1. **DOE AWARD NUMBER:** DE-FC26-06NT42931

   **RECIPIENT:** Michigan Technological University

2. **PROJECT TITLE:** An Approach to Recover Hydrocarbons from Currently Off-Limit Areas of the Antrim Formation, MI Using Low-Impact Technologies

   **PRINCIPAL INVESTIGATOR:** Dr. James R. Wood

3. **REPORT DATE:** April, 2007

   **Reporting Period:** October 1, 2006 - March 31, 2007
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6. EXECUTIVE SUMMARY

The goal of this project is to develop and execute a novel drilling and completion program in western Antrim County near the Leelanau Peninsula of Northern Michigan (Figures 1 and 2). The target is the gas in the Lower Antrim Formation which is a widespread Upper Devonian (Figure 3) 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, about one-third of Michigan’s total gas production (Wollensak, 1991). If successful, this project will open up significant acreage now off-limits to gas and oil exploration due to statutory restrictions. In addition to meeting statutory requirements, the proposed drilling plan should produce the resource more efficiently because horizontal wells will be used, and the environmental impact will be lessened since fewer wells will be needed to drain a prospect.

The central problem is that a great deal of potentially productive shale lies within areas that are off-limits to gas development due to surface constraints such as topography, wetlands, or housing. In addition to these constraints, the Michigan Department of Environmental Quality (MDEQ) requires that 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 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 100 feet of casing below the glacial drift. Further, fracture stimulation cannot be conducted within 50 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 things stand now, a large amount of productive Antrim shale can neither be accessed nor completed in a conventional sense due to State regulations. This leaves a vast resource of domestic gas unobtainable for conventional development.

Our plan is simple and is referred to as the “J-well” design. We propose to drill a vertical or slant well 100 feet below the glacial drift, set required casing, then angle back up to tap the resource lying between the base of the drift and the conventional vertical well (Figure 4). Details of the well are given in the accompanying text. Figure 5 is a map that shows the approximate acreage that will become available if this approach proves successful.

To date we have passed one major hurdle, obtaining drilling permits from MDEQ for two wells, the demonstration well AG-A-MING 4-12 HD (API: 21-009-58153-0000) and a disposal well 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). We are now constructing infrastructure support (surface facilities and transfer lines) in anticipation of a July-August spud date for the demonstration well.
We have also begun work on the main deliverables for this project, mainly maps showing the new prospective area opened up and standard geological maps (structure and isopach) of the sub-members of interest in the Antrim Formation. Details are presented in the text.
7. RESULTS OF WORK DURING REPORTING PERIOD

7.1 APPROACH

7.1.1 Data Collection

Data for the Lower Peninsula Antrim Trend has been collected from the Michigan DNR, 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. We estimate that we now have in hand most (90%) of the data that will be required for this project. We still need to gather data from our industry partner, Jordan Energy, LLD, on the demonstration well, but we have received the plan of the demonstration well (Appendix II. Demonstration Well) as well as detailed information on several new wells in the vicinity of the project well (the Bargy #16-14, Drogt #2-36, Kamp #5-12, Reske #10-24, Cherry Ke #2-36, Paradis #11-36, and the brine disposal well, Dorman B B4-26 SWD). We also have been given the results from a recent micro-gravity survey that Jordan had run by an independent contractor to help define the base of the glacial drift in the vicinity of the test well.

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 CO2 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. Production data will be requested from MichCon and the Michigan Well Core Repository.

7.1.2 Mapping

We have developed preliminary maps of:

1. Antrim Structure (Northern Lower Peninsula)
2. Structure contour maps of Lachine, Paxton, and Norwood formations.
3. Isopach contour maps of Lachine, Paxton, and Norwood formations.
4. Base of Glacial Drift map based on gravity anomaly data of western Antrim County (Milton Bradley project area)

These maps are reproduced here in Appendix III. Geologic Mapping, and will be analyzed and refined further during the Mapping task (Task 2) of the project. See discussion below (7.2 Results and Discussion for more details on these maps.)
The following maps are in progress:

5. Isopach map of Glacial Drift
6. Symbolized map of bedrock recorded by well

We will describe each map in more detail and in context of the project in the next (March-October 2007) reporting period when the demonstration well will have been drilled and we have the full suite of promised maps completed.

7.1.3 Current Status of Demonstration Well

The demonstration well, A-GA-MING #4-12HD and #4-12HD1 is part of the Milton Bradley Project in west Antrim County developed by Jordan Development Company, LLC. In addition to the LINGO demonstration well, Jordan Development plans to develop the prospect with six vertical wells, and one disposal well (see Figure 2). The horizontal section of the demonstration well must remain within the 240 acre boundary set up in the PRU (Production Unit). The six 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.

Presently Jordan is installing flow lines and production lines which must be completed before wells can be placed on production. This accounts for the change in spud date for the LINGO well from March to July-August timeframe. The complete specifications for the A-GA-MING 4-12 as provided by Jordan are provided in Appendix II.

7.2 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.

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. The map images are displayed in Appendix III. Geologic Mapping.

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 Appendix IV. Antrim Shale Play.

Appendix Figures 17-1 through 17-12 are structure and isopach maps for the Lachine, Paxton, and Norwood formations in the Northern Michigan Antrim Trend and also localized to Antrim County. Appendix Figure 17-13 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 Appendix Figure 17-13 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. We will continue to analyze this problem but will likely conclude that our large-scale map is suggestive at best (but does indicate the additional acreage opened up).

More detailed interpretations of the Antrim will be attempted when the maps are complete. At this stage it appears that the 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.

### 7.3 CONCLUSION

This Lingo project is on schedule with a major milestone (well permitting) accomplished and the task matrix well in hand. Promised deliverable maps are all started and some are nearing completion. The next major phase will be the demonstration well itself, scheduled to spud in late July-early August.

The major accomplishment so far has to be convincing the Michigan DNR that the approach to tapping Antrim gas reserves via a novel approach involving drilling a lateral through the required casing zone and then angling back up met regulatory requirements. The DNR had no objections and is 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.

It is anticipated the more “take home” lessons will emerge as the demonstration well itself is drilled. If is in place by early September as anticipated, then we will have time to monitor production and access performance during the timeframe of this project. We expect that the drilling program will either serve as a template for similar development, or 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. DOE Contract No. DE-FC22-94BC14983)
8. PROPRIETARY OR CLASSIFIED DATA

None.
9. STATUS REPORTING

9.1 Cost Status

### COST PLAN / STATUS
Michigan Technological University
DE-FC26-06NT42931

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| Variance                  |     |     |     |     |     |     |     |     |
| Federal Share             | 6,068 | 4,048 | 0 | 0 |     |     |     |     |
| Non Federal Share         | -17,413 | 17,416 | 0 | 0 |     |     |     |     |
| Total Variance - Quarterly (Federal and Non-Federal) | -11,345 | 21,464 | 0 | 0 |     |     |     |     |
| Cumulative Variance       | -11,345 | 10,119 | 10,119 | 10,119 |     |     |     |     |

As of the end of the second quarter, this project has spent $10,119 less of the federal share than planned. The non-federal share of costs was all spent in the first quarter. The variance resulted from personnel costs being lower than anticipated in this time frame.
### 9.2 Milestone Status

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<td>Drilling has not started, but Drilling Prognosis has been developed along with the well schematic and directional drilling survey for the horizontal laterals. Expected Spud date will be in August 2007.</td>
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10. SUMMARY OF SIGNIFICANT ACCOMPLISHMENTS

1. A major hurdle was cleared when the MDEQ (Michigan Department of Environmental Quality) issued permits for the project demonstration wells in January, 2007. Until these permits were in hand the status of the entire project was uncertain. But the State of Michigan has agreed that the proposed “J-well” solution to drilling the shallow Antrim gas meets environmental requirements. In some cases it is more desirable because it reduces the number of wells and exposes more of the well bore to pay.

2. The demonstration well has been designed (see Appendix Figures 16-1 and 16-2 and write-up in Appendix II. Demonstration Well) with the slant, drain and horizontal leg. It now remains to drill this configuration (the next hurdle) and then monitor production.

11. ACTUAL OR ANTICIPATED PROBLEMS

It is possible that the J-well design will not work as anticipated. If so, fixes will have to be improvised after drilling. We cannot anticipate specific problems at this time, but note that this is a new well configuration for production and is not a proven design.

12. PRODUCTS AND TECHNOLOGY TRANSFER

12.1 Publications
None at this time.

12.2 Website
The project website has been established, and project figures and reports are being added to the site as the project progresses.
http://www.geo.mtu.edu/svl/LINGO/

12.3 Networks or collaboration fostered
None at this time.

12.4 Technologies/Techniques
None at this time.

12.5 Inventions/Patent Applications
None at this time.

12.6 Other products
None at this time.
12.7 Project Meetings

October 16, 2006  The project kickoff meeting was held at the Core Repository in Kalamazoo, Michigan. Attendees were J. Wood, W. Quinlan, W. Harrison and M. Gruener.

December 15, 2006  J. Wood held project consultation meetings with W. Quinlan and E. Taylor in Traverse City, MI.

March 12-14, 2007  The annual DOE project meeting was held in Tampa, Florida. Attendees were J. Wood, C. Asiala, W. Quinlan, W. Harrison, and M. Gruener.

13. REFERENCES


14. FIGURES
Figure 1. Location map of Northern Michigan. The project demonstration well, AG-A-MING 4-12HD, is designated by a red star, and the gray area is the geologic subcrop of the Upper Devonian which contains the Antrim.
Figure 2. Location map showing planned horizontal laterals of demonstration well, AG-A-Ming 4-12HD and 4-12HD1. Other well locations are recently drilled gas wells.
Figure 3. Subset of Michigan stratigraphic column from the Glacial Drift through the Dundee formation (Stratigraphic Nomenclature for Michigan, MI-DEQ).

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<td>Ganshaw Mbr</td>
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<td>Ferron Point Fm</td>
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<td>Rogers City Ls</td>
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<td>Dundee Ls</td>
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DE-FC26-06NT42931
Progress Report
An Approach to Recover Hydrocarbons from Currently Off-Limit Areas of the Antrim Formation, MI Using Low-Impact Technologies
Michigan Technological University
Figure 4. 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.
Figure 5. 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.
15. 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 all 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
ASSISTANT SUPERVISOR OF WELLS
16. APPENDIX II. Demonstration Well

16.1 Well Drilling Acronym List

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
</tr>
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<tbody>
<tr>
<td>BOD</td>
<td>Base of Drift</td>
</tr>
<tr>
<td>CBL</td>
<td>Cement Bond Log</td>
</tr>
<tr>
<td>CCL</td>
<td>Casing Collar Log</td>
</tr>
<tr>
<td>CIBP</td>
<td>Cast Iron Bridge Plug</td>
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<tr>
<td>CSG</td>
<td>Casing</td>
</tr>
<tr>
<td>DDC</td>
<td>Directional Drilling Contractors</td>
</tr>
<tr>
<td>ESP</td>
<td>Electrical Submersible Pump</td>
</tr>
<tr>
<td>KCL</td>
<td>Potassium Chloride</td>
</tr>
<tr>
<td>KOP</td>
<td>Kick Off Point</td>
</tr>
<tr>
<td>LT&amp;C</td>
<td>Long Threads and Collars</td>
</tr>
<tr>
<td>MIRU</td>
<td>Move In and Rig Up</td>
</tr>
<tr>
<td>MWD</td>
<td>Measurement While Drilling</td>
</tr>
<tr>
<td>MWL</td>
<td>Measurement Wire Line</td>
</tr>
<tr>
<td>PBTD</td>
<td>Plug Back Total Depth</td>
</tr>
<tr>
<td>RD</td>
<td>Rig Down</td>
</tr>
<tr>
<td>RU</td>
<td>Rig Up</td>
</tr>
<tr>
<td>TD</td>
<td>Total Depth</td>
</tr>
<tr>
<td>TIH</td>
<td>Trip In Hole</td>
</tr>
<tr>
<td>TOH</td>
<td>Trip Out of Hole</td>
</tr>
<tr>
<td>TVD</td>
<td>True Vertical Depth</td>
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</table>

16.2 Jordan Development Drilling Plan for Demonstration Well

A-GA-MING #4-12HD
DRILLING PROGNOSIS
(March 7, 2007)

1. MIRU.

2. Drill 12-1/4” hole to KOP at approximately 100’.

3. RU DDC. TIH with directional tools to drill surface hole ahead to an angle of approximately 23 degrees at surface casing point (projected to approximately 430’ with BOD at approximately 320’).
   Land pipe as close to minimum set depth requirement as possible to conserve TVD which will be required to build needed angle below surface CSG.

4. Run 32# J-55 8-5/8” CSG to TD and cement to surface.

5. Drill out cement and shoe.
6. TIH with directional tools and 7-7/8” bit. Test CSG and shoe.
7. RU Geologist.
8. Drill ahead on Pilot Hole in accordance with directional drilling plan, building to an angle across the Lachine and Norwood of approximately 65 degrees.
   Drill to a TVD depth of approximately 850’ TVD to allow at least 100’ TVD of sump to set production pump. TOH.

9. Run 5-1/2” 15.5# J-55 LT&C CSG to TD and cement to surface.
10. RU MWL. Run Gauge Ring to PBTD.
11. Run Gamma/CCL/CBL. RD MWL
12. TIH with DP and CIBP and set for combined Norwood and Lachine leg. TOH.
13. RU Baker. TIH with Whipstock and one trip milling system.
15. TOH and lay down mills. RD Baker.
16. Circulate hole clean with 3% KCL mud.
17. TIH with 4-3/4” bit and motor and cut curve, landing at the base of the Norwood.
17. TOH.
18. TIH with motor and drill ahead on combined Norwood/Lachine lateral section in accordance with directional plan. Some inclination will also be required to compensate for rise in formation dip in the northerly direction.

***Above all, the entire lateral should be drilled at an incline to allow produced fluid to drain back to the heel during production***

19. Circulate hole clean. Pump out of hole to remove any remaining cuttings. TOH.
20. TIH with 45 degree circulating sub. Rotate and wash to TD. Pump out of hole.
21. Make up retrieving tools. TIH and retrieve Whipstock. TOH.
22. TIH with bit. Drill up CIBP and chase to TD.
23. TOH.
24. TIH with ESP.
25. RD. Release Rig.
Appendix Figure 16-1. Directional drilling survey showing 240-acre spacing and slant of horizontal lateral.
Appendix Figure 16-2. Well bore schematic of project demonstration well.
17. APPENDIX III. Geologic Maps

The maps in this appendix have been developed using the most recent data from the Michigan Department of Environmental Quality. These are preliminary maps in the study, and will be analyzed and refined as the project progresses. The map set consists of structure and isopach maps of the three Antrim formations (Lachine, Paxton, and Norwood) over the Northern Lower Peninsula of Michigan, and also over Antrim County, Michigan. Also included in the map set is a spot map showing the formation directly at the Base of Glacial Drift, and an isopach map of the Glacial Drift.

Appendix Figure 17-1. Structure contour map of Lachine formation, contour interval is 50 feet.
Appendix Figure 17-2. Structure contour map of Paxton formation, contour interval is 50 feet.
Appendix Figure 17-3. Structure contour map of Norwood formation, contour interval is 50 feet.
Appendix Figure 17-4. Isopach map of Lachine formation, contour interval is 5 feet.
Appendix Figure 17-5. Isopach map of Paxton formation, contour interval is 5 feet.
Appendix Figure 17-6. Isopach map of Norwood formation, contour interval is 5 feet.
Appendix Figure 17-7. Structure contour map of Lachine Formation over Antrim County, MI. Contour interval is 50 feet.
Appendix Figure 17-8. Structure contour map of Paxton formation over Antrim County, MI. Contour interval is 50 feet.
Appendix Figure 17-9. Structure contour map of Norwood formation over Antrim County, MI. Contour interval is 50 feet.
Appendix Figure 17-10. Isopach map of Lachine formation over Antrim County, MI. Contour interval is 5 feet.
Appendix Figure 17-11. Isopach map of Paxton formation over Antrim County, MI. Contour interval is 5 feet.
Appendix Figure 17-12. Isopach map of Norwood formation over Antrim County, MI. Contour interval is 5 feet.
Appendix Figure 17-13. Bedrock formation map showing the formation directly below the Glacial Drift.
Appendix Figure 17-14. Glacial Drift Isopach map with a contour interval of 50 feet, using the Inverse to a Power gridding algorithm.
Appendix Figure 17-1. Structure contour map of Lachine formation, contour interval is 50 feet.
Appendix Figure 17-2. Structure contour map of Paxton formation, contour interval is 50 feet.
Appendix Figure 17-3. Structure contour map of Norwood formation, contour interval is 50 feet.
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Appendix Figure 17-7. Structure contour map of Lachine Formation over Antrim County, MI. Contour interval is 50 feet.
Appendix Figure 17-8. Structure contour map of Paxton formation over Antrim County, MI. Contour interval is 50 feet.
Appendix Figure 17-9. Structure contour map of Norwood formation over Antrim County, MI. Contour interval is 50 feet.

**Antrim County, MI Structure Contour Map - Norwood Fm.**

Contour Interval: 50 feet (Inverse Distance to a Power)  Michigan GeoRef  J. Wood, C. Aerial

58153 AG-A-MING 4-12 HD and 4-12 HD1  Control Wells  04/16/2007

Subsurface Visualization Lab
Michigan Technological University

Appendix Figure 17-9. Structure contour map of Norwood formation over Antrim County, MI. Contour interval is 50 feet.
Appendix Figure 17-10. Isopach map of Lachine formation over Antrim County, MI. Contour interval is 5 feet.
Appendix Figure 17-11. Isopach map of Paxton formation over Antrim County, MI. Contour interval is 5 feet.
Appendix Figure 17-12. Isopach map of Norwood formation over Antrim County, MI. Contour interval is 5 feet.
Appendix Figure 17-13. Bedrock formation map showing the formation directly below the Glacial Drift.
Appendix Figure 17-14. Glacial Drift Isopach map with a contour interval of 50 feet, using the Inverse to a Power gridding algorithm.
18. **APPENDIX IV. Antrim Shale Play**

From presentation by Dr. William B. Harrison, III, Western Michigan University presented during the Annual DOE project meeting in March 2007.

### 18.1 Antrim Shale Timeline

**Late 1920’s:** Michigan’s commercial production begins in Devonian strata (Saginaw area). Drillers regularly note shows in Antrim.

**1940:** Rinehart & Hickok complete an Antrim test in Otsego County (34-30N-3W); it produces minor gas for 2 yr.

**1965:** Independent Murrell Welch proves economic viability of Antrim gas with successful pool development in south Chester twp., Otsego County (29N-2W).

**1969:** First Niagaran pinnacle discoveries in N. Michigan. Antrim shows recorded in essentially all Niagaran wells as the play grows - labeled “nuisance shows”.

**1975:** Northern Michigan land & oil develops successful Antrim projects in Otsego County (29N-3W, 30N-2W).

**1987:** Underutilized Niagaran infrastructure, improved completion techniques, concept of Antrim “projects” with many wells feeding a central production facility (CPF), and non- conventional fuels tax incentives trigger modern play levels and production growth.

**1992:** Antrim wells must be completed or in progress by 01/01/93 to qualify for NCF section 29 tax credits, which expired 12/31/02. Drilling reaches peak in 1992 with 1189 completed wells. Industry and regulatory agencies agree to voluntary 80-acre Antrim spacing on all new projects.

**1995:** Establishment of uniform spacing plan (USP) option for Antrim projects allows greater operator discretion in locating individual wells within a project. 80-acre spacing is mandated play-wide.

### 18.2 Antrim Completions and Project Operations

1. After drilling and logging, selected high interest zone(s) in the Lachine Member (core and thin section photos are shown in Appendix Figures 18-1 and 18-2) and Norwood Member pays are identified for stimulation.
2. The optimal pay in the thinner (15-22’ thick), lower Norwood Member pay is selectively perforated and stimulated with a light sand-nitrogen frac. Two sand sizes are typically used.

3. Optimal intervals in the higher Lachine pay (overall thickness 55-80’) are selectively perforated; either a single or multistage sand-nitrogen frac of the Lachine is performed, with frac size(s) larger than for the Norwood.

4. Wells are flowed back to the project’s Central Production Facility (CPF) via PVC flowlines, either single (all fluids commingled) or dual phase (some gas/water separation at the wellhead).

5. At the CPF, dewatering of the gas is accomplished, typically via glycol treatment at dehy towers. Gas is compressed to sales line pressure (typically around 1300 PSIA) via a 4-stage compressor and sent out via stainless steel sales lines. (In areas lacking electricity, some of the dewatered, compressed gas is returned to the well via pipeline to power for drillstring gas lift systems.)

6. Each Antrim project typically injects formation water into a single salt water disposal (SWD) well, in underlying Devonian carbonates of the Dundee Formation or upper Detroit River Formation. SWD’s are typically located at the CPF facility and controlled by Federal EPA regulations.

7. Gas is sent via the sales lines to large CO₂ removal facilities to reduce the 5-30% CO₂ content of Antrim gas to sales quality. It is sent to common carrier residential and commercial use lines from the CO₂ facility.

18.3 Antrim Drilling, Logging, and Evaluation

1. Antrim wells in Northern Michigan are drilled to depths ranging from 600-2000’ (true vertical). Horizontal wells comprise about 1% of all wells to date, with varying commercial success. Directional drilling has been an effective means to reach drainage areas with restricted surface accessibility. Antrim tests are conventionally drilled with a water-based mud system—air drilling has not become a practice in the play.

2. By State statute, surface casing is required to a depth 100’ (vertical) below the base of the Glacial Drift, the regional fresh water aquifer. (Drift depth range in the play area: 300-1100.’)

3. Production casing is typically run through the entire Antrim pay section and into a varying amount of “rathole” drilled into the Traverse Group. (Many wells drilled into the early 1990’s were open-hole completions, this is very uncommon today.)

4. In early 1990’s, many wells were not open hole logged. Evaluation and completion was defined by sample logs, ROP logs or cased hole gamma ray/collar correlation logs that identified the “hot” zones.

5. Many operators continue to use open hole logging in only a limited fashion, relying chiefly on mudlogs, ROP logs, and cased hole GR logs. Others evaluate the quality of Antrim pay by induction logs and porosity logs akin to the evaluation used in “conventional” reservoirs.

6. The advent of open hole fracture indicator logs has made their use both widespread and effective in Antrim evaluation. This includes such tools as the UBI (Schlumberger), CAST (Halliburton), and CBIL (Baker).

7. Coring and use of core data is extremely limited. No new cores in the main play area since the mid 1990’s.
18.4 Conclusions

1. The Upper Devonian Antrim Shale is a major gas producer in the Michigan Basin (Appendix Figure 18-3).
2. The Antrim Shale is classic black shale that produces natural gas by desorption processes into a complex network of fractures.
3. The distribution of high total organic carbon and natural fractures are keys to good productivity.
4. Gas in place can be measured by geochemical rock analyses and suggest 0.5 to 1.0 BCF per 40 acres in the northern part of the basin.
5. Variable production history of project areas can be explained by reservoir rock properties measurable from core, logs and drill cuttings.
Appendix Figure 18-1. Core photo of Lachine member of Antrim Formation in Welch-St. Chester #18, Otsego Co. (photo courtesy of WMU Core Repository).
Appendix Figure 18-2. Thin section of Lachine member in Welch-St. Chester #18, Otsego Co. (1486 ft. 100X, photo courtesy of WMU Core Repository).
Appendix Figure 18-3. Annual and cumulative Antrim Shale gas production from data provided by the Michigan Public Service Commission.