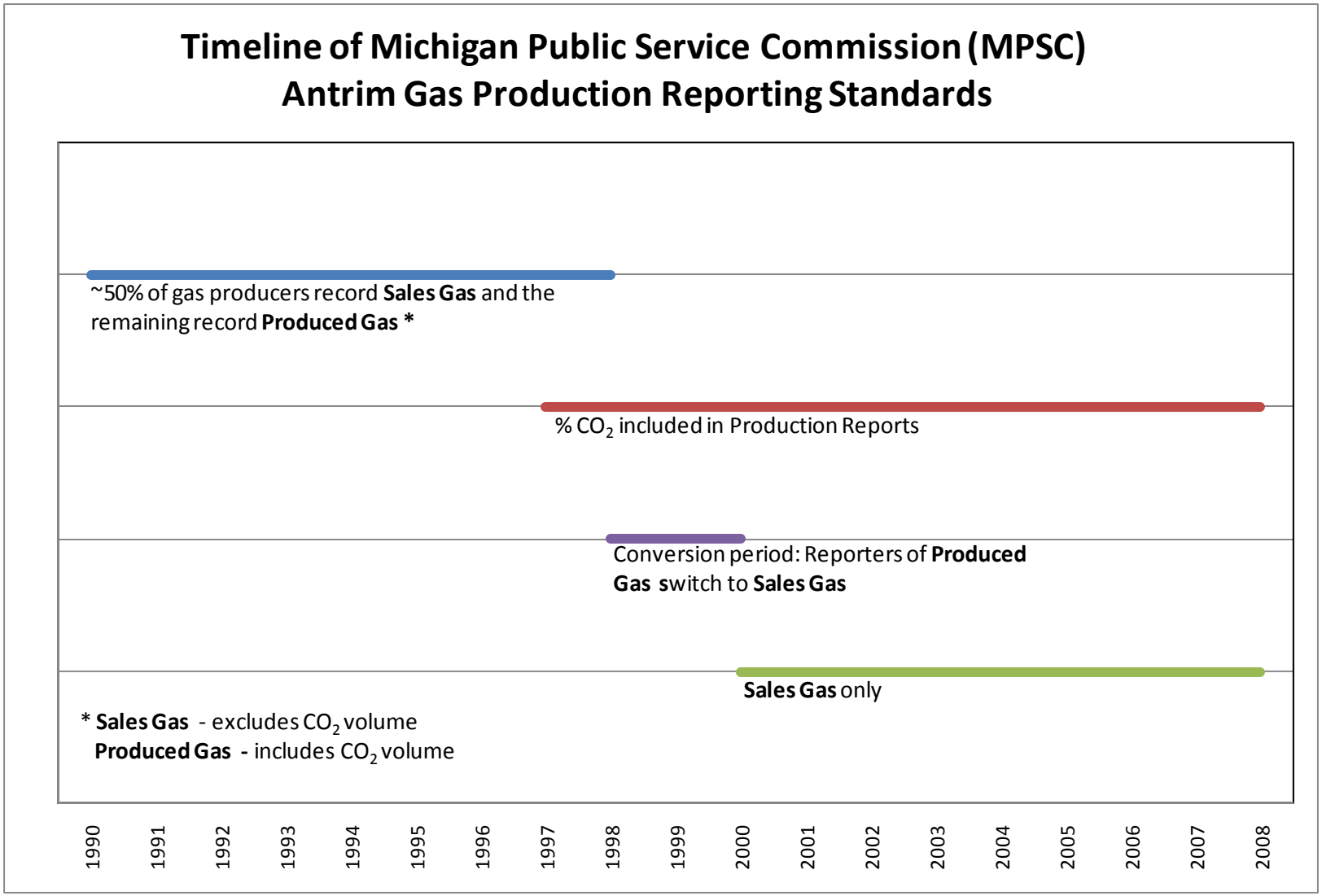


Figure 16. Timeline and definition of how carbon dioxide production has been historically recorded and archived by the Michigan Public Service Commission.

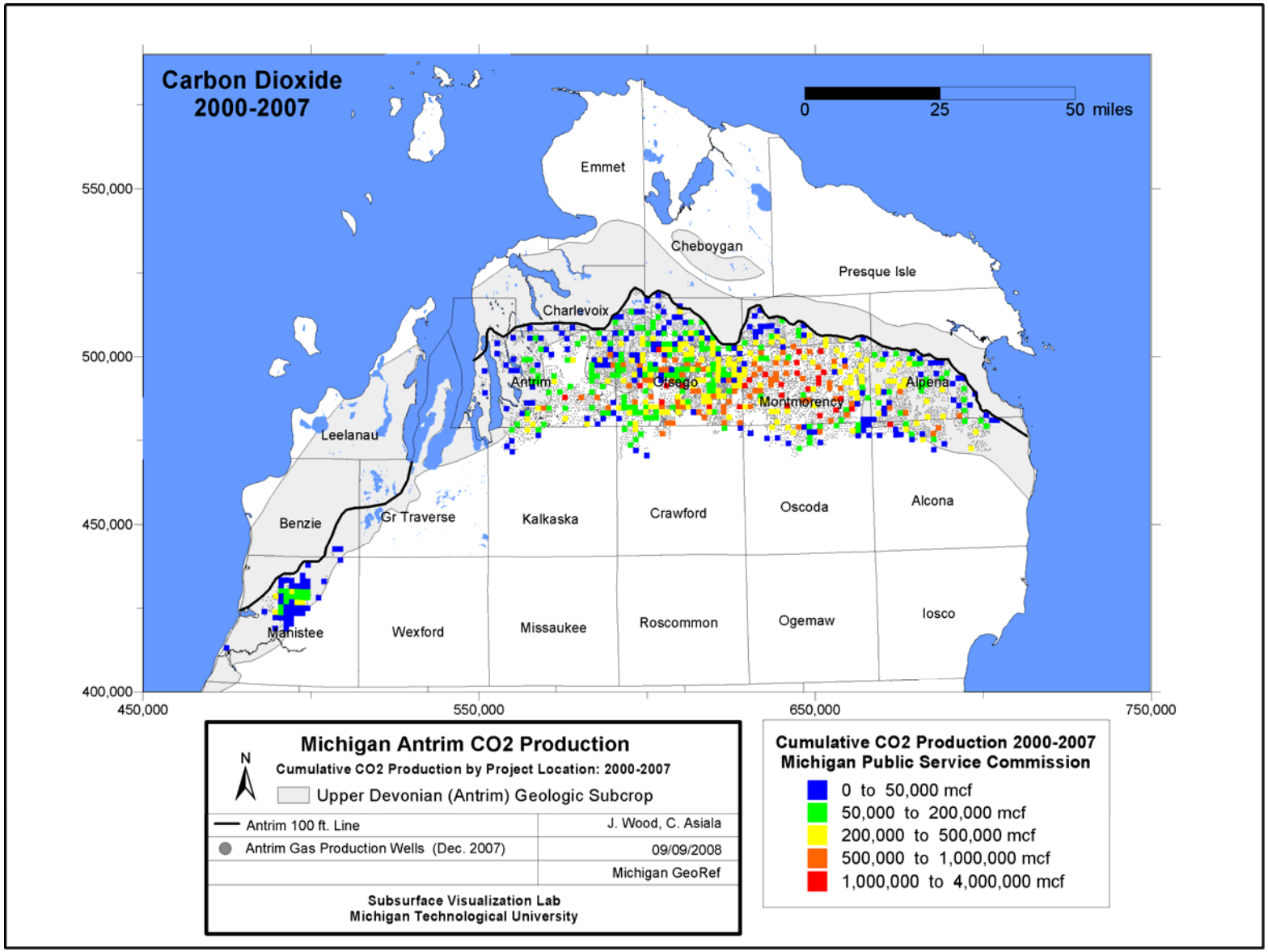


Figure 17. Production map showing the distribution of cumulative CO_2 produced from 2000 through 2007 over northern Michigan.

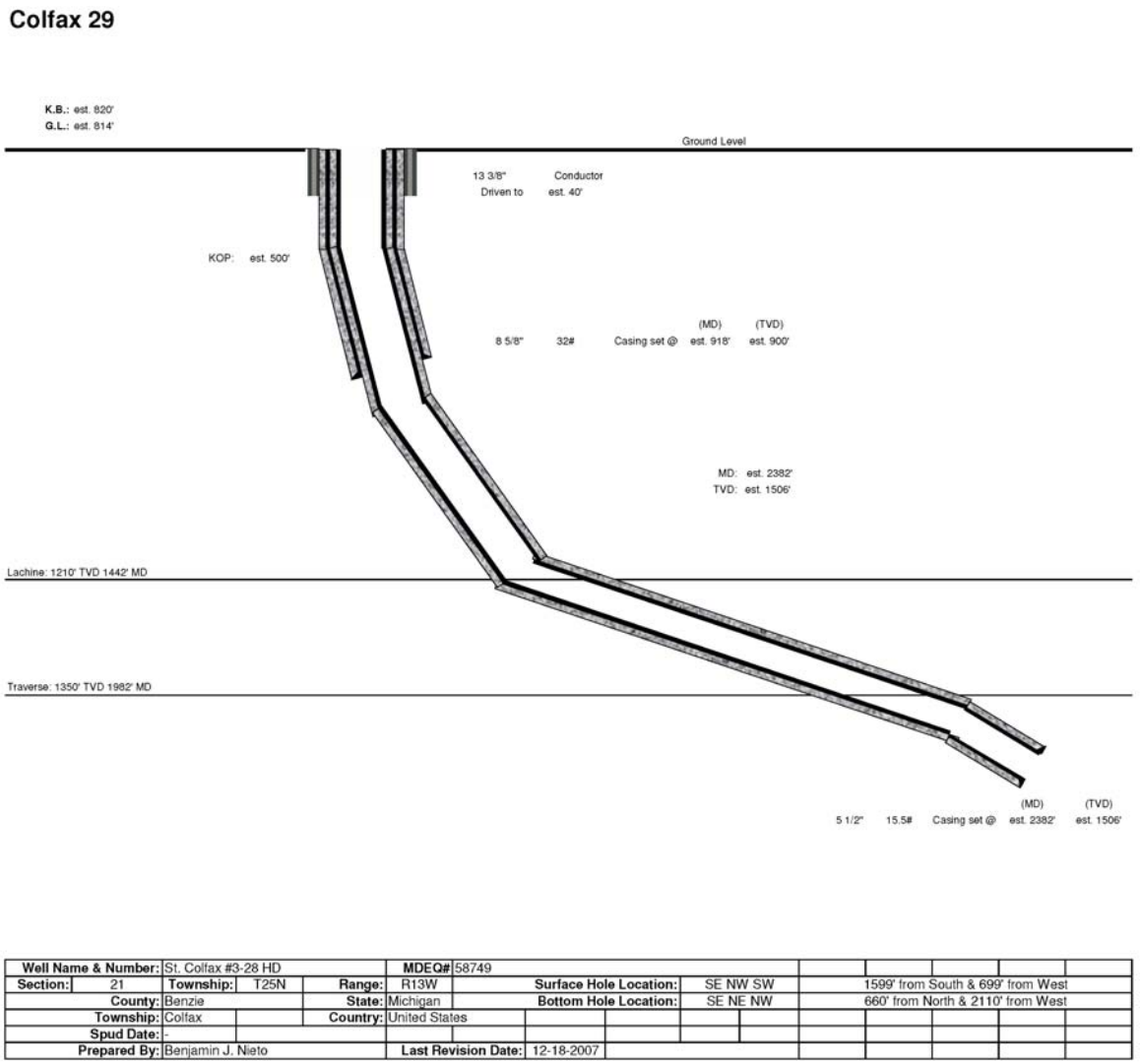


Figure 18. Redesigned well configuration for project demonstration well, St. Colfax 3-28 HD, designed after the initial tests of the original "J" well configuration. This well is a cased hole drilled to near horizontal (75 to 85 degrees) and carried through the Antrim section in a slightly downward inclination. Perforated completion intervals were then shot through the pipe and individually fracture treated.

DEQ MICHIGAN DEPARTMENT OF ENVIRONMENTAL QUALITY – OFFICE OF GEOLOGICAL SURVEY

RECORD OF WELL COMPLETION

By authority of Part 615 or Part 625 of Act 451 PA 1994, as amended. Non-submission and/or falsification of this information may result in fines and/or imprisonment.

(Submit 3 copies within 60 days of well completion.)
☒ Part 615 Oil/Gas Well ☐ Part 625 Mineral Well

Permit number/deepening permit no.	API number
58749	21-019-58749-00-00

Type of well (after completion): Gas

Well name & number: State Colfax #3-28 HD

Name and address of permittee
Jordan Development Company, L.L.C.
1503 Garfield Road North
Traverse City, MI 49686

Directionally drilled (check one)	Previous permit numbers	Total depth of well
☒ Yes ☐ No	N/A	M.D. 2400' T.V.D. 1522'

Surface location	Subsurface location (if directionally drilled)
SE ¼ of NW ¼ of SW ¼ Section 21 T 25N R 13W	SW ¼ of SE ¼ of SW ¼ Section 21 T 25N R 13W
Township: Colfax	Township: Colfax
County: Benzie	County: Benzie
Footages: North/South East/West	Footages: North/South East/West
1599 Ft. from South line and 699 Ft. from West line of Sec.	371 Ft. from South line and 1430 Ft. from West line of Sec.

Part 615 - oil/gas wells			Part 625 - mineral wells		
Date well completed	Producing formation(s)	Injection formation(s)	Date of first injection	Disposal formation(s)	Solution formation(s)
2-26-2008	Antrim Shale	N/A	N/A	N/A	N/A

COMPLETION INTERVALS(S)

Date	Number holes	Perforation or open hole interval	Open	
			Yes	No
2-25-2008	4 SPF	2026'-2032',2035'-2040',1998'-2008',1836'-1846'	X	
2-26-2008	4 SPF	1794'-1799',1779'-1784',1735'-1740',1721'-1726',1703'-1708',	X	
		1682'-1687',1649'-1654',1627'-1632',1596'-1600',1577'-1582',		
		1557'-1562',1330'-1340'		

STIMULATION BY ACID OR FRACTURING

Date	Interval treated	Materials and amount used
2-25-2008	2026'-2032',2035'-2040'	15% Acid: 700 gals, Sand: 47,157# 20/40 4,700# 12/20
2-25-2008	1998'-2008',1836'-1846'	15% Acid: 1000 gals, Sand: 50,900# 20/40 5,700# 12/20
2-26-2008	1794'-1799',1779'-1784'	15% Acid: 1000 gals, Sand: 25,800# 20/40 6,000# 12/20
2-26-2008	1735'-1740',1721'-1726'	15% Acid: 1000 gals, Sand: 26,700# 20/40 1,600# 12/20
2-26-2008	1703'-1708',1682'-1687'	15% Acid: 1000 gals, Sand: 25,400# 20/40 4,900# 12/20
2-26-2008	1649'-1654',1627'-1632'	15% Acid: 1000 gals, Sand: 25,500# 20/40 5,900# 12/20
2-26-2008	1596'-1600',1577'-1582',1557'-1562'	15% Acid: 1000 gals, Sand: 25,400# 20/40 5,100# 12/20
2-26-2008	1330'-1340'	15% Acid: 1000 gals, Sand: 26,600# 20/40 7,300# 12/20

PRODUCTION TEST DATA

Oil Bbls/day	Gravity °API	Condensate Bbls/day	Gas MCF/day	Water Bbls/day	H_2S Grains/100 ft^3.	B.H.P. and depth
N/A	N/A	N/A	150 est.	400 est.	N/A	N/A

CERTIFICATION "I state that I am authorized by said owner. This report was prepared under my supervision and direction. The facts stated herein are true, accurate and complete to the best of my knowledge."

Name and title (print or type)	Signature	Date
Benjamin J. Nieto, Authorized Agent		

Submit to: OFFICE OF GEOLOGICAL SURVEY
MICHIGAN DEPARTMENT OF ENVIRONMENTAL QUALITY
PO BOX 30256
LANSING MI 48909-7756

EQP 7130 (rev. 8/2004)

Figure 19. Record of Completion for the St. Colfax 3-28HD well in Benzie County, MI.

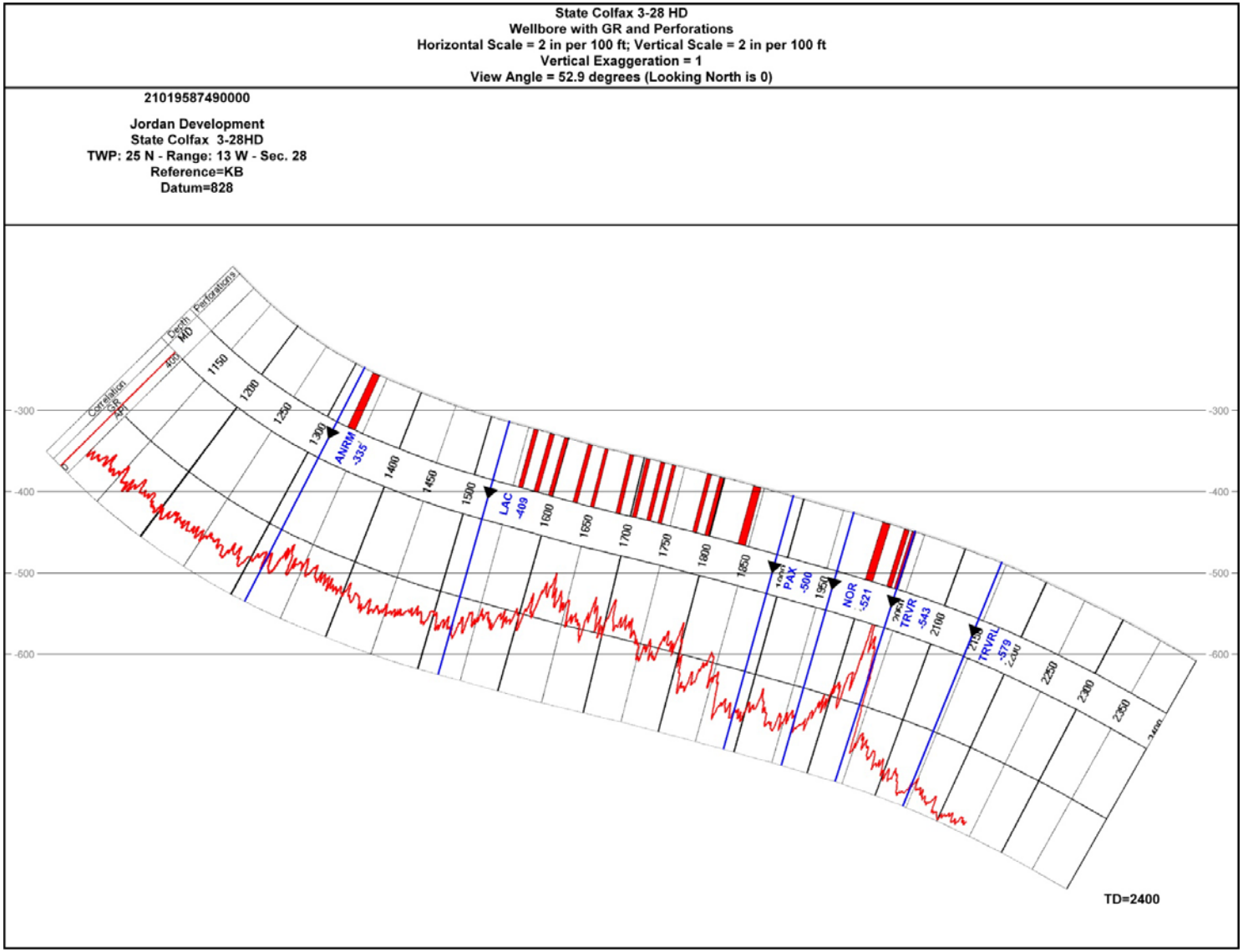


Figure 20. Cross section of Gamma Ray log over the cased well path of the demonstration well, St. Colfax 3-28 HD in Benzie County, MI. Blue lines mark the formation tops of the Antrim, Lachine, Paxton, Norwood, and Traverse formations. The red bars mark the perforation intervals.

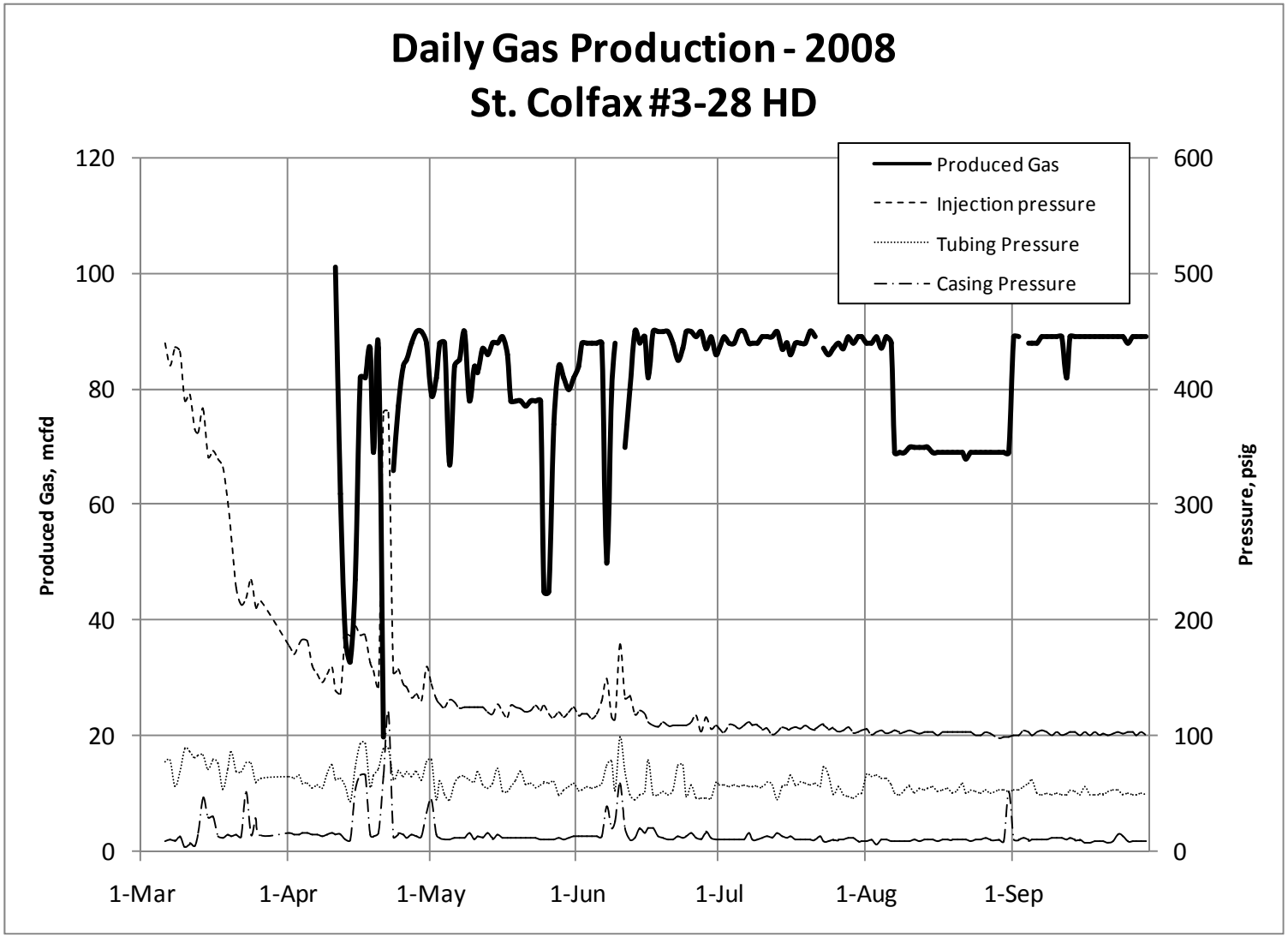


Figure 21. Daily gas production and injection pressure data for the project demonstration well, Colfax 3-28 HD in Benzie County, MI. The lateral for this well was drilled with a cased hole downward sloping configuration with perforated completion intervals shot through the pipe and individually fracture treated.

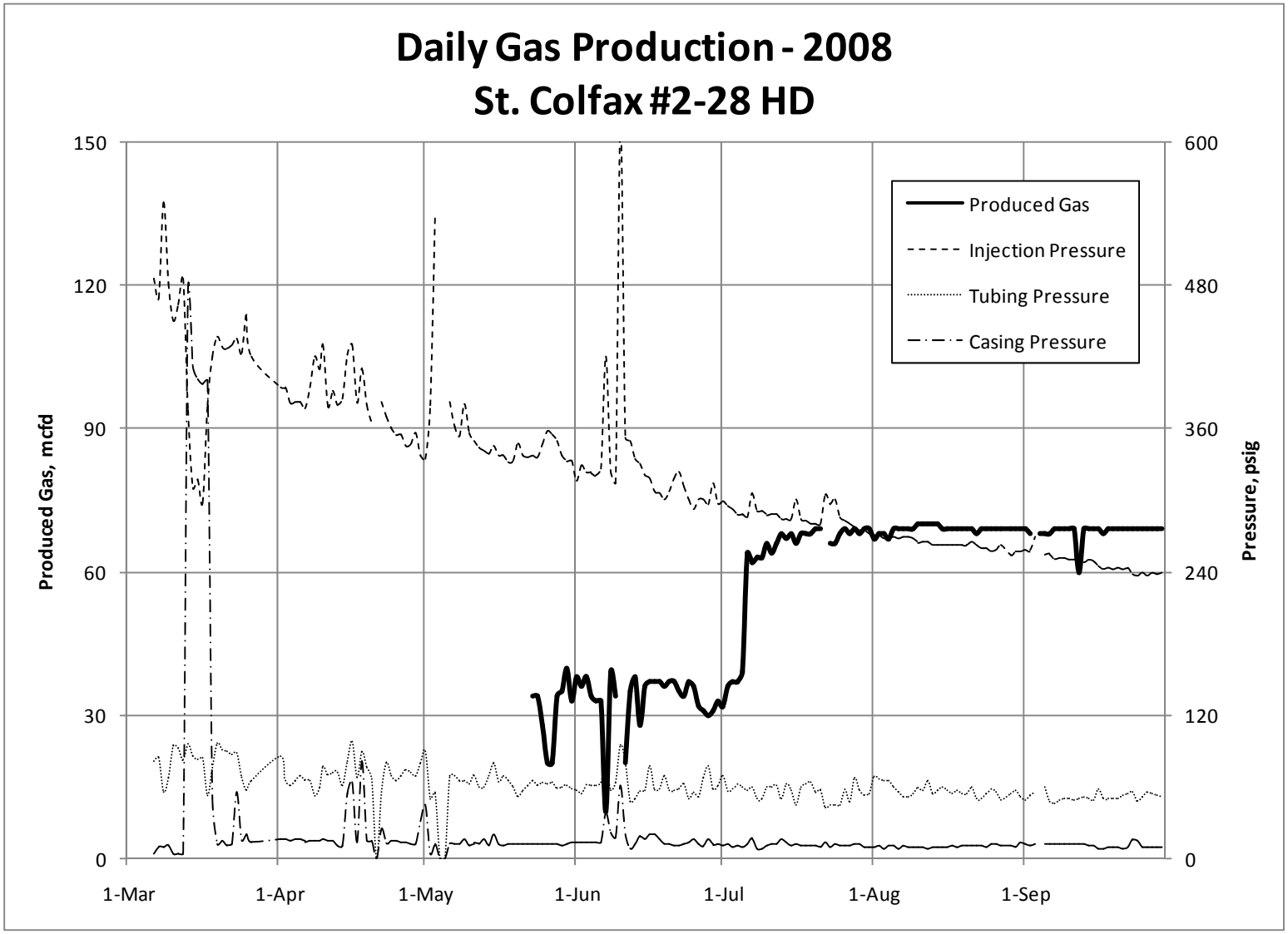


Figure 22. Daily gas production and injection pressure data for the Colfax 2-28 HD, the well drilled near the project demonstration well in Benzie County, MI with the same cased hole downward sloping configuration.

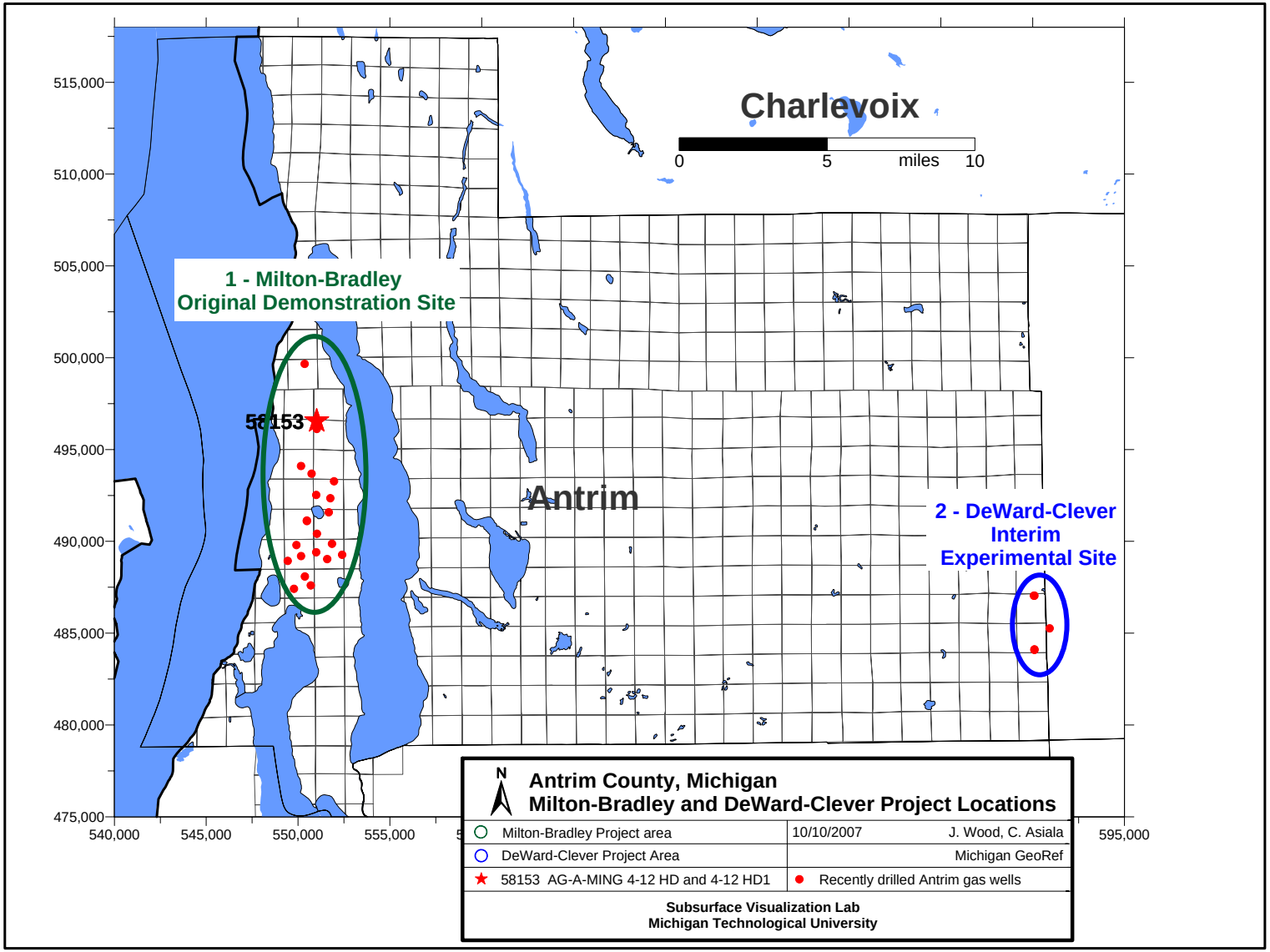


Figure 23. Location map comparing the locations of the DOE LINGO project area, Milton-Bradley, to the Deward Clever project area, where the "J" well configuration for the horizontal wells has been put to practice.

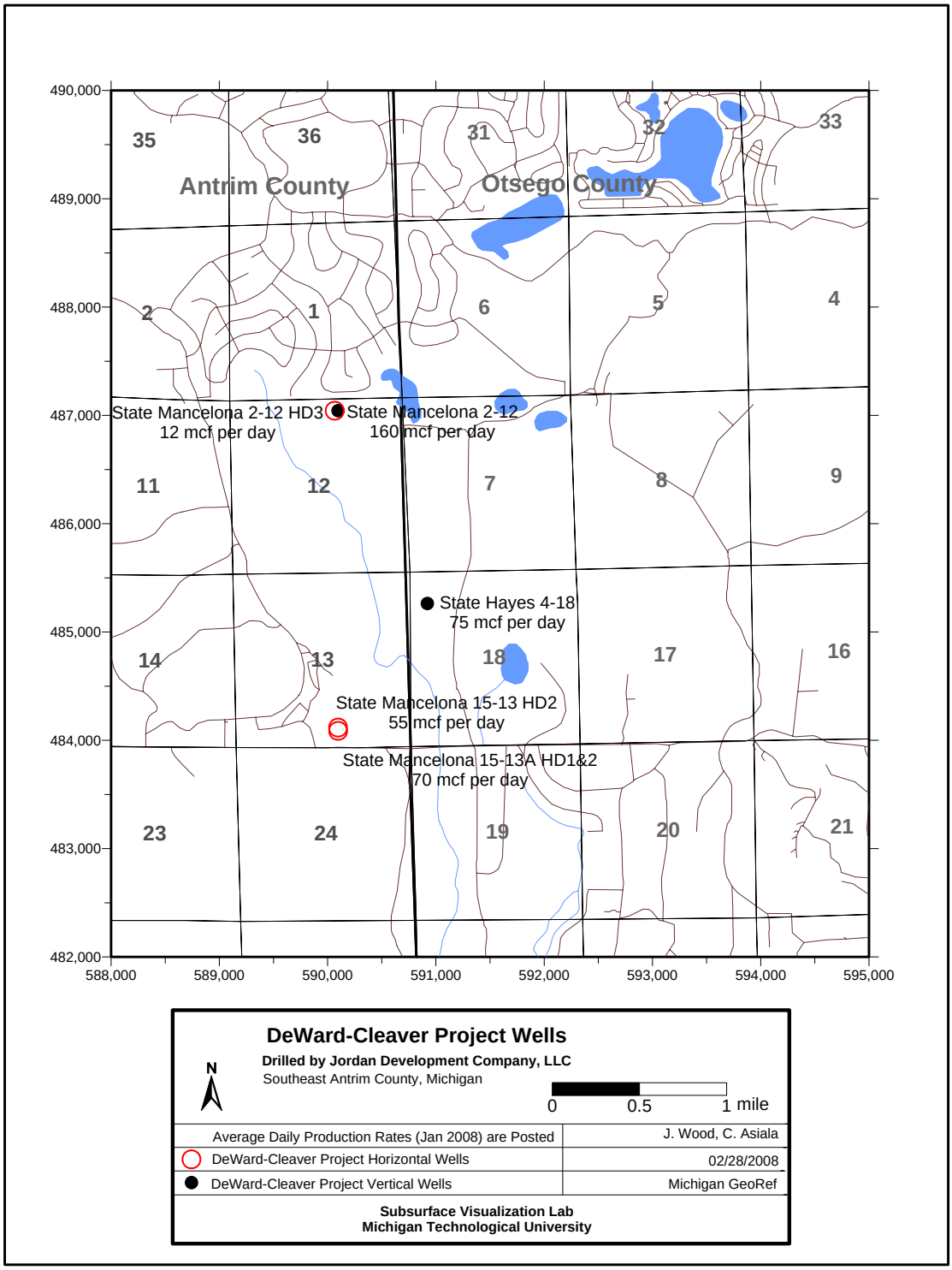


Figure 24. Location map of the Deward Cleaver project where the "J" well configuration has been tested.

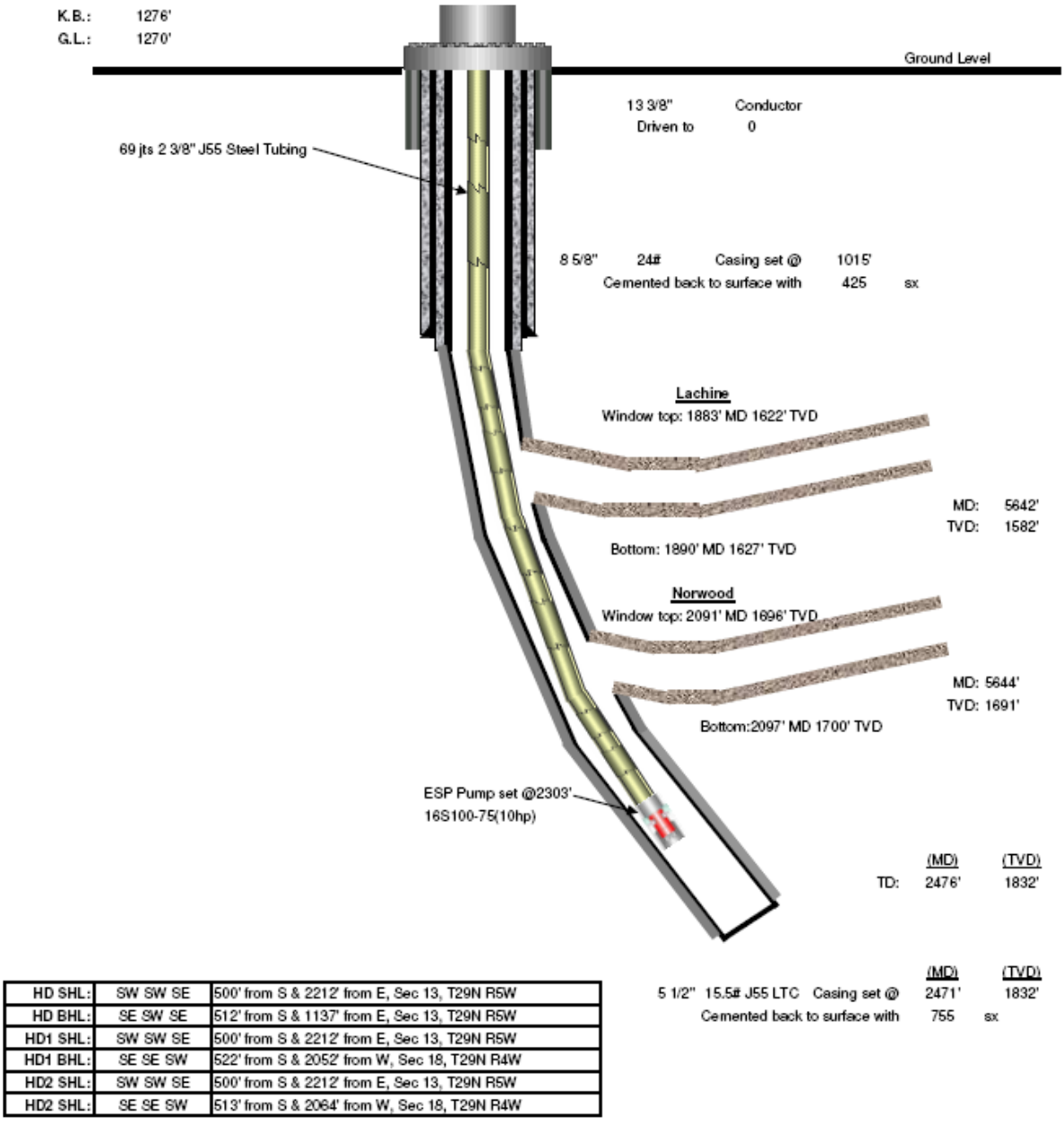


Figure 25. Well bore schematic of the "J" well configuration of the State Mancelona #15-13A HD1 & HD2 (Permit 57452) horizontal wells in the Deward Clever project in southeast Antrim County, MI.

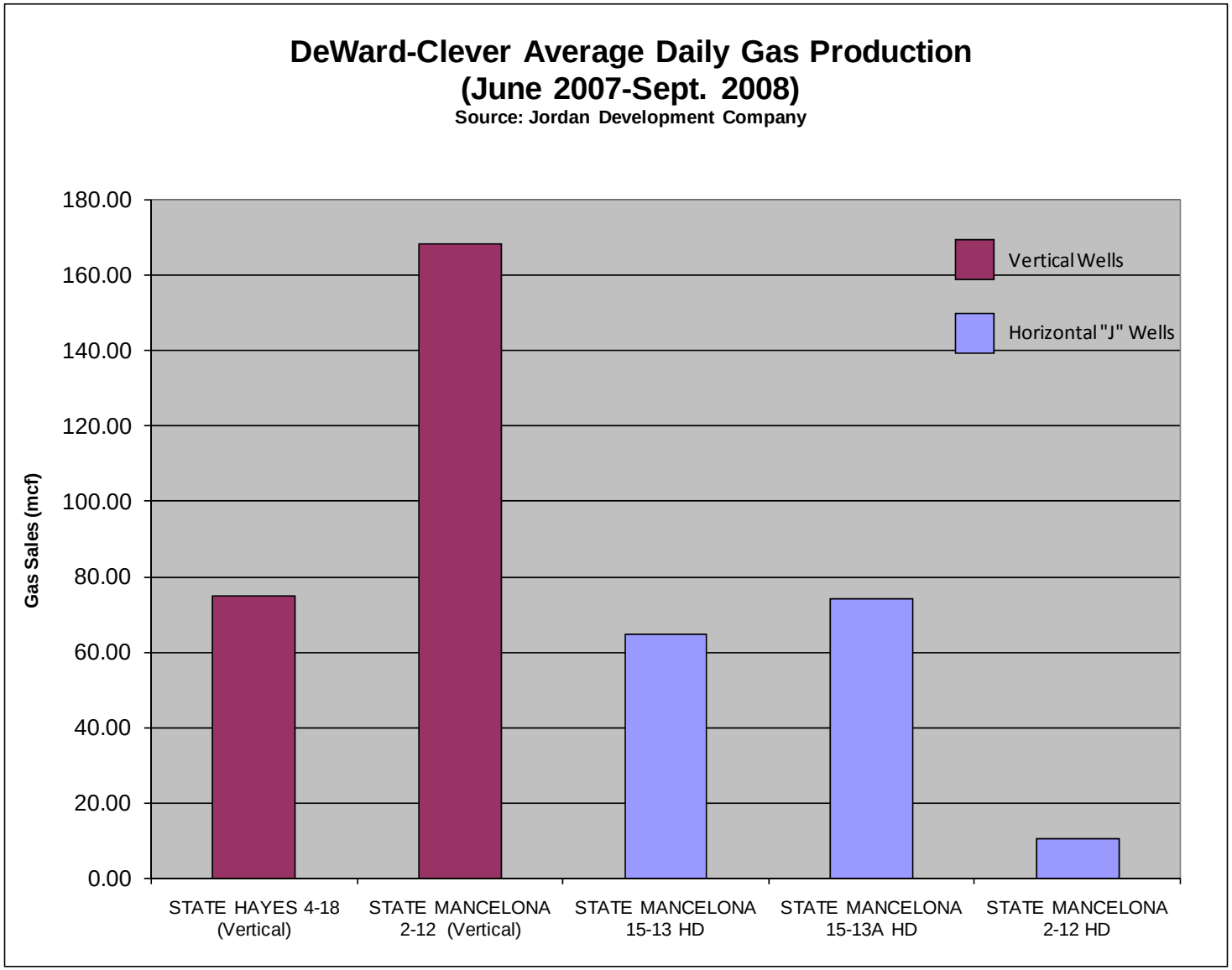


Figure 26. Comparison of average daily Antrim gas production for the Deward Clever project wells located in southeast Antrim County. The horizontal wells are using the "J" well configuration originally planned for the LINGO project demonstration well.

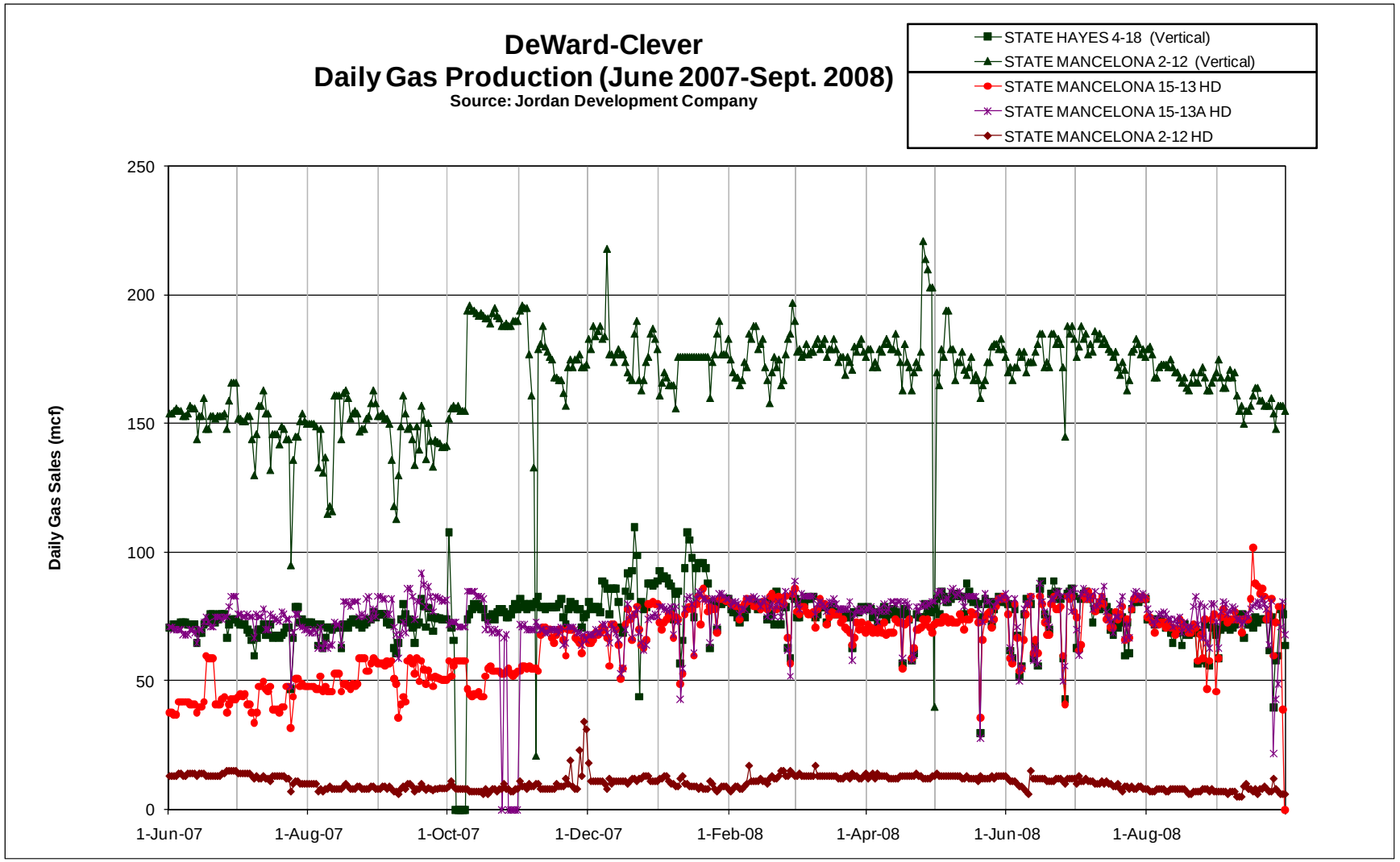


Figure 27. Daily Antrim gas production for the Deward Clever project wells located in southeast Antrim County. The horizontal wells are using the "J" well configuration planned for the LINGO project demonstration well.

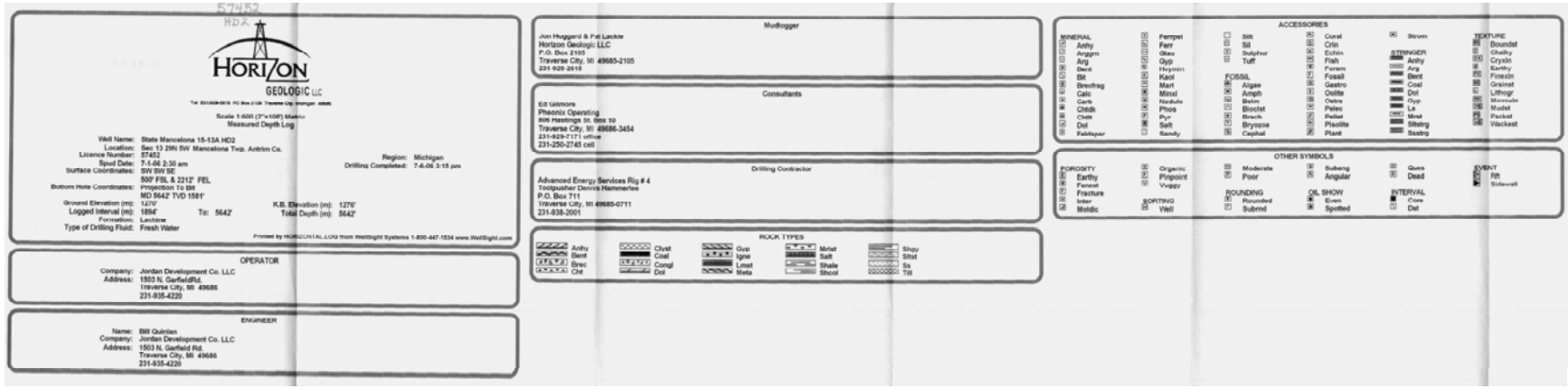


Figure 28a. Mud log and well bore cross section of Lachine leg of the State Mancelona 15-13A HD2 (API: 21-009-57452-0200) well in the Deward Cleaver project area in east Antrim County, MI. The lateral was drilled with an upward slope (the "J" well configuration) in an open uncased hole with no fracturing or perforating through the Lachine member of the Antrim formation. The following segments display the lengths of the log from a measured depth range of 1800-5660 feet, and the center track displays a true vertical depth range of 1560-1660 feet.

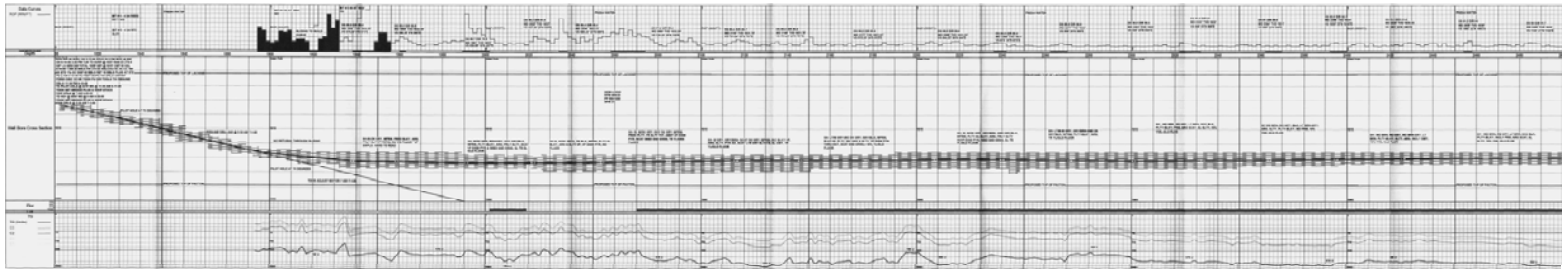


Figure 28b. Horizontal leg through the Lachine member, 1800-2500 feet, well bore on center track, vertical scale is 1560-1660 feet, true vertical depth.

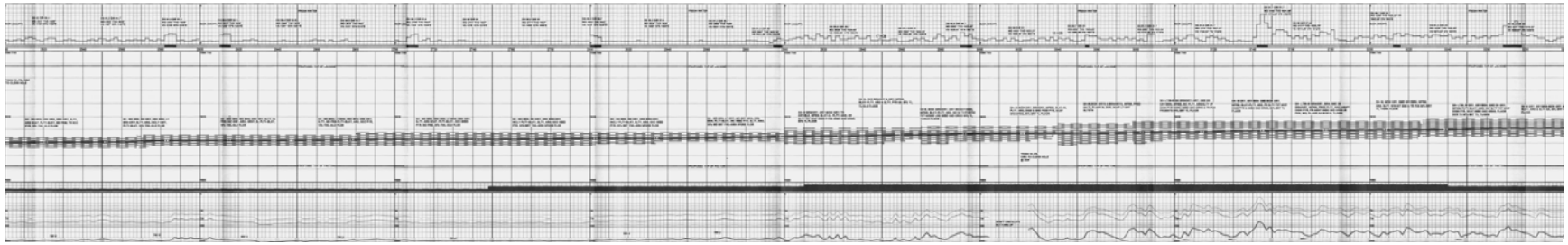


Figure 28c. Horizontal leg through the Lachine member, 2500-3300 feet, well bore on center track, vertical scale is 1560-1660 feet, true vertical depth.

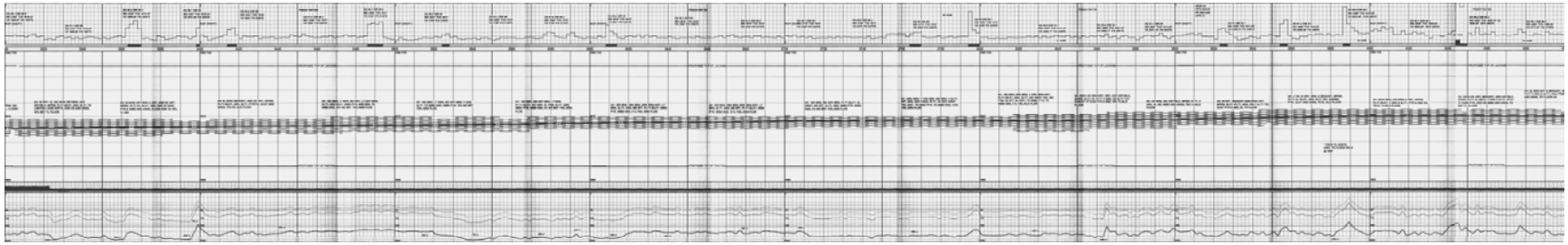


Figure 28d. Horizontal leg through the Lachine member, 3300-4100 feet, well bore on center track, vertical scale is 1560-1660 feet, true vertical depth.

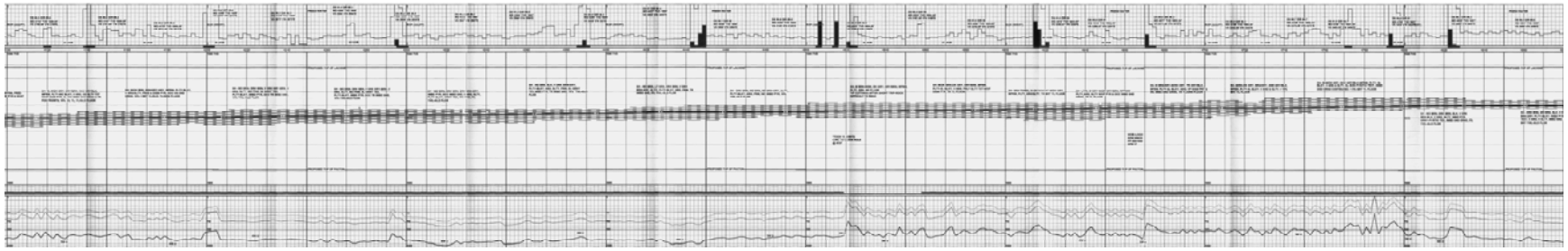


Figure 28e. Horizontal leg through the Lachine member, 4100-4900 feet, well bore on center track, vertical scale is 1560-1660 feet, true vertical depth.

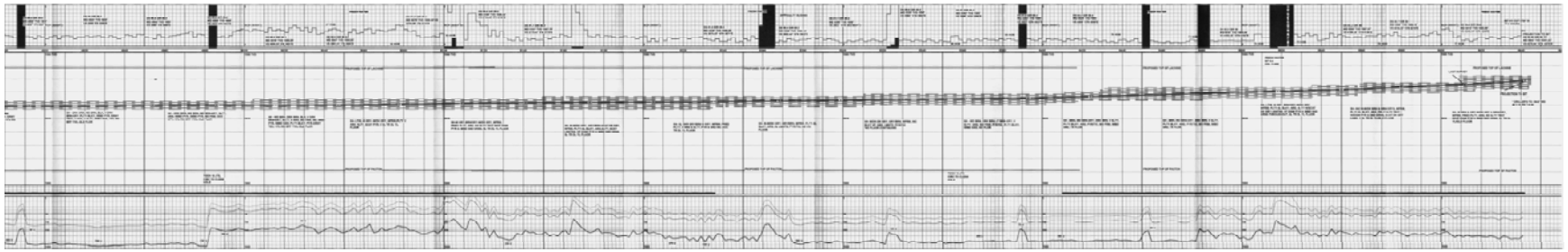


Figure 28f. Horizontal leg through the Lachine member, 4900-5660 feet, well bore on center track, vertical scale is 1560-1660 feet, true vertical depth.

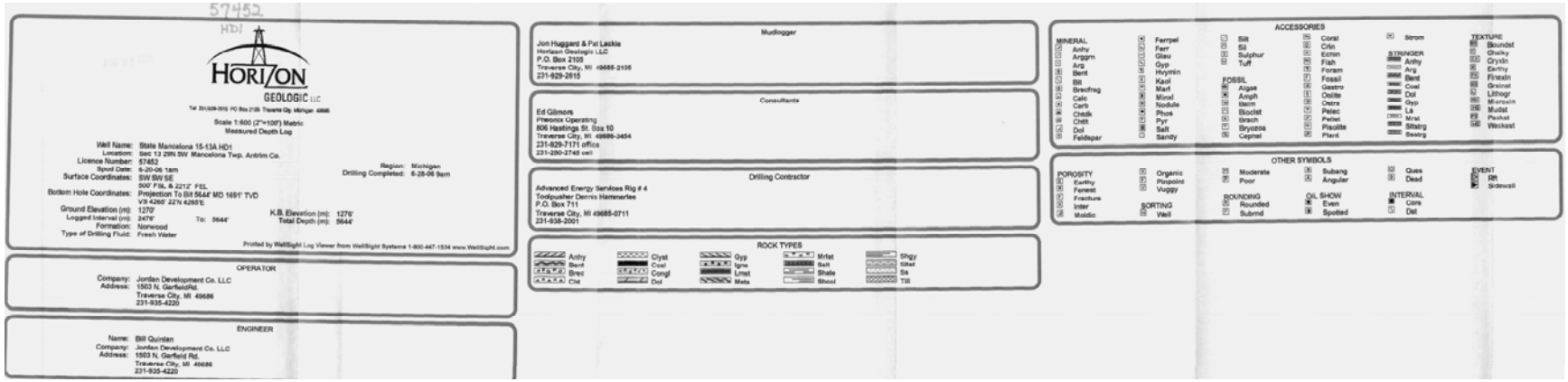


Figure 29a. Mud log and well bore cross section of Norwood leg of the State Mancelona 15-13A HD1 (API: 21-009-57452-0100) well in the Deward Cleaver project area in east Antrim County, MI. The lateral was drilled with an upward slope (the "J" well configuration) in an open uncased hole with no fracturing or perforating through the Norwood member of the Antrim formation. The following segments display the lengths of the log from a measured depth range of 2000-5640 feet, and the center track displays a true vertical depth range of 1680-1730 feet.

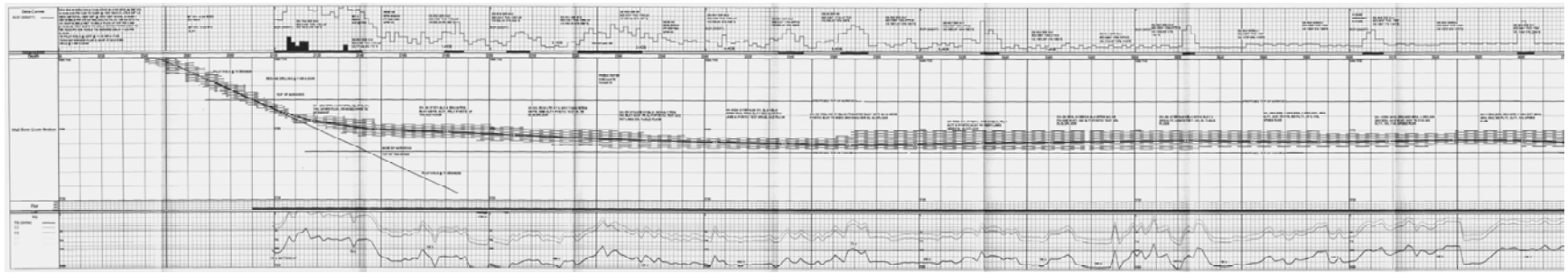


Figure 29b. Horizontal leg through the Lachine member, 2000-2700 feet, well bore on center track, vertical scale is 1680-1730 feet, true vertical depth.

Figure 29c. Horizontal leg through the Lachine member, 2700-3500 feet, well bore on center track, vertical scale is 1680-1730 feet, true vertical depth.

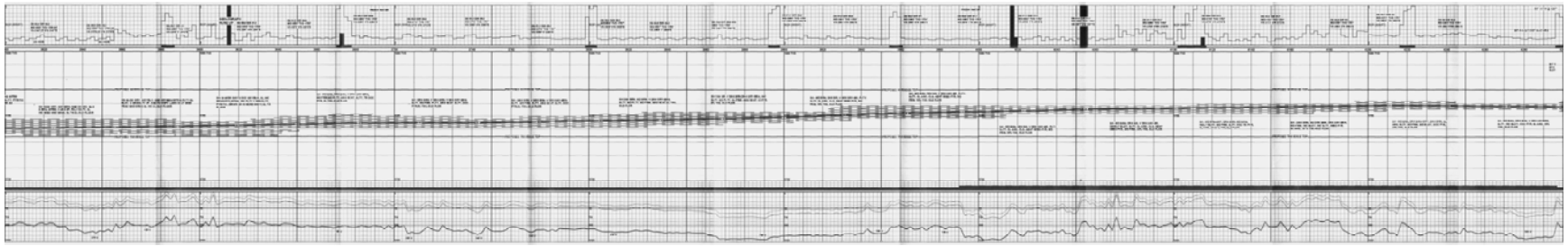


Figure 29d. Horizontal leg through the Lachine member, 3500-4300 feet, well bore on center track, vertical scale is 1680-1730 feet, true vertical depth.

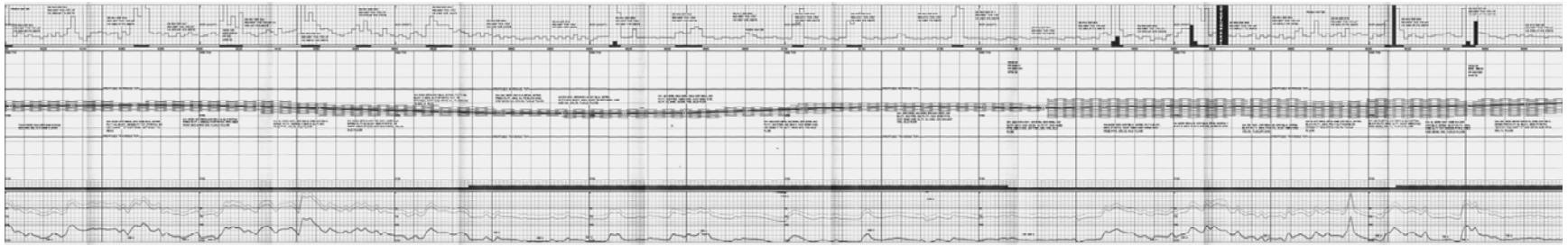


Figure 29e. Horizontal leg through the Lachine member, 4300-5100 feet, well bore on center track, vertical scale is 1680-1730 feet, true vertical depth.

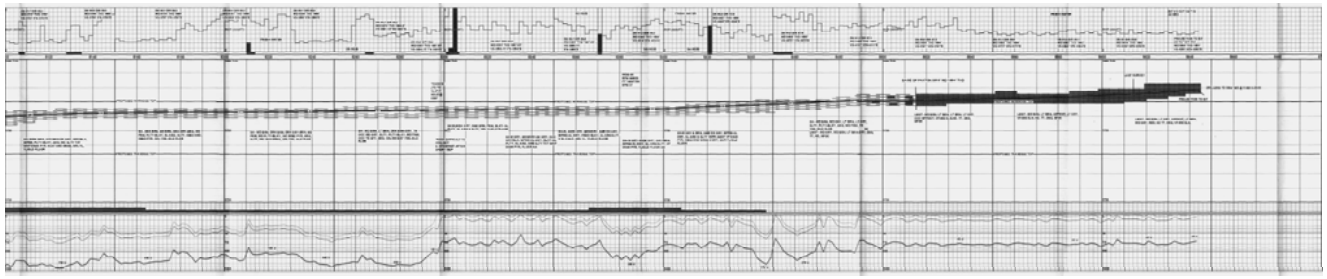


Figure 29f. Horizontal leg through the Lachine member, 5100-5640 feet, well bore on center track, vertical scale is 1680-1730 feet, true vertical depth.

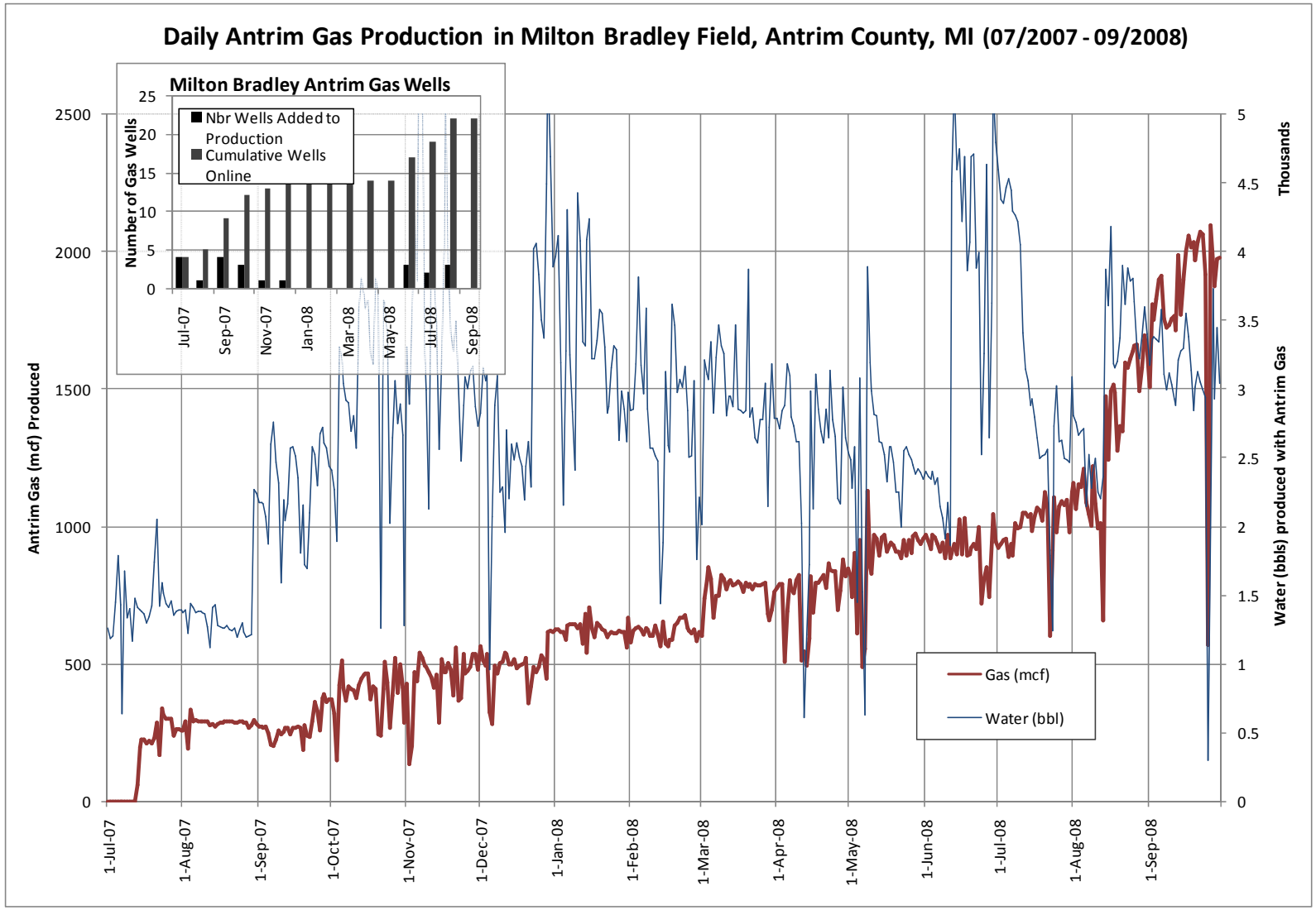


Figure 30. Antrim gas, and water produced with Antrim gas, from the vertical wells in the Milton Bradley project area in Antrim County, MI, the location of the AG-A-MING 4-12HD, the original LINGO project demonstration well. The inset chart shows the total number of vertical wells added to the project per month, and the cumulative number of wells put on the production line through September 30, 2008.

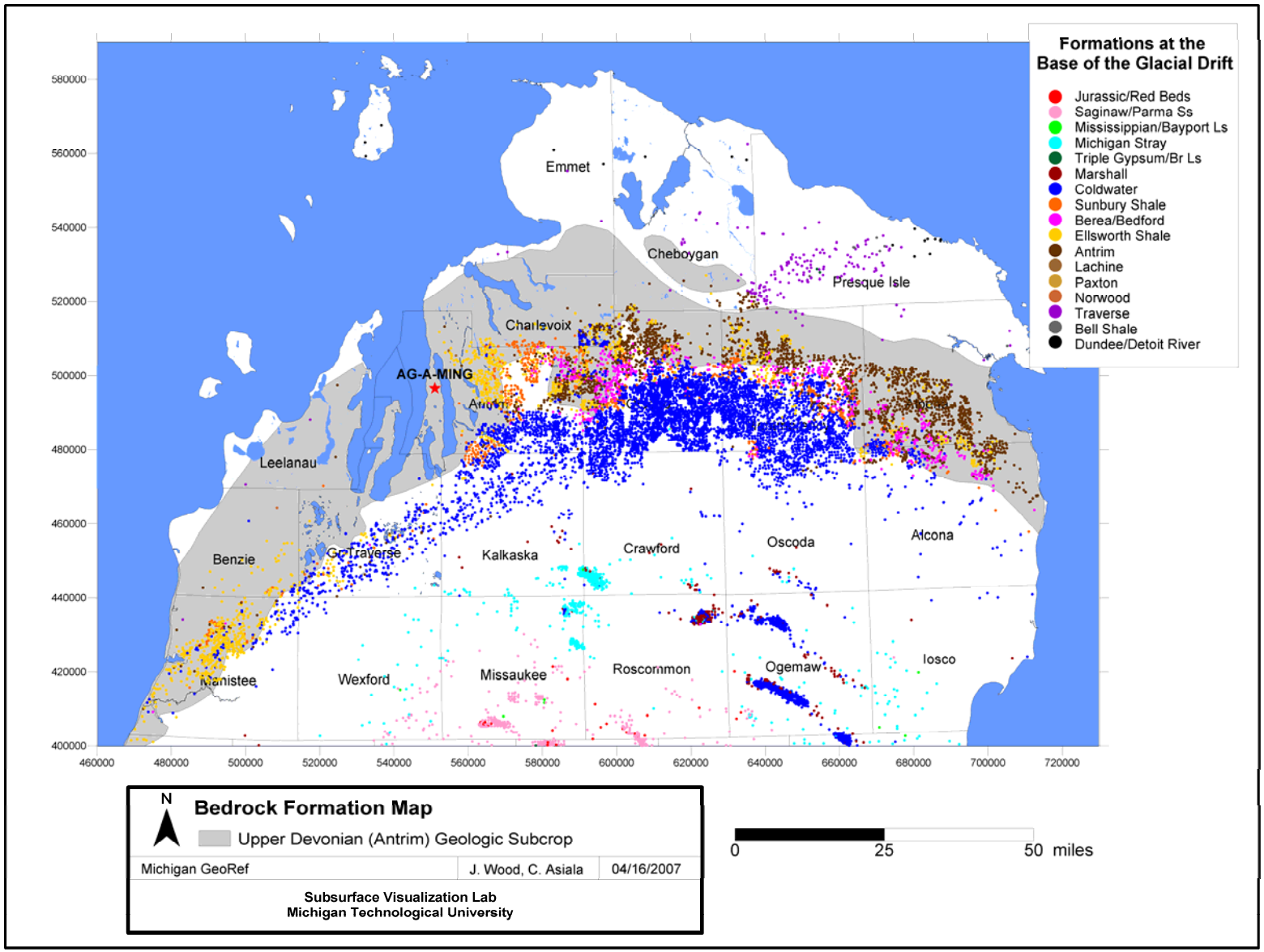


Figure 31. Bedrock formation spot map showing the formation directly below the Glacial Drift based on formation top picks recorded in the Michigan DEQ formations database.

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6. LIST OF ACRONYMS AND ABBREVIATIONS

ANRM:	Antrim Formation
LAC:	Lachine member of Antrim Formation
PAX:	Paxton member of Antrim Formation
NOR:	Norwood member of Antrim Formation
TRVR:	Traverse Formation
BOD:	Base of Glacial Drift
LINGO:	Low Impact Natural Gas and Oil
DEQ:	Michigan Department of Environmental Quality

7. ACKNOWLEDGMENTS

We thank Landmark Graphics Corporation for the use of their software in producing the cross section images used in this report. We also thank Neuralog, Inc for the use of their digitizing software.

APPENDIX I. State Casing Statute Instruction 1-94

STATE OF MICHIGAN
DEPARTMENT OF NATURAL RESOURCES

SUPERVISOR OF WELLS INSTRUCTION 1-94
CERTIFICATION OF CASING AND SEALING OF SURFACE CASING

INTRODUCTION

The Supervisor of Wells Act, 1939 PA 61, as amended (Act 61), prohibits oil field practices which may cause pollution, damage to or destruction of fresh water supplies. The purpose of these instructions is to further ensure the protection of fresh ground water. For all wells drilled pursuant to Act 61 after the effective date of these instructions, the Supervisor of Wells will require that a knowledgeable geologist or mud logger determine the proper depth to set surface casing to ensure that the casing will properly seal and protect all fresh water aquifers. The following requirements are issued in conjunction with and in addition to the provisions of Rule 301, 302, 303, 306, and 309 of the Rules promulgated pursuant to Act 61 (Rules), Supervisor's Instruction No. 1-87 (S.I. 1-87) and Special Order No. 2-73, amended (S.O. 2-73). This Instruction shall become effective January 15, 1994.

INSTRUCTION

1. Casing shall be run from the surface to a depth no less than:

   a. 100 feet into competent bedrock and
   b. 100 feet below all fresh water aquifers occurring below the glacial drift.

The casing shall be cemented in accordance with the Rules, S.O. 2-73, S.I. 1-87, and Supervisor of Wells requirements.

2. Each application and permit to drill shall provide geologic and depth information necessary to comply with the surface casing requirements stated in #1 above.

3. A knowledgeable geologist or mud logger on site shall determine the proper depth as provided in item #1 at which to set surface casing. To further ensure the protection of fresh ground water supplies, the running of casing and the cementing operation shall be supervised by the drilling rig tool pusher and/or a qualified representative of the permittee.

4. The geologist or mud logger shall enter into the drilling rig daily log book the following:

   a. The depth to bedrock.
   b. The base of other fresh water aquifers as specified by the permit to drill.
   c. The total depth of the surface casing hole.
   d. The signature and name of the geologist/mud logger.

5. The drilling rig tool pusher or qualified representative of the permittee shall enter in the drilling rig daily log book the following:

   a. Depth where surface casing was set.
   b. Amount and volume of cement used.
   c. Amount and volume of cement circulated to surface.
   d. Amount and volume of additional cement used if grouted.
   e. Any problems encountered while running or cementing the surface casing.
   f. The signature and name of the person certifying this information.

6. Within thirty days of the completion of the drilling operation, the permittee of the drilling operation shall furnish a certification of the proper sealing and protection of fresh water aquifers on a form prescribed by the Supervisor of Wells. The certification shall be signed by the geologist or mud logger who determined the depth to set the surface casing and by the permittee or a company officer. The certification shall describe any unusual hole conditions or problems encountered during the drilling or while running or cementing the casing.

Date: 12/15/93

R. Thomas Segall

R. THOMAS SEGALL
ASSISTANT SUPERVISOR OF WELLS

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

One West Third Street, Suite 1400
Tulsa, OK 74103-3519

1450 Queen Avenue SW
Albany, OR 97321-2198

539 Duckering Bldg./UAF Campus
P.O. Box 750172
Fairbanks, AK 99775-0172

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