Permit No. 21759

Co. G. W. Strake

Farm Winnie Van Koevering No. 1

Twp. Jamestown Co. Ottawa

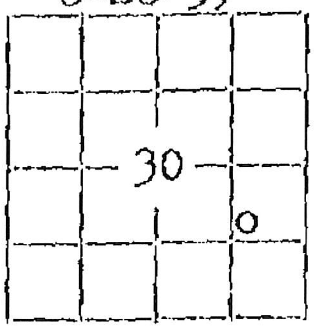
Loc. SW NE SE Sec. 30 T. 5N R. 13W.

990' from N and 890' from E line of ¼ Sec.

330' from S and 430' from W property line

Contractor McClure Drilling Co.

Comm. 8-6-59 Comp. 8-28-59



CASING RECORD

Size	Length	Pulled
14"		
10"	294	Cemented
8¼"		
6⅝"		
5 3/16"		

MUDDING AND CEMENTING RECORD

Date	Size	No. Sacks	Company
	10"	205	
	8¼"		
	6⅝"		
	5 3/16"		

GEOLOGICAL FORMATION RECORD

Elevation 685' RT 683.2' RF

Drift to

Mar. 146-170

Ant. 1310
Tr. Fm. 1561
Tr. Ls. 1620

Det. Riv. Anhy. 1950
poros. 1968-2020
Bass Is. 2552
Salina 2674
A-2 Dol. 2821
A-1 2986
Wh. Niag. 2356

Trenton 3335

T. D.

P. B.

I. P. (N) D & A

I. P. (A)

Plug. Comp.

Circulate hole with mud from total depth
to approx. 1700'.
Spot 50 sacks of cem. thru the Traverse pay
zone and fill solidly with mud to just
below the surface pipe.
Place 5 sacks of cem. on top of mud in
hole and fill with mud from cem. to
approx. 20' from surface.
Place 5 sacks of cem. on top of mud in hole.
Cut surface pipe off below plow depth and
weld a heavy steel plate on top of pipe
in hole.

8-28-59: Drilling at approx. 4268' at time of
inspection - took plugging instructions along
with me as had been requested by [illegible],
of McClure Drilling Co. On 2nd inspection
in evening, they were drilling at approx.
4284'. They will go to 4308' and run
an electric log. They probably won't
plug this well until tomorrow. BB
8-29-59: Just going in the hole to break
drill pipe down. Electric log was run
by Schlumberger and completed at 10:00 P.M.
Filled hole with heavy mud to Traverse
and spotted 50 sacks of cement. Filled
hole to just below surface pipe
and spotted 5 sacks. Filled to the
surface & placed 5 more sacks. Welder
will weld a steel cap on top as soon
as possible. BB
10-13-59: Checked for final plugging approval.
Well surface O.K. But some clean up work
necessary. Referred to F A D [illegible] BB

B.7 A map showing the vertical and areal extent of surface waters and subsurface aquifers containing water with less than 10,000-ppm total dissolved solids. A summary of the present and potential future use of the waters must accompany the map.

Figure A.4-4 (Section A.4) is a topographic map of the disposal well area, and shows there to be no mappable surface water features in the immediate vicinity of the Autumn Hills RDF. Absence of surface water features was verified through survey (Section A.4). Figure B.7-1 (Section B.7) presents the Michigan Stratigraphic Column. The Michigan Groundwater Atlas discusses aquifers present in Michigan (Olcott, 1992). Data from this source indicates that the Autumn Hills RDF is underlain by the fresh water Glacial Drift aquifer and is located at the western extent of the Mississippian Marshall Sandstone aquifer, where present. Data indicates that all units below the Marshall exhibit a TDS in excess of 10,000 ppm (Tables B.7-1 and B.7-2).

Therefore, the top of the USDW is defined as the surficial Glacial Drift unit and the base of the USDW is defined as the base of the Glacial Drift or Marshall Sandstone, where present. This depth to the base of the USDW corresponds to the top of the underlying Coldwater Shale.

The base of the lowermost USDW is approximately 220 feet below ground surface at the proposed IW-1 well location, based on and oil and gas data. Figure B.7-2 presents a structural contour map constructed at the top of the Coldwater Shale, which is equivalent to the base of the USDW at the Site (i.e., base of the Glacial Drift and/or Marshall Sandstone). Figure B.7-3 presents an isopach of the USDW that includes the Glacial Drift and Marshall Sandstone (where present). Figure B.7-4 presents a map of oil and gas wells located within approximately one mile of the Autumn Hills RDF, and shows the indicated thicknesses of the Glacial Drift and Marshall Sandstone as reported in the drillers logs. For the three oil and gas wells located within the Autumn Hills RDF boundary (Michigan Permit Nos. 15347, 4528, and 12352), the thickness of the Glacial Drift is reported as 135 feet, 78 feet, and 348 feet, respectively. At these same wells, the thickness of the Marshall Sandstone is reported as 75 feet, 122 feet, and 0 feet, respectively. Total USDW thicknesses at these three wells, based on drillers logs, are 210 feet, 200 feet, and 348 feet, respectively. Based on this information, the based of the USDW is conservatively assigned as 350 feet below ground surface.

As seen on Figure B.7-4, the Marshall Sandstone is consistently present to the north and northeast of the Facility boundary. To the west, south, and east, the Marshall Sandstone is sporadic and thinner, with zero reported Marshall thickness in nine of the 12 wells included in the map area. Within an approximate one-mile radius of the Site, the thickness of the Glacial Drift ranges between 78 to 348 feet, and the thickness of the Marshall Sandstone ranges between 0 to 122 feet, although where the Glacial Drift is thickest, the Marshall is not present. Therefore, the total USDW thickness within an approximate one-mile radius ranges between 110 to 348 feet. Figure B.7-5 is a potentiometric surface map for the USDW at the Autumn Hills RFD, showing groundwater flow to the west/southwest. Depth to water in this figure is approximately

23 feet near the well location. Potentiometric surface data from Facility monitor wells indicates a depth to water of approximately 45 feet.

Water quality calculations were evaluated from well log data from the Consumers Energy Station non-hazardous Class I wells (Mirant wells) that are completed in the Mt. Simon Sandstone to assess the USDW assignment. These wells are located approximately 4.5 miles northwest of the Autumn Hills RDF site. Calculations were evaluated to assess estimated water quality in the shallow Glacial Drift and Marshall Sandstone intervals into the underlying Coldwater Shale. Wireline log data from more proximal wells is generally not available for these intervals, as casing is generally advanced into the Coldwater, and logs are not run above this depth. At the Mirant wells, resistivity logs were run from below conductor casing to below the Coldwater Shale.

Calculations presented below were evaluated based on the wireline log data from the Mirant (Now Consumer's Energy at Zeeland) IW-1 well (Section 17, T5N, R14W). At this well, Glacial Drift is encountered at the surface, the Marshall Sandstone top occurs at 208 feet RKB (195 ft BGL), and the Coldwater Shale top occurs at 246 feet RKB (235 ft BGS). Calculations were evaluated at several depths in both the Marshall Sandstone and Coldwater Shale to estimate water quality as sodium chloride (NaCl), in parts per million (ppm). As there was no porosity logging in this interval, a porosity value of 25% is assumed for the Marshall Sandstone, and a porosity value of 15% is assumed for the Coldwater Shale. Based on the resistivity data from this well, the water quality in the uppermost Glacial Drift interval appears to be more fresh (i.e., deep resistivity values are higher) relative to the underlying Marshall Sandstone, therefore water quality calculations were only evaluated for the Marshall and Coldwater Shale intervals. Table B.7-1 presents depths, deep formation resistivities from logs (Rt), calculated formation water resistivities (Rw), and estimated salinity as ppm NaCl.

Water quality calculations were evaluated using Archie's equation, and assuming 100% water saturation (Sw). The calculation for this evaluation is as follows:

$$Sw^n = aRw / \phi^m Rt$$

Where:

- n = Saturation exponent (assumed = 2)
- a = Tortuosity factor (assumed = 1)
- Rw = Formation water resistivity at formation temperature
- ϕ = Porosity
- m = Cementation exponent (assumed = 2)
- Rt = True resistivity of formation (Deep resistivity, e.g., RILD)

Therefore, in a water zone where Sw = 1, Rw = ϕ^2Rt. Calculating Rw for a certain interval and accounting for temperature at depth (only a few degrees above estimated average annual temperature of 47 degrees Fahrenheit at these shallow depths), an estimate of water quality as ppm NaCl can be determined from Schlumberger's

Petrotek

"Resistivity of NaCl Water Solutions" Gen-6 chart (Schlumberger, 2009). These results are summarized in Table B.7-1.

TABLE B.7-1. CALCULATED WATER QUALITY IN MARSHALL SANDSTONE AND COLDWATER SHALE, MIRANT IW-1 WELL

Depth (ft RKB)	Rt (ohmm)	Rw (ohmm)	NaCl (ppm)
Marshall Sandstone			
208 – 216	36.8 (ave.)	2.3	3,300
230	25.6	1.6	4,900
244	17.9	1.1	7,000
Coldwater Shale			
250	17.9	0.4	20,000
300	7.3	0.16	57,000
400	4.3	0.10	100,000

Table B.7-2 provided at the end of this section presents a summary of regional water quality data available in the vicinity of the Autumn Hills RDF that are available in the USGS Produced Waters Geochemical Database (USGS, 2017). There are reported samples from 56 wells in Ottawa County, and portions of the surrounding counties Allegan, Kent, and Muskegon that are summarized in Table B.7-2, and this table also provides the geographical extent of the wells that are summarized. Most of the samples are from the Devonian-age Traverse Group, with a few additional samples of the Devonian-age Detroit River Group and Dundee Limestone. There are also multiple samples from the Silurian-age Salina Group and a single sample from the Ordovician-age Trenton Formation. All of these samples are well in excess of 10,000 mg/L TDS, with the lowest reported value of approximately 44,000 mg/L from a sample from the Traverse. All but three of the samples are above 100,000 mg/L, and the majority of these samples are above 200,000 mg/L.

It is noted that there is a single sample presented in Table B.7-2 from the Marshall Sandstone, from a well to the west of Autumn Hills RDF in Kent County. It was noted from this sample that the chloride (Cl) concentration increases considerably with depth, from 40 ppm Cl at 433-453 feet, to 1,150 ppm Cl from 522-570 feet, to 8,050 ppm Cl from 640-797 feet. This is consistent with water quality calculations presented for the Marshall in Table B.7-1, as well as regional observations of increasing TDS concentrations in this aquifer (Westjohn and Weaver, 1998).

The Coldwater Shale that underlies the Glacial Drift/Marshall USDW is noted as a regional confining unit across the state (Westjohn and Weaver, 1996). The authors do note that in some places, the Coldwater confining unit will produce small quantities of water and typically contain high concentrations of TDS. These areas of water yield in the Coldwater are located far distant from the Autumn Hills RDF in the Thumb Area of

Michigan (more than 150 miles to the northeast) and Westjohn and Weaver (1996) note that TDS concentrations in these wells range from 17,700 to 39,000 mg/L.

The assignment of the Glacial Drift and Marshall Sandstone as the lowermost USDWs in the vicinity of the Autumn Hills RDF is supported by local and regional water quality data. Water quality calculations and regional water quality data indicate that at depths below these USDWs, water quality as TDS is well in excess of 10,000 mg/L, and likely exceeds 100,000 mg/L from several hundred feet below the top of the Coldwater Shale.

REFERENCES

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Schlumberger, 2009. Log Interpretation Charts. 2009 Edition.

Westjohn, D.B., and Weaver T.L., 1996. Hydrogeologic Framework of Mississippian Rocks in the Central Lower Peninsula of Michigan. USGS Water Resources Investigations Report 94-4246, 46 pp.

Westjohn, D.B., and Weaver T.L., 1998. Hydrogeologic Framework of the Michigan Basin Regional Aquifer System. USGS Professional Paper 1418, 45 pp.

Table B.7-2. Regional Water Quality Data near Autumn Hills RDF

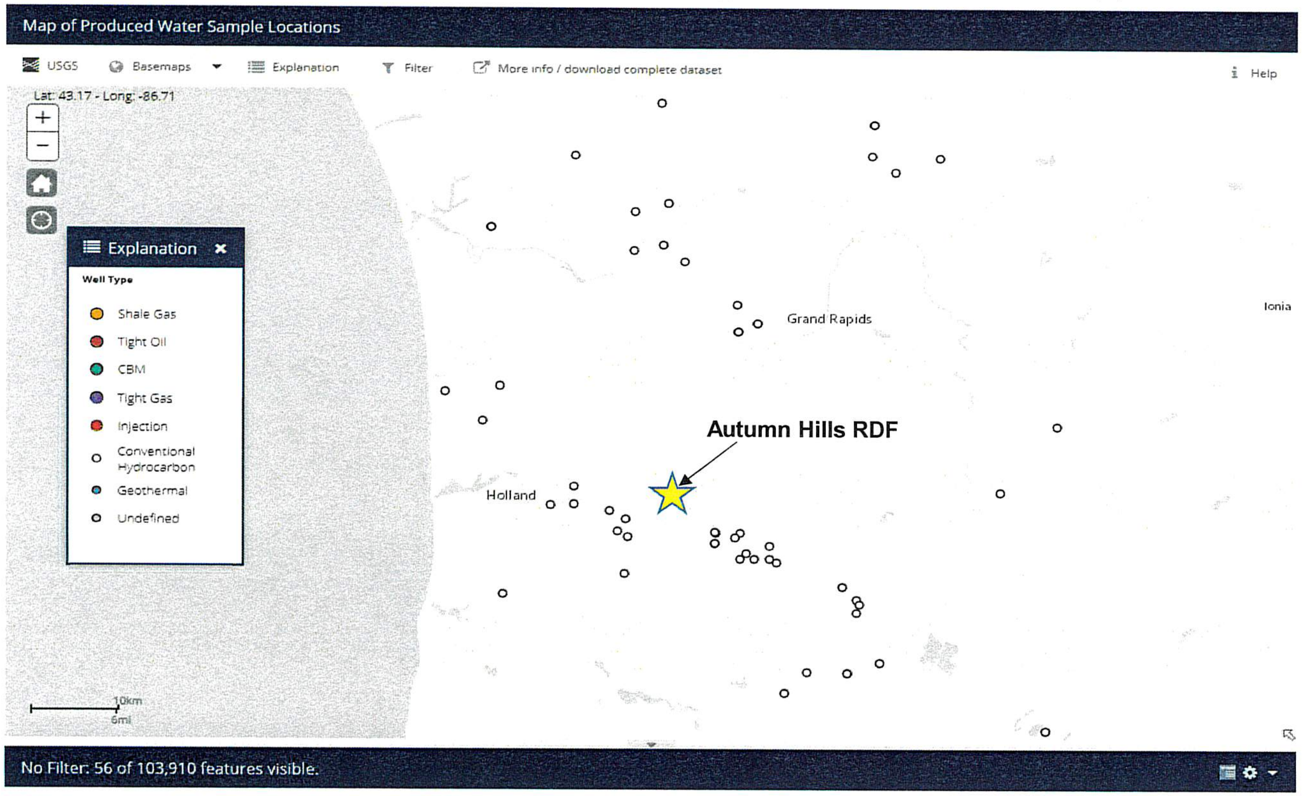
ID USGS	API	COUNTY	DATE SAMPLE	DATE ANALYS	PERMIT	DFORM	FORMATION	DEPTH UPPER	DEPTH LOWER	DEPTH WELL	SG	TDS USGS	TDS
20684	21005141270000		1980-10-08	1980-12-05	14127		Traverse Group	1593	1597		1.188	265,490	
20689	21005203170000		1980-10-08	1980-12-05	20317		Traverse Group	1696	1703		1.165	227,460	
20691	21015128620000		1980-10-07	1980-12-05	12862		Traverse Group	1851	1854		1.176	252,290	
20694	21005073100000		1976-06-02	1976-07-27	7310		Traverse Group	1471	1474			268,433	
20697	21005134170000		1976-04-09	1976-06-10	13417		Traverse Group	1784	1789		1.176	258,329	
20724	21005199690000				19969		Detroit River Group	2106	2135		1.139	194,809	
20725	21005199690000		1980-10-08	1980-12-05	19969		Detroit River Group	2106	2110		1.211	292,480	
20732	21005255050000				25505		Salina A-1 Carbonate	3128	3160		1.238	342,606	
20737	21025280070000		1980-10-08	1980-12-05	28007		Salina A-1 Carbonate	2757	2772		1.214	287,800	
20738	21005355540000		1984-02-07		35554		Salina A-1 Carbonate	3050	3103			314,627	
20801*	21081175350000				17535		Marshall Sandstone						
20847	21081031440000			1937-08-17	3144		Traverse Group		2406		1.226	364,000	
20848	21081007730000			1930-11-10	773		Detroit River Group		2218		1.175	259,692	
20860	21139005370000			1930-10-27	537		Trenton Formation		5470		1.239	349,302	
20867	21139219810000		1976-04-09	1976-06-10	21981		Traverse Group	1923	1932		1.196	264,490	
20868	21139210920000		1980-10-07	1980-12-05	21092		Traverse Group	1877	1887		1.199	278,650	
20869	21139070510000				7051		Traverse Group	1892	1934			320,430	
20921	21081159620000		1976-06-03	1976-07-27	15962		Traverse Group	2337	2342		1.217	327,277	
20923	21005107420000		1976-06-02	1976-07-27	10742		Traverse Group	1520	1530		1.181	269,129	
62004	21005057600000	Allegan	1939-07-06			Traverse	Traverse	1740		1735	1.145	240,619	210,148
62005	21005057600000	Allegan	1939-04-04			Traverse	Traverse	1690	1693	1735	1.146	239,362	239,362
62006	21005054130000	Allegan	1938-12-23			Traverse	Traverse Limestone	1796	1800	1800	1.135	222,448	195,989
62122	21081061150000	Kent				Monroe	Traverse	2326	2337	2764	1.182	316,954	316,954
62123	21081061150000	Kent				Monroe	Dundee	2738	2746	2764	1.206	359,225	297,865
62124	21081085340000	Kent				Traverse	Traverse Limestone	2275	2282	2282	1.175	296,476	296,476
62125	21139095250000	Ottawa	1942-11-17			Traverse	Traverse	1906	1909	1911	1.073	110,370	110,370
62126	21139065920000	Ottawa	1939-12-20			Traverse	Traverse	1938		1938	1.205	381,188	381,188
62127	21139070990000	Ottawa	1940-06-25			Traverse	Traverse	2203	2204	2211	1.211	375,941	375,941
62128	21139076720000	Ottawa	1941-05-06			Traverse	Traverse	1983	1992	1992	1.207	360,785	360,785
62129	21139085550000	Ottawa	1941-05-09			Traverse	Traverse	1974	1976	1980	1.206	357,320	357,320
62130	21081091660000	Kent	1942-02-20			Ste Peter	St Peter	5122	5125	5222	1.128	205,764	205,764
62131	21081091660000	Kent	1942-02-20			Ste Peter	St Peter Sand	5167	5222	5222	1.191	327,511	327,511
62132	21139076240000	Ottawa	1940-06-25			Traverse	Traverse	1550	1555	1570	1.118	193,041	193,041
62133	21139069690000	Ottawa	1940-01-23			Traverse	Traverse	1602	1607	1607	1.166	280,205	240,313
62134	21139078260000	Ottawa	1940-09-20			Traverse	Traverse Limestone	1550		1567	1.187	317,311	317,311
62135	21139080500000	Ottawa	1940-10-10			Traverse	Traverse	1498	1503	1503	1.033	43,481	43,481
62138	21005070310000	Allegan	1940-06-26			Traverse	Traverse	1528	1575	1575	1.116	190,211	190,211
62139	21005085960000	Allegan	1942-02-09			Traverse	Traverse	1556	1557	1557	1.183	320,268	320,268
62140	21005076040000	Allegan	1940-06-26			Traverse	Traverse	1516		1516	1.181	322,636	322,636
62141	21005069020000	Allegan	1939-11-17			Traverse	Traverse	1591	1593	1593	1.156	261,234	225,981
62142	21005070180000	Allegan	1939-12-14			Traverse	Traverse Limestone	1589	1596	1596	1.15	249,153	249,153
62143	21005082690000	Allegan	1941-05-06			Traverse	Traverse	1653	1658	1684	1.136	216,529	216,529
62144	21005068540000	Allegan	1939-12-20			Traverse	Traverse			1461	1.161	277,312	277,312
62145	21005054740000	Allegan	1938-12-23			Dundee	Monroe	1970		1995	1.186	319,737	269,593
62146	21005066810000	Allegan	1940-01-23			Traverse	Traverse	1956	1958	1938	1.19	328,379	275,949
62147	21005054740000	Allegan	1938-12-27			Dundee	Traverse Limestone	1668		1995	1.122	198,419	176,844
62187	21121094740000	Muskegon	1944-05-20			Monroe	Traverse Limestone	1844		2601	1.21	369,658	369,658
62188	21005081740000	Allegan	1940-11-14			Traverse	Traverse	1493	1494	1541	1.175	297,891	297,891
62225	21005211000000	Allegan	1958-08-23			Sylvanian	Salina A 2 Dolomite	2345	3100	2772	1.22	311,985	311,985
62226	21005205080000	Allegan	1957-05-23			253 Slazl	Salina A 2 Dolomite	2384	3104	2741	1.225	382,841	382,841

Table B.7-2. Regional Water Quality Data near Autumn Hills RDF

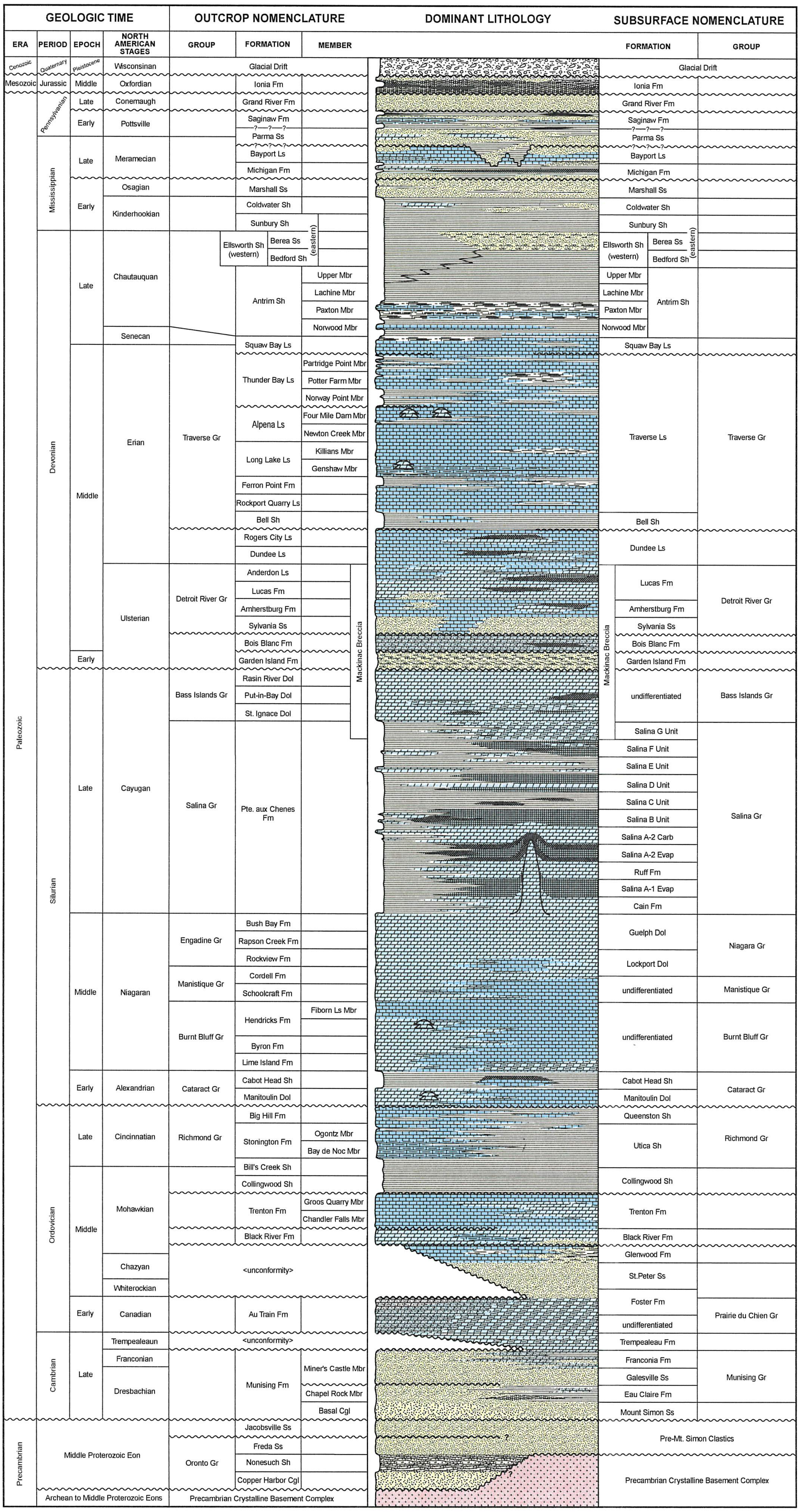
ID USGS	API	COUNTY	DATE SAMPLE	DATE ANALYS	PERMIT	DFORM	FORMATION	DEPTH UPPER	DEPTH LOWER	DEPTH WELL	SG	TDS USGS	TDS
62227	21005211000000	Allegan	1958-08-23			2535 Lazl	Salina A 2 Dolomite	2345	3100	2772	1.222	380,169	380,169
62347	21139308140000	Ottawa	1976-03-07			A-1 Carb-Niagaran	Traverse	1711	1788	3285	1.063	87,659	87,659
62348	21139308140000	Ottawa	1976-03-16				Traverse	3247	3285	3285	1.222	299,696	299,696
62376	21005260110000	Allegan	1980-10-08			A-1 Salt	Salina Group Salina A-1 U	3160	3199	3214	1.064	85,370	85,370
62377	21005146050000	Allegan	1980-10-08			Traverse	Salina Group Upper Siluri	2757	2772	1601	1.214	287,800	287,800
62378	21005139490000	Allegan	1980-10-08			Traverse Lime	Traverse Group Mid Devoni	1593	1597	1625	1.188	265,490	265,490

* - For ID USGS 20801 (Marshall Sandstone), the following was provided in the "Remarks" column: "From a hearing 11/29/1973: 40 ppm chlorides from 433-453 feet; 1150 ppm chloride from 522-570 feet; 8050 ppm chloride from 640-797 feet"

Source: USGS Produced Waters Geochemical Database (2017, v. 2.3). Wells identified from Map Viewer within window shown below. (https://energy.usgs.gov/EnvironmentalAspects/EnvironmentalAspectsofEnergyProductionandUse/ProducedWaters.aspx)



STRATIGRAPHIC NOMENCLATURE FOR MICHIGAN



Michigan Dept. of Environmental Quality
Geological Survey Division
Harold Fitch, State Geologist
and
Michigan Basin Geological Society

Stratigraphic Nomenclature Project Committee:
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Mr. Robert F. Reynolds
Dr. David B.Westjohn
Mr. Mark S. Wollensak

2000

Acknowledgements

This work is the product of the combined efforts of the geological communities of Michigan and the surrounding states and provinces. Below are given just a representative few of the contributors:

Academia: Dr. Aureal T. Cross, Michigan State University; Dr. Robert H. Dott, Jr., University of Wisconsin; Mr. William D. Everham, Ph.D. Candidate, Michigan Technological University.

Government: Dr. Terry R. Carter, Ontario Ministry of Natural Resources; Mr. John M. Esch, Michigan Department of Environmental Quality; Dr. Brian D. Keith, Indiana Geological Survey; Mr. Lawrence H Wickstrom, Ohio Geological Survey.

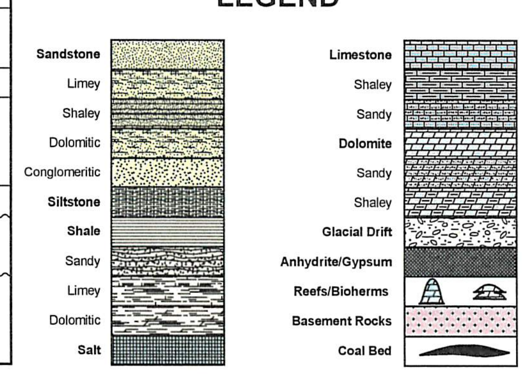
Industry: Mr. Donald J. Bailey, Consultant; Mr. Jimmy R. Myles, Scot Energy; Mr. Dan E. Pfeiffer, Pfeiffer Exploration Services.

A complete listing of all contributors will be found in the Stratigraphic Lexicon for Michigan, of which this column is an integral part.

RELATED TERM CORRELATION

STRATIGRAPHIC POSITION	RELATED TERMS
Ionia Fm	Jurassic Red Beds
Michigan Fm	Clare Dolomite, Brown Lime, Stray Dolomite, Stray Sandstone, Stray-Stray Sandstone, Stray-Stray-Stray Sandstone, Triple Gyp
Coldwater Sh	Coldwater Red Rock, Speckled Dolomite, Wier Sand
Antrim Sh	Charlton Black Shale Member, Elltrim, Chester Black Shale Member, Upper Black Shale, Light Antrim, Lower Black, Lower Antrim Middle Antrim, Middle Gray Antrim, Dark Antrim, Middle Gray Shale, Unit 1A, Unit 1B, Unit 1C, Crappo Creek Grey Shale Member
Dundee Ls	Reed City Member/Dolomite/Anhydrite
Lucas Fm	Freer Sandstone, Horner Member, Iutzi Member, Massive Salt/Anhydrite, Sour Zone, Big Anhydrite, Richfield Zone/Member/Sandstone, Big Salt
Amherstburg Fm	Filer Sandstone, Meldrum Member, Black Lime
St. Ignace Dolomite	Salina H Unit
Salina B Unit	Big Salt, B Salt
Ruff Formation	Salina A-1 Carbonate, Rabbit Ears Anhydrite,
Cain Fm	Salina A-0 Carbonate
Guelph Dolomite	Brown Niagara, Niagaran Reef, Pinnacle Reef, Engadine Dolomite
Lockport Dolomite	Gray Niagara, White Niagara
Burnt Bluff Gr	Clinton Formation
Trenton Fm	Cap Dolomite
Black River Fm	Van Wert Zone, Sneaky Peak, Black River Shale
Glenwood Fm	Goodwell Unit, Zone of Unconformity
St. Peter Sandstone	Bruggers Sandstone, Jordan Sandstone, Knox Sandstone, Massive Sand
Prairie du Chien Gr	Foster Formation, New Richmond Sandstone, Lower Knox Carbonate, St. Lawrence Formation, T-PDC, Oneota Dolomite, Brazos Shale
Trempealeau Fm	Lodi Formation
Galesville Ss	Dresbach Sandstone
Pre-Mt. Simon Clastics	Precambrian "Red Beds"

LEGEND

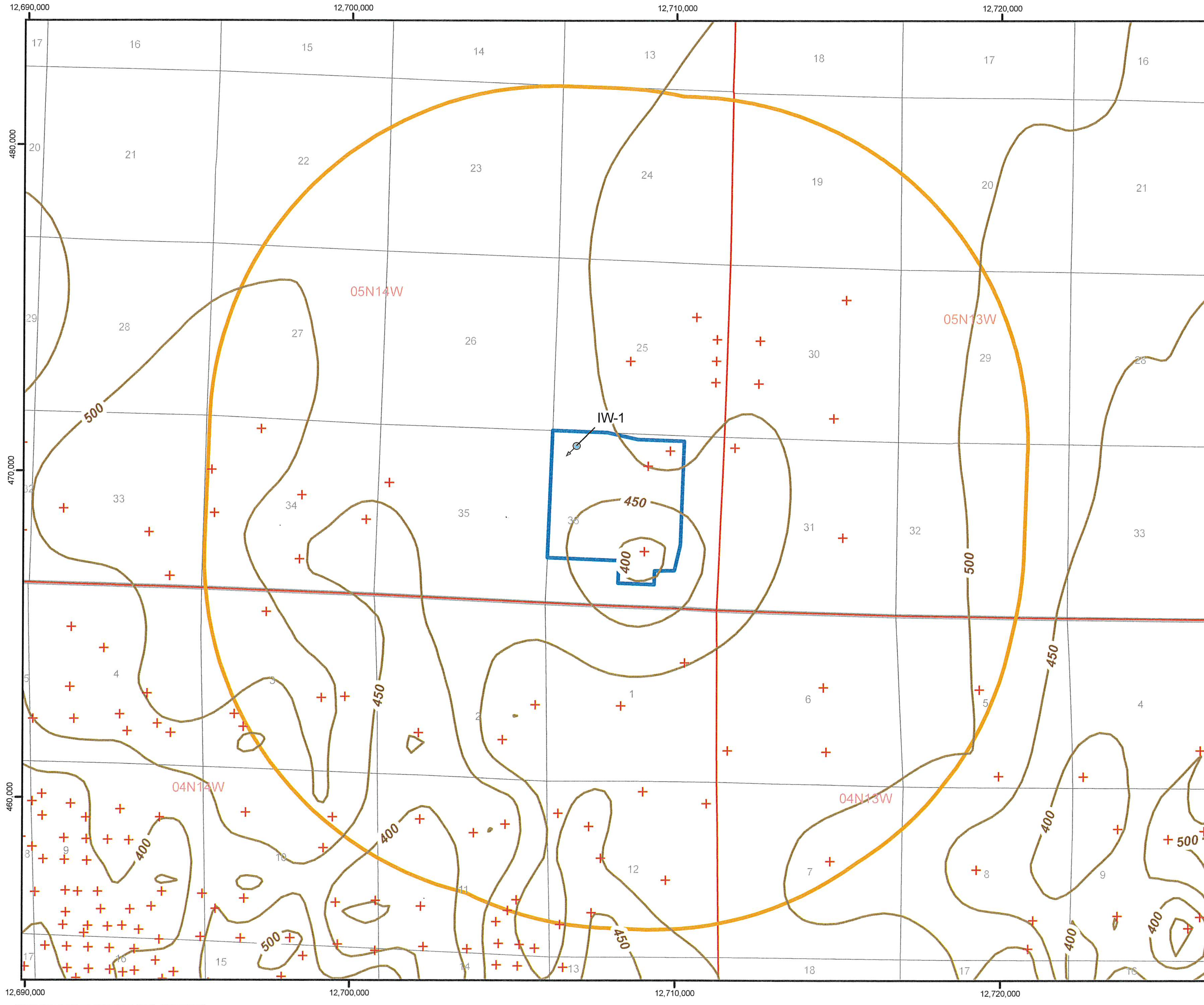


WASTE MANAGEMENT

Figure B.7-1
Stratigraphic Nomenclature for Michigan
2018 Autumn Hills - MDEQ Class I Permit

Scale: NTS	Date: April 2018	
2018_WM_MDEQ_Fig_B.7-1.ai	By: JLM	Checked: AP

Petrotek
5935 South Zang Street, Suite 200
Littleton, Colorado 80127 USA
303-290-9414
www.petrotek.com



Legend

- IW-1 - Proposed Location
- Coldwater Formation Data Point
- Coldwater Shale Structure Contour - 50ft CI
- Autumn Hills RDF
- Autumn Hills RDF - 2 Mile AOR

All datum are subsea elevations

N

0 2,000 4,000 6,000 Feet

WASTE MANAGEMENT

Figure B.7-2
Base of USDW, Coldwater Formation
Structure Contour Map

2018 Autumn Hills - MDEQ Class I Permit

Scale: 1:36,000	Date: April 2018	
2018_WM_MDEQ_Fig_B.7-02.mxd	By: JLM	Checked: AP

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Littleton, Colorado 80127 USA
303-290-9414
www.petrotek.com

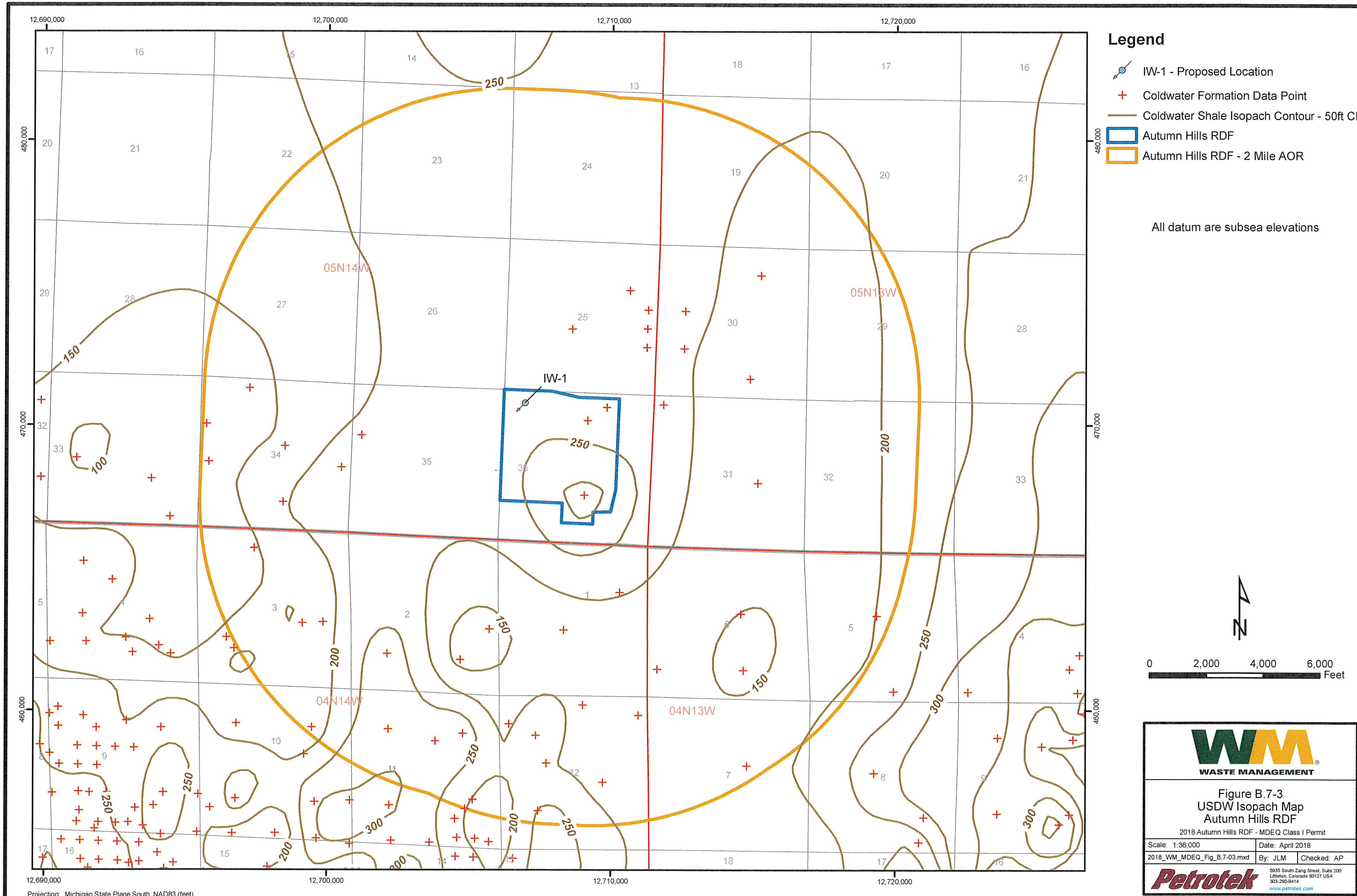


Figure B.7-3
USDW Isopach Map
Autumn Hills RDF

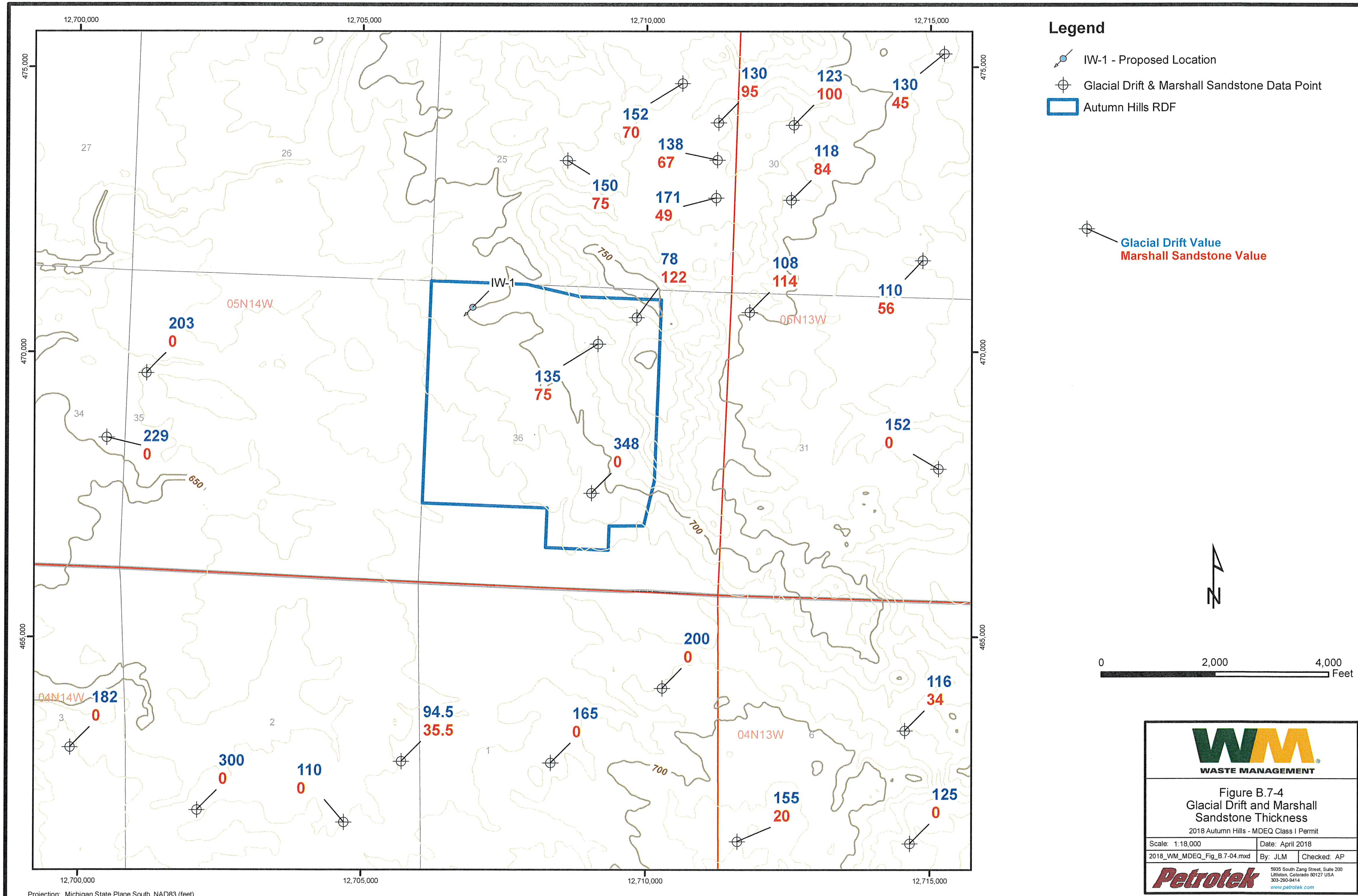
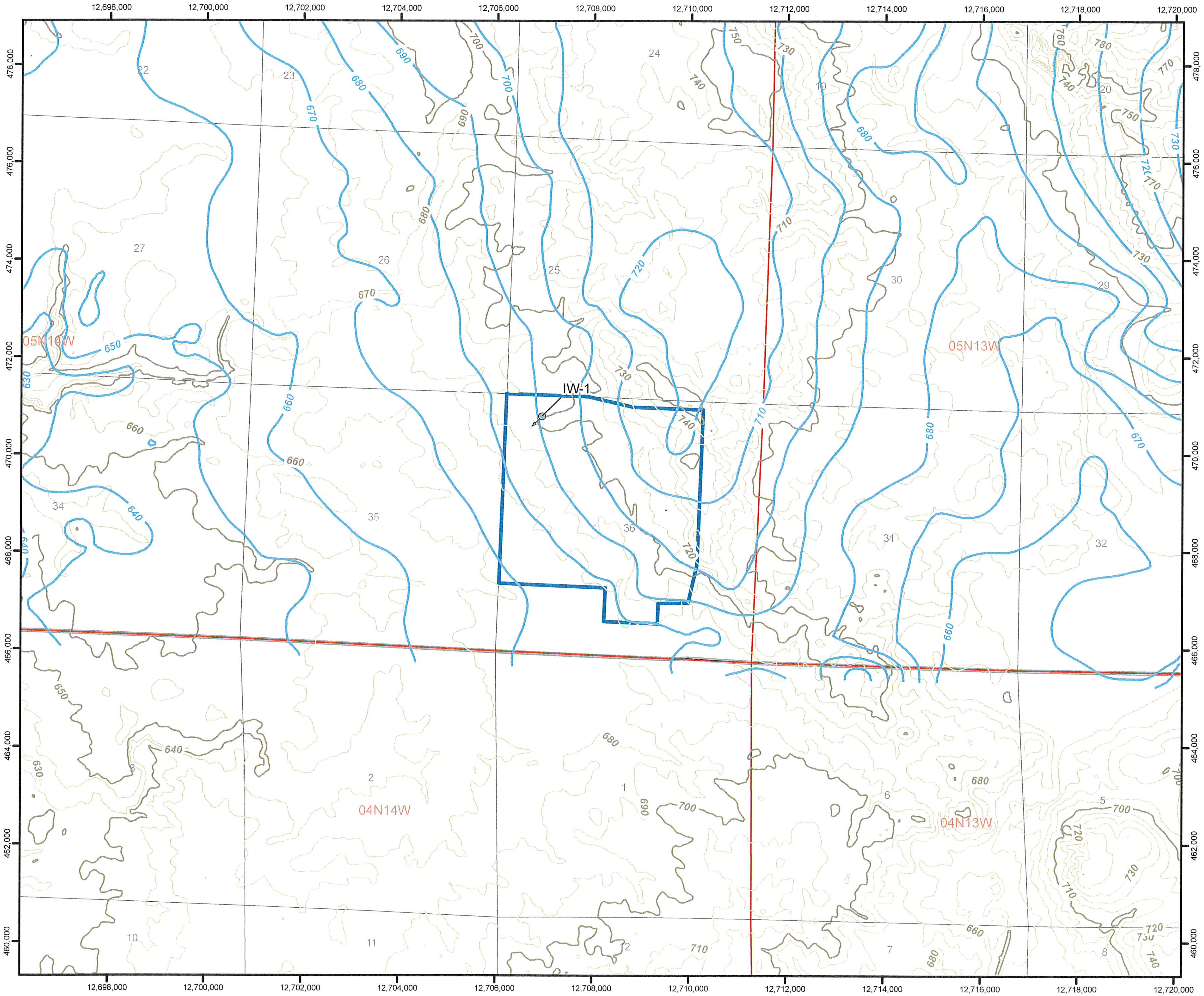


Figure B.7-4
Glacial Drift and Marshall Sandstone Thickness
2018 Autumn Hills - MDEQ Class I Permit



Projection: Michigan State Plane South, NAD83 (feet)

Legend

- IW-1 - Proposed Location
- Ground Water Potentiometric Contours, Elevation AMSL
- Autumn Hills RDF

Surface Elevation Contours, AMSL, C.I. 10ft.

N

0 2,000 4,000 Feet

WASTE MANAGEMENT

Figure B.7-5
Potentiometric Surface Map,
Autumn Hills RDF
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Scale: 1:24,000	Date: April 2018
2018_WM_MDEQ_Fig_B.7-05.mxd	By: JLM / Checked: AP

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B.8 Geologic maps and stratigraphic cross sections of the local and regional geology.

B.8.1 Regional Geology

B.8.1.1 General History of the Michigan Basin

The Michigan Basin is an intracratonic basin that occupies an area of about 80,000mi^2 (Catacosinos et al., 1991) (Figure B.8-1). The basin is nearly circular and was created by four different styles of subsidence: trough-shaped, regional tilting, narrow basin-centered and broad basin-centered (Howell and van der Pluijm, 1999). The basin is centered on Michigan's southern peninsula and is generally separated from other nearby basins by major arches. The basin is characterized structurally by several Paleozoic anticlines that trend northwest-southeast, which some authors (e.g., Wood and Harrison, 2002) present in association with basement faults or lineaments.

The Michigan Basin contains as much as 16,000 feet of sedimentary rock, covered by up to 1,200 feet of Pleistocene-age glacial drift (Catacosinos et al., 1991). Figure B.8-2 is a Geologic Map of Michigan, showing the subcrop configuration of strata in the Michigan Basin. The Precambrian basement underlying the Michigan Basin is part of the Superior Province, and is approximately 1.2 to 1.5 billion years old. About 5,000 feet of thickened Precambrian-age sedimentary rock occurs above basement along a north-south trending linear trend associated with a gravity anomaly that has been interpreted by Catacosinos, et al. (1991) and others to be a portion of a buried ancient rift system. Adjacent to this trend, Cambrian rocks occur above the crystalline Precambrian basement, as is the case at the Autumn Hills RDF site (referred hereafter as the Site).

A gradual marine transgression occurred through the Late Cambrian. Late Cambrian deposits including the Mt. Simon Sandstone, Eau Claire Formation, Galesville (Dresbach) Sandstone, and Franconia Formation are probably marine in origin, with the source of sedimentary material originating from northeast. By the end of the Cambrian Period, most of the United States was under water. This circumstance continued through the Ordovician in the Michigan Basin area. Cambrian-Lower Ordovician units were deposited within a northerly transgressing epicontinental sea; the units are predominantly siliciclastic and can be over 4,500 feet thick in the center of the basin.

The Lower Ordovician Trempealeau Formation and Prairie du Chien Group were also generally deposited in a marine environment. A minor regression preceded the deposition of the onshore/nearshore St. Peter Sandstone. Deposition of the offshore marine shale and carbonates of the Trenton and Black River Formations was followed by another regression, with an accompanying unconformity. The late Ordovician Richmond Group, which includes the Utica Shale, is composed of shale deposited in a deep water environment.

During the Silurian, the Michigan Basin was an interior sea surrounded by low-lying land areas that partially isolated the sea from other bodies of water. In the absence of a significant nearby source of clastic material, the main deposits of the Silurian were evaporite and reef deposits. The Middle Silurian Niagara Formation was deposited throughout the lower peninsula of Michigan, and is composed of carbonate reef deposits. Progressive isolation of the Basin with respect to water influx is evidenced by deposition of the Salina Formation, which contains evaporates including anhydrite and halite that were deposited in the relatively restricted inland sea. During the Silurian, over 3,000 feet of sediment was deposited in the center of the Michigan Basin.

The base of the Devonian Period is represented by an unconformity as the seas regressed and land emerged, which was followed by transgression and subsequent deposition of carbonate-rich sequences through the early and middle Devonian. The Devonian Detroit River Group consists of carbonates and evaporites, with some shale. The Dundee Formation, which consists of carbonates, was deposited after the Detroit River Group. During the Late Devonian, uplift in the Appalachian Region to the east provided a siliclastic sediment source and subsequent deposition of shale-rich sequences including the shale of the Antrim Formation, Ellsworth Formations and Mississippian Coldwater Formations.

Devonian rocks are capped by the deposition of predominantly siliciclastic units during the Mississippian and Pennsylvanian periods. Depositional environments found during this time period include marine, coastal, and terrestrial environments, and represent a return to continental systems. Terrigenous Jurassic "Red Beds" are present in the center of the Basin (Catacosinos, et al., 1991).

B.8.1.2 Regional Structural Geology

The Autumn Hills RDF is located on the southwestern flank of the Michigan Basin as illustrated by the Geological Map of Michigan, shown in Figure B.8-2. The Michigan Basin resulted from epeirogenic down warping during the Paleozoic Era, and subsidence of the basin controlled the deposition of sedimentary units during the Paleozoic. Each Paleozoic unit dips toward the center of the basin, and also generally thickens basinward. The basin extends into northwest Ohio and northeast Indiana and covers all of the Lower Peninsula of Michigan. The structural axis of the Findlay Arch is southeast of the Basin and the axis of the Kankakee Arch is to the southwest. Regional dip in the Site vicinity is to the northeast at 40 to 60 feet per mile.

Catacosinos et al. (1991) states that at least "three structural platforms" were present in the Michigan Basin that differentially affected isopach and facies relationships within stratigraphic units. These platforms were located in the southeastern, northeastern, and southwestern portions of the Basin. Structural features present in the Basin were characterized by northwest-southeast trending features that Catacosinos indicates some authors believe are the result of vertical tectonics, possibly anticlines and/or horst and graben sequences. Catacosinos states that "almost all the faulting in the Precambrian tends to die out upwards and that only a few of the largest faults extend through the Middle Devonian Section. Faulting across the Mississippian-Pennsylvanian unconformity has not yet been reported."

According to Catacosinos et al. (1991), during Late Precambrian time rifting occurred across the midcontinent, as evidenced by a rift zone in Michigan Basin basement rocks. Rifting was followed by thermal subsidence creating a "sag basin" in the late Cambrian. Basin subsidence began during the early Ordovician with concurrent deposition of thick stratigraphic sequences. The current northwest-southeast structural grain apparent in regional structural maps (e.g., Figure B.8-3) was imposed in late Mississippian to Pennsylvanian "possibly as the result of flexural foreland subsidence in response to the Alleghenian-Hercynian Orogeny…" (Catacosinos et al., 1991).

Milstein (1989) states that the distribution of Cambrian strata indicates "successively younger beds overlap to lie directly on the Precambrian…This suggests that the regional configuration of the Precambrian surface, during Cambrian times, was similar to its present shape". Milstein (1989) also suggests that isopachous variations in overlying Cambrian units reflect irregularities on the Precambrian surface: "prominent Precambrian features like the Washtenawa Anticlinorium in southeastern Michigan, and the Bowling Green Fault located along the Leawee and Monroe County boundary, are both reflected in the Cambrian sediments."

Wood and Harrison (2002) explored the occurrence and expression of faults within the Michigan Basin through mapping of post-Silurian sediments. They concluded that the "Michigan Basin is cut by numerous (12+) major faults lying below the glacial drift and below the topmost Jurassic sediments". The lineations generally trend northwest-southeast (Figure B.8-3). These lineations are dominant features of the subsurface topography and are well documented, occurring as structural features expressed in units from at least the Late Devonian (Dundee time) to the Mississippian. Wood and Harrison (2002) state "These faults carve out [a] large depression in the Central Michigan Basin and appear to be responsible for shallow anticlines that hold or held a significant portion of the hydrocarbons in the Michigan Basin". The origin of these faults was attributed to deep-seated normal basement faults "rooted in the Precambrian rift sequence". Figure B.8-3 presents the location of these northwest-southeast trending features (Dundee Lineaments) presumably associated with basement faults. Faults are not projected in the vicinity of the Site AOR.

B.8.1.3 Regional Stratigraphy

Figure B.7-1 presents the stratigraphic column for Michigan. Figures B.8-4 and B.8-5 are regional cross sections available from the literature, and show regional stratigraphic continuity and geologic structure across the southwestern portion of the Michigan Basin.

B.8.1.3.1 Precambrian (Lower Confining Zone)

The Precambrian crystalline basement is described as primarily metasedimentary gneiss (mafic and felsic) formed by the metamorphism of igneous rock as well as shales, sandstones, carbonate and iron formations. Igneous intrusions may also occur within these units. The Precambrian basement is estimated to occur at approximately 6,600 feet below ground surface (ft BGS), or approximately 5,900 feet below mean sea level (ft BMSL) at the Site (Figure B.8-6), and serves as the lower Confining Zone. Based on the regional structural contour map presented in Figure B.8-6, the depth to the Precambrian is approximately 5,840 feet BMSL, however based on more recent data analysis from nearby wells, projected depth to the Precambrian basement is slightly lower in elevation, which is detailed further in Section B.8.2.2.1. In southwest Michigan near the Site, the Precambrian dips at approximately 50-60 feet per mile to the northeast, toward the center of the Michigan Basin and may occur at least 14,000 feet or more below ground surface near the basin center.

B.8.1.3.2 Cambrian and Lower Ordovician Systems (Injection Interval and Injection Zone)

The Cambrian is composed of the Mt. Simon Sandstone and the Munising Group that includes the Eau Claire Formation, Galesville (Dresbach) Sandstone, and the Franconia Formation. The Trempealeau Formation and Prairie du Chien Group are Lower Ordovician in age. The Mt. Simon, Eau Claire, Galesville (Dresbach), Franconia, Trempealeau Formations and Prairie du Chien Group are included in the injection zone. The Mt. Simon is the injection interval.

Units from the Franconia to the top of the Mt. Simon comprise the Munising Group, although various authors have also included the Mt. Simon in the Munising Group. For the purposes of this report, the Munising Group is assumed to consist of the Mt. Simon, Eau Claire, Dresbach, and Franconia Formations.

Mt. Simon Sandstone (Injection Interval)

The Mount Simon Sandstone (Mt. Simon) is a massive sandstone that is present in the subsurface throughout much of Ohio, Indiana, Illinois, and the lower peninsula of Michigan. Figure B.8-7 is an isopach of the Mt. Simon in the Michigan Basin, and Figure B.8-8 is a structure contour map constructed at the top of the Mt. Simon. The Mt. Simon is thickest within the central portions of the Basin, and reaches a thickness of approximately 1,240 feet in the Gratiot County region. The Mt. Simon thins dramatically to the east side of the state, but thickens again in the southwestern portion of the State in Berrien County toward the Illinois Basin.

In the southern peninsula of Michigan, the Mt. Simon typically lies unconformably above the Precambrian Crystalline Basement Complex and is projected to occur at approximately 5,578 feet BGL (or 4,875 feet BMSL) at the Site. Western Michigan University (WMU) (1981) indicates that the Mt. Simon varies in thickness from 100 feet to over 1,000 feet thick in the lower Peninsula of Michigan (Figure B.8-7), and also subcrops with the Munising Group in the Upper Peninsula. While the regional isopach map indicates a Mt. Simon thickness of approximately 900 feet, more recent data analysis from nearby wells indicates that the Mt. Simon is approximately 1,000 feet thick in the Site area (detailed in Section B.8.2.2.2).

The Mt. Simon is described as a subrounded to rounded quartzitic sandstone that is generally fine to coarse grained and well sorted. It is pink to red, with a greater abundance of feldspar at the base of the unit. WMU (1981) states that "glauconite, anhydrite, and green shale are present in minor amounts with local dolomite cement". Barnes et al. (2009) indicate that the Mt. Simon is composed of three basic units: a basal arkosic unit, a middle quartz arenite-glauconite unit, and an upper shale-rich unit that grades conformably into the Eau Claire Formation. Some authors and wellsite geologists may have attributed basal pre-Mt. Simon sediments to be part of the basal arkosic Mt. Simon unit.

Regional porosity development is generally related to the burial depth, with better porosity developed in areas with less overburden (Barnes et al. 2009). State-wide, literature has generally indicated that Mt. Simon porosity typically ranges from 4-20% and may also vary laterally where sandstones grade into more shale or carbonate-rich facies.

The Mt. Simon is a common target for fluid injection, and is under scrutiny as a potential target for CO_2 sequestration. WMU (1981) states that with respect to the Mt. Simon as a whole, regionally the "the permeable Cambrian quartz sandstone, siltstone, and arenaceous dolomite suitable for fluid injection comprise about 27% of the stratigraphic column". Barnes et al. (2009) conclude that "The Mount Simon Sandstone in Michigan is an important saline reservoir target for geological sequestration of CO_2 in Michigan". Various authors have concluded that the Mt. Simon has both the capacity to accept injectate and has "cap rocks" suitable to arrest vertical fluid migration.

Eau Claire Formation

The Eau Claire Formation (Eau Claire) occurs conformably above the Mt. Simon in the southern peninsula of Michigan, and consists of interbedded sandstones, siltstones, and shales may also include thinly bedded dolomites (Milstein, 1989). It is described as appearing similar to the Mt. Simon, particularly in lower portions where the two units are conformable and the contact is therefore somewhat gradational. In the center of the Michigan Basin, the Eau Claire is composed of up to 100% shale and dense siltstone (UIPC, 1989), with the proportion of shale in the formation decreasing toward the basin margins.

The thickness of the Eau Claire varies considerably within the Michigan Basin. WMU (1981), states that the Eau Claire ranges from 0-1,500 feet thick in the Michigan Basin, with the thickest deposits occurring in the central portion of the Basin. Milstein (1989) believes there to be about 800 feet of Eau Claire in the central portion of the basin.

Milstein (1989) mapped the Eau Claire showing a maximum thickness of over 800 feet near the central basin and thinning to less than 100 feet along the eastern margin of the state (Figure B.8-9). The Eau Claire is mapped by Milstein (1989, Figure B.8-9) as being approximately 300 feet thick at the Site. More recent data analysis from nearby wells indicates that the Eau Claire is approximately 200 feet thick in the Site area (detailed further in Section B.8.2.2.2).

The top of the Eau Claire occurs at about 4,600 feet BMSL (Figure B.8-10) in southern portions of Ottawa County near the Site area, and dips to the northeast, reaching a maximum depth of over 13,000 feet in the center of the Michigan Basin. Local data analysis from nearby wells indicates that the actual top of the Eau Claire occurs at approximately 4,670 feet BMSL (detailed further in Section B.8.2.2.2). While the Eau Claire is included in the Injection Zone, shale rich layers of this approximately 200 feet thick sequence provide significant barriers to vertical fluid movement from the Mt. Simon and local well data confirms that it tends to serve as an aquiclude.

Galesville (Dresbach) Sandstone and Franconia Formation

The Galesville (Dresbach) Sandstone is also thickest in the central portion of the Michigan Basin, reaching its greatest thickness of over 600 feet in Gladwin County. It is approximately 100-200 feet thick in southwest Michigan and is approximately 145 feet thick in the Site area. The Dresbach generally thickens to the northeast in the Michigan Basin, as seen in Figure B.8-11 that presents a regional isopach map of the Galesville/Dresbach. While the regional isopach map indicates a thickness of approximately 100 feet near the Site area, more recent data analysis from nearby wells indicates an estimated thickness of approximately 145 feet (further detailed in Section B.8.2.2.2). The Galesville is described as medium grained silica-cemented sandstone that may have glauconite and dolomite, with some siltstone and shaley units present locally.

The Franconia Formation includes "a wide array of glauconitic dolomitic sandstone, shale, and sandy dolomite" that is sometimes indistinguishable from the underlying Galesville Sandstone. Milstein (1989) states that the Franconia is composed of a light pink to gray quartz sandstone that contains pyrite and abundant glauconite, but can be readily identified by gamma ray log. The Franconia has a maximum thickness of about 800 feet, and is estimated to be approximately 120 to 140 feet thick in the Site area based on analysis of nearby wells that is further detailed in Section B.8.2.2.2.

Trempealeau Formation

The Trempealeau Formation is Lower Ordovician in age and is a buff to light brown dolomite that can be sandy, shaley, and cherty, with some glauconite. Literature suggests that the formation is likely composed (from the top down) of the St. Lawrence, Lodi, and Jordan members (WMU, 1981). The St. Lawrence member is a sandy dolomite with dolomitic shales. The Lodi is a sandy dolomite with interbedded stringers of shale and sandstone, while the Jordan sandstone is fine grained quartz sandstone to sandy dolomite. This formation represents a transition between underlying sand-rich units and overlying carbonate rich intervals. Figure B.8-12 presents a regional isopach map of the Trempealeau Formation, and Figure B.8-13 presents a regional structural contour map. The Trempealeau Formation is approximately 200 feet thick below the Site area, and is more than 900 feet thick in the center of the Michigan Basin.

Prairie du Chien Group

The Prairie du Chien Group is Lower Ordovician in age, and consists of various layers primarily comprised of gray, sandy dolomite and dolomitic sandstone and includes the Shakopee [Foster] Formation as well as other major units identified by WMU (1981) as the Oneota Dolomite, New Richmond Sandstone, and Shakopee Dolomite. WMU (1981) states that in the subsurface "the entire Prairie du Chien Group has characteristics similar to dolomite", and indicates that in some areas (near subcrop) the Prairie du Chien is porous. Smith, et al. (1993) described the Prairie du Chien Group as carbonate-dominated mixed carbonate siliciclastic sediments "deposited in and adjacent to shallow tropical seas that flooded most of the central North American craton during the Early Ordovician…[and] consists of sandy, silty and relatively pure dolomites and minor quartzarenites that underwent intermittent reworking by waves and unidirectional currents". Smith et al. (1993) also state that "In the subsurface of the Michigan basin, dolomites of the Oneota Formation overlie silty-glauconitic dolomites of presumed Trempealeauan age, and are overlain by silty-sandy dolomites and dolomitic siltstone of the basal Shakopee [Foster] Formation". The Shakopee is heterogeneous and consists of interbedded silty and sandy dolomites, with dolomitic siltstones, sandstones and shales. In the central Michigan Basin, Smith et al. (1993) state that the Shakopee is overlain by shales of varying thickness, that in turn are overlain by the St. Peter Sandstone.

The contact between the Prairie du Chien and overlying units is unconformable in many locations. WMU (1981) indicates that the Prairie du Chien is overlain by the Post Knox Unconformity. Milstein (1984) also identified a "Zone of Unconformity" which occurs above the Prairie du Chien, but this interval is not present in Ottawa and Allegan counties. Sandstone intervals above the Prairie du Chien (e.g., St. Peter Sandstone) are discussed by some authors as part of the Prairie du Chien Group. However, since the sandstone sequences are not present in the Site area, the Prairie du Chien only includes the carbonate sequences for the purposes of this permit. The Prairie du Chien of Michigan is generally represented by this same name in Illinois, Wisconsin, and Indiana, and it is equivalent to the upper part of the undifferentiated Knox Dolomite of Ohio and to the Beekmantown Dolomite, the Gunter Sandstone, the Gasconade Dolomite, the Roubidoux Formation, the Jefferson City Dolomite, and the Cotter Dolomite of Kentucky.

Milstein (1983) mapped the Prairie du Chien as about 550 feet thick in the Site area. Figure B.8-14 presents this regional isopach map of the Prairie du Chien Group, and Figure B.8-15 presents a regional structural contour map. The Prairie du Chien is a gas producer in limited portions of the central Michigan Basin, with the deepest of these