North Dakota Geological Survey

Examination of Hydrocarbon Saturation within the upper Black Island Formation (Garland Member), Winnipeg Group

By

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Figures

Plate

Appendixes (CD version only)

Introduction

The Black Island Formation represents the lower portion of the Winnipeg Group, which was deposited during a middle Ordovician marine transgression (LeFever et al., 1987). Consisting mostly of sandstone interbedded with shaly to shale intervals (Fig. 1), the Black Island Formation has produced over 17 million barrels of oil equivalent (boe) from only 18 vertical wells (Nesheim, 2012). Clean quartz arenite intervals within the Garland Member (upper Black Island Fm.) have been the primarily completion target of Winnipeg productive wells (Nesheim, 2012) and are the focus of this publication.

Geology

The Black Island Formation has been broken down into two members (Ellingson, 1995; Ellingson & LeFever, 1995), the lower Hawkeye Valley Member and the upper Garland Member (Fig. 1). The Hawkeye Valley Member consists primarily of redbeds, oxidized shales to sandstones (Fig. 1) deposited in a continental fluvial/deltaic setting (Ellingson, 1995; Ellingson & LeFever, 1995). The Garland Member was deposited in a shallow marine setting (Ellingson, 1995; Ellingson & LeFever, 1995) and consists primarily of two lithofacies: shaly to silty bioturbated sandstone representing lower to upper offshore (subtidal) deposits, and fine to medium grained, rounded to well rounded, well sorted, massive to cross-bedded quartz arenites representing foreshore/shoreface deposits. Through examination of cores and logs of the Garland Member, there appear to be three foreshore/shoreface sandstone (quartz arenite) intervals preserved within the Garland Member: Sandstones A, B, and C (Fig. 1). Sandstones A-C are assumed to be shoreline deposits, but could also consist in part of similar sandstone bodies such as bar sand deposits.

Sandstone A tends to be the thickest of the three main quartz arenite intervals within the Garland Member. Sandstone A reaches thicknesses of around 50 ft. along the Nesson Anticline (Fig. 2), away from which it thins in all directions. Sandstones B and C tend to be thinner than Sandstone A, reaching maximum thicknesses of 13 (Fig. 3) and 15 ft. (Fig. 4). Sandstones B and C are also more irregular in their distribution and thickness than Sandstone A, but extend further to the south. The thickness variations and irregular distributions of Sandstones B and C may be a function of deposition and/or preservation. In an eastward trend, the gamma ray signature of the Garland Member decreases (Plate 1, cross-section A-A') and Sandstones A-C appear to merge together, which is why the isopachs in this publication end approximately in central North Dakota (Figs. 2-4).

Observations

Along the Nesson and Antelope Anticlines, the entire Black Island section appears to be hydrocarbon charged based on core analyzes (Fig. 5) and production. From compiled core data, the silty to shaly bioturbated sandstones along the Nesson and Antelope Anticlines average 5.0% porosity and 0.26 millidarcies of permeability with 13.3% oil saturation and 45.0% water saturation while the non-

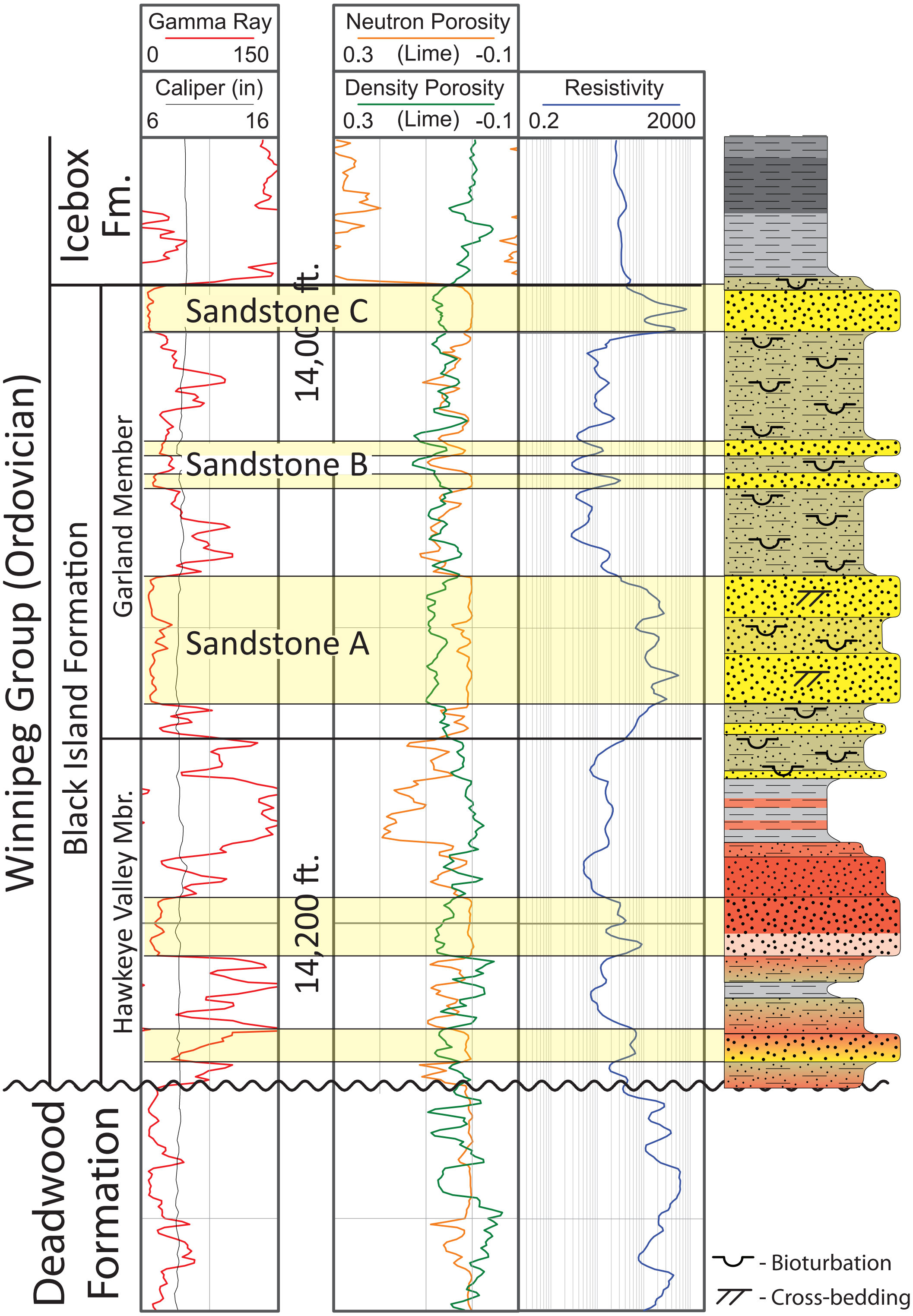


Figure 1. Composite example log and illustrated core of the Black Island Formation along the Nesson and Antelope Anticline area. Wireline log sets from Amerada Hess's Pederson #14-22 (NDIC: 12363, API: 33-105-01340-00-00, Sec. 14, T157N, R95W) and Brenna-Lacey 1 #32 (NDIC: 13405, API: 33-053-02397-00-00, Sec. 1, T152N, R95W) were combined to display the typical log signatures of the Garland Sandstones A, B, and C of the area. Illustrated core lithologies (right) are based off of several partial Black Island cores, primarily including: Amerada's Antelope Unit "A" #1 (NDIC: 2373, API: 33-053-00410-00-00, Sec. 1, T152N, R95W), Amerada Hess's Brenna Lacey 1 #32 and Oscar Moe #32-43 (NDIC: 13647, API: 33-053-02459-00-00, Sec. 32, T153N, R94W). Depths correlate with that of the Brenna-Lacey 1 #32.

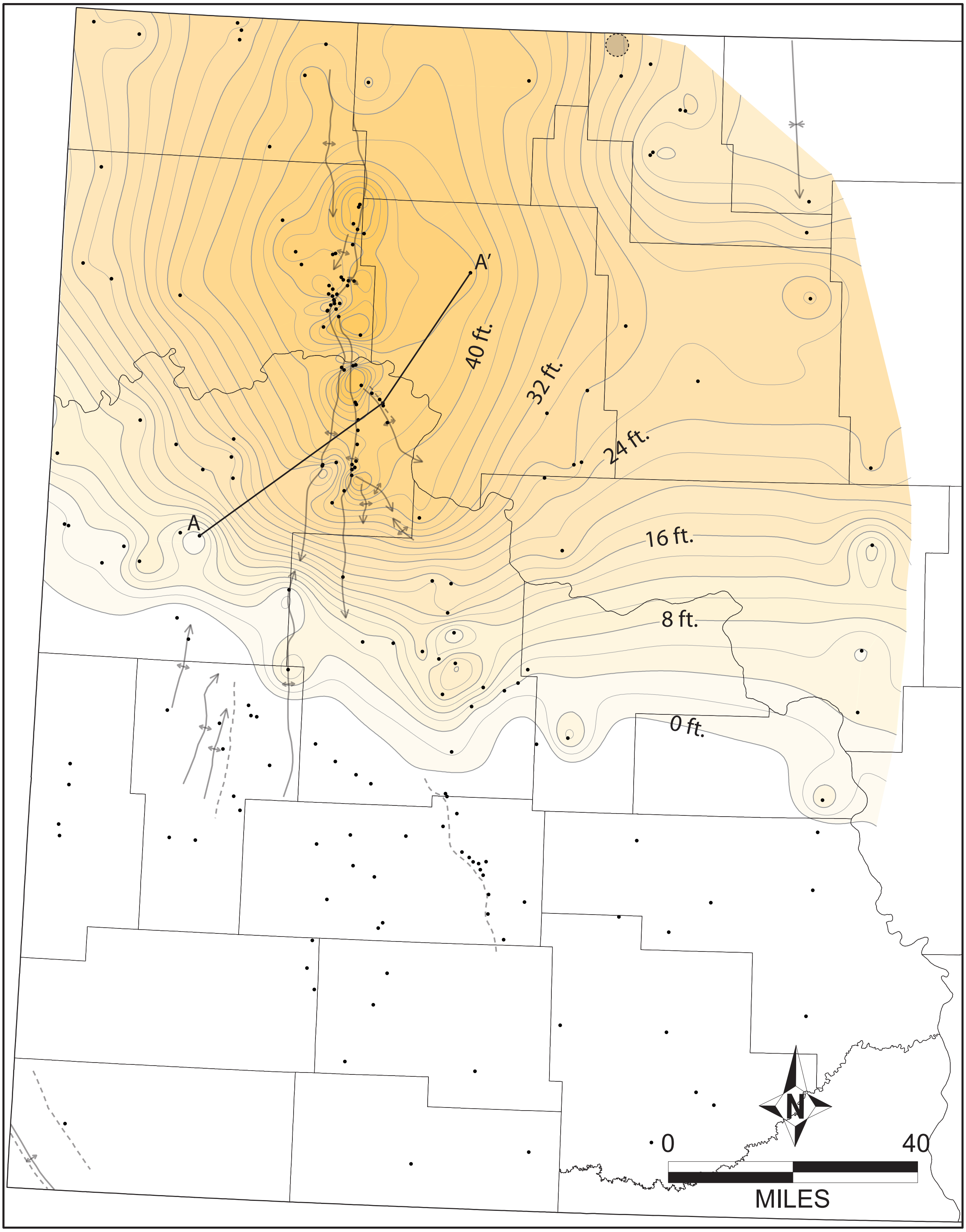


Figure 2. Isopach of Sandstone A from the Garland Member, upper Black Island Formation. Black dots show the location of control wells. Contour lines are in 2 ft. intervals. A-A' shows the location of the Figure 5 cross-section.

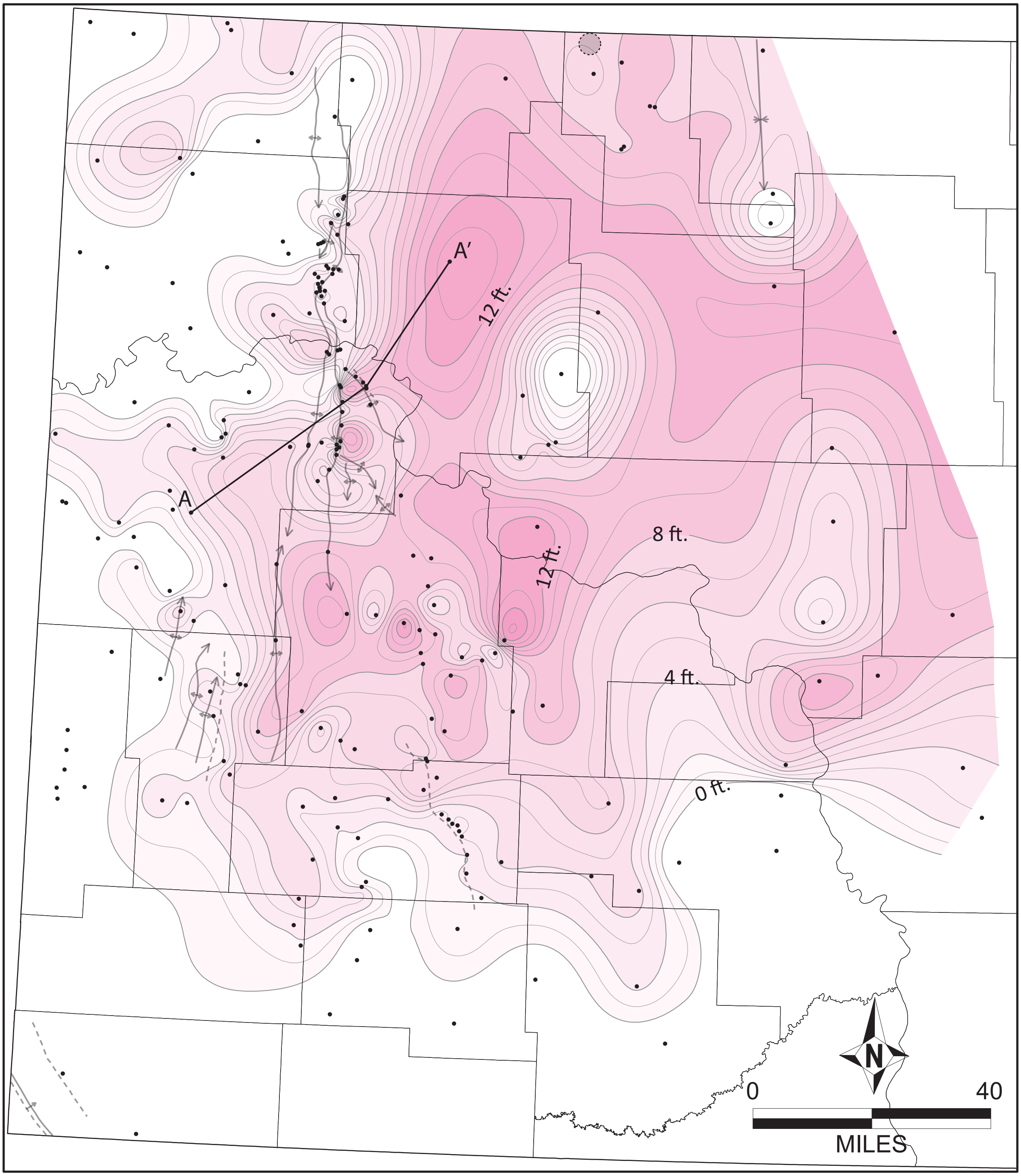


Figure 3. Isopach of Sandstone B from the Garland Member, upper Black Island Formation. Black dots show the location of control wells. Contour lines are in 1 ft. intervals. A-A' shows the location of the Figure 5 cross-section.

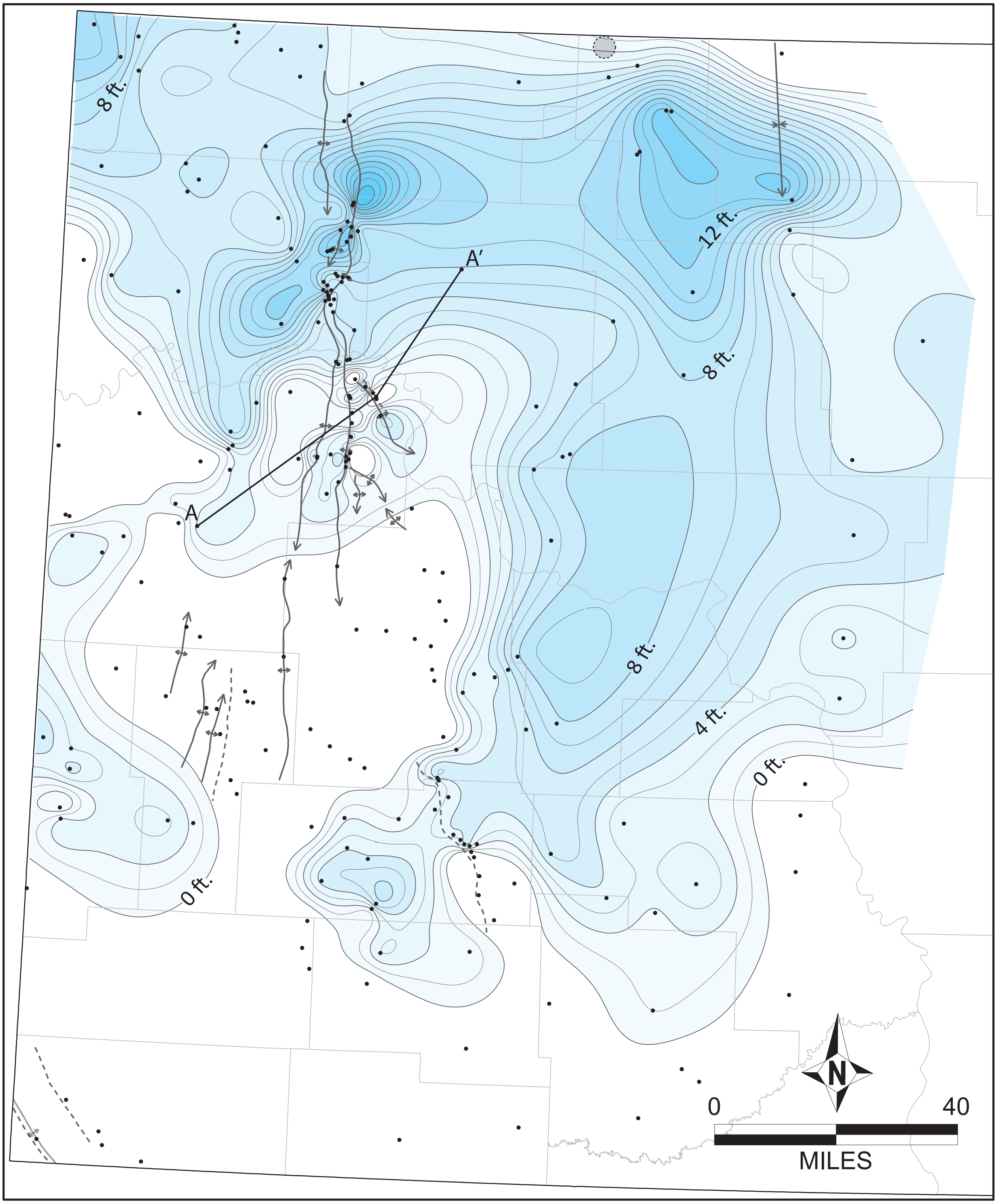


Figure 4. Isopach of Sandstone C from the Garland Member, upper Black Island Formation. Black dots show the location of control wells. Contour lines are in 1 ft. intervals. A-A' shows the location of the Figure 5 cross-section.

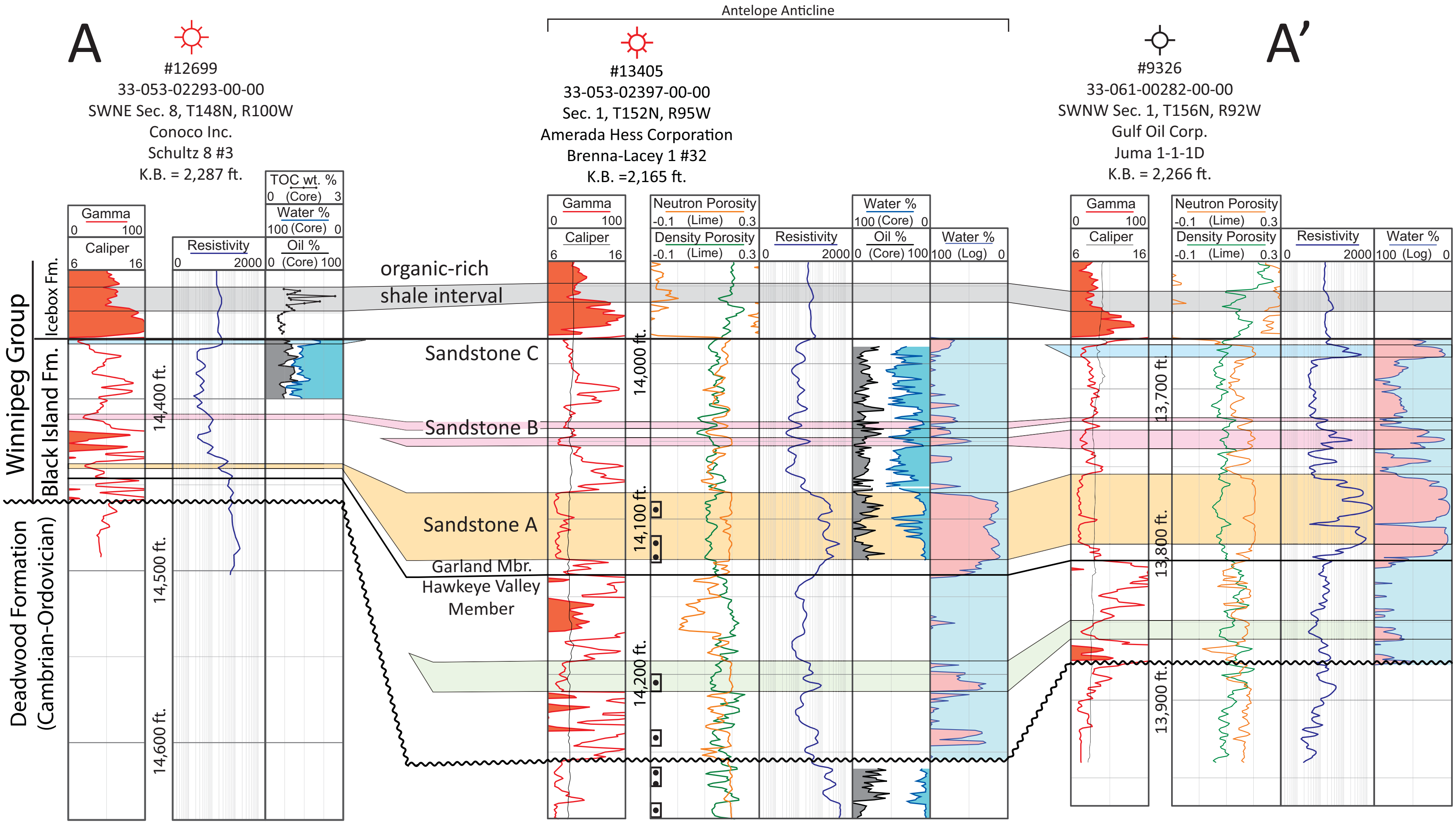


Figure 5. East-West Cross-Section of the Black Island Formation with core and log analysis data. TOC wt. % data for Conoco’s Schultz 8 #3 was measured from core samples collected from the lower 25 ft. of the Icebox Formation. While there is a lack of core data for the Hawkeye Valley Member, perforations within the interval yield gas with minimal water suggesting overall good hydrocarbon saturations.

bioturbated sandstones (Sandstones A-C) average 5.7% porosity and 0.29 millidarcies permeability with 14.8% oil saturation and 22.6% water saturation. Production from vertical wells along the Nesson and Antelope Anticlines yields primarily dry gas (~90% methane) with low amounts of water and condensate (Nesheim, 2012). High gas concentrations explain why the core data displays significant empty pore space (oil sat + water sat << 100%) in that gas will easily escape a core's pore space shortly after a core is cut. The low water production indicates that most of the water saturation observed in core is irreducible (immobile) for both the bioturbated and non-bioturbated intervals.

Away from significant structure, limited core data suggests the Black Island Formation may be continually hydrocarbon charged. For example, from Conoco's Schultz 8 #3 (Fig. 5), an upper Black Island core (Garland Member), consists of 30 ft. of silty to shaly bioturbated sandstone. Core analysis data from this interval averages 6.4% porosity and 0.36 millidarcies permeability with 29.2% oil saturation and 54.7% water saturation. These core analysis averages are similar to that of the bioturbated sandstones along the Nesson and Antelope Anticlines, where the Black Island produces hydrocarbons with a low water cut.

Methodology

To examine the regional distribution of hydrocarbon charge within the Black Island Formation, log analysis is required due to the limited amount of Black Island cores. Both along and away from structure, the clean, quartz arenite intervals (Sandstones A-C) within the Garland Member consistently display high resistivity and neutron porosity cross-over signatures (Fig. 5, Plate 1 A-A' & B-B'), indicating these intervals are charged with significant amounts of gas. In order to better quantify these observations, water saturations were calculated for Sandstone A using the Archie Equation (Eq. 1).

Eq. 1

$$S_w = (a \times R_w) / (R_t \times \phi^m)^{1/n}$$

Where:

- S_w = water saturation for interval of interest (uninvaded zone)
- R_w = resistivity of formation water at formation temperature
- R_t = true formation resistivity (i.e., deep resistivity)
- ϕ = porosity
- a = tortuosity factor
- m = cementation exponent
- n = saturation exponent

For several of the components within the Archie equation, constants were assumed. A tortuosity factor (*a*) of 0.81 and a cementation exponent (*m*) of 2.0 were used, which are the recommended values for consolidated sandstones from Asquith and Krygowski (2004). A saturation exponent (*n*) of 2.0 was also assumed.

Formation water resistivity is a function of the total dissolved solids (TDS) content and the formation temperature. To examine the TDS content of the water within the Black Island Formation, water analysis data was compiled from water produced from the Black Island through production and drill stem tests (DST's) (Fig. 6). Based largely on water analyzed from productive wells completed only in the Black Island, a TDS of 225,000 mg/L was used to calculate formation water resistivity. In order to adjust the formation water resistivity for temperature, bottom hole temperatures were compiled from DST's run on the Black Island Formation (Fig. 7).

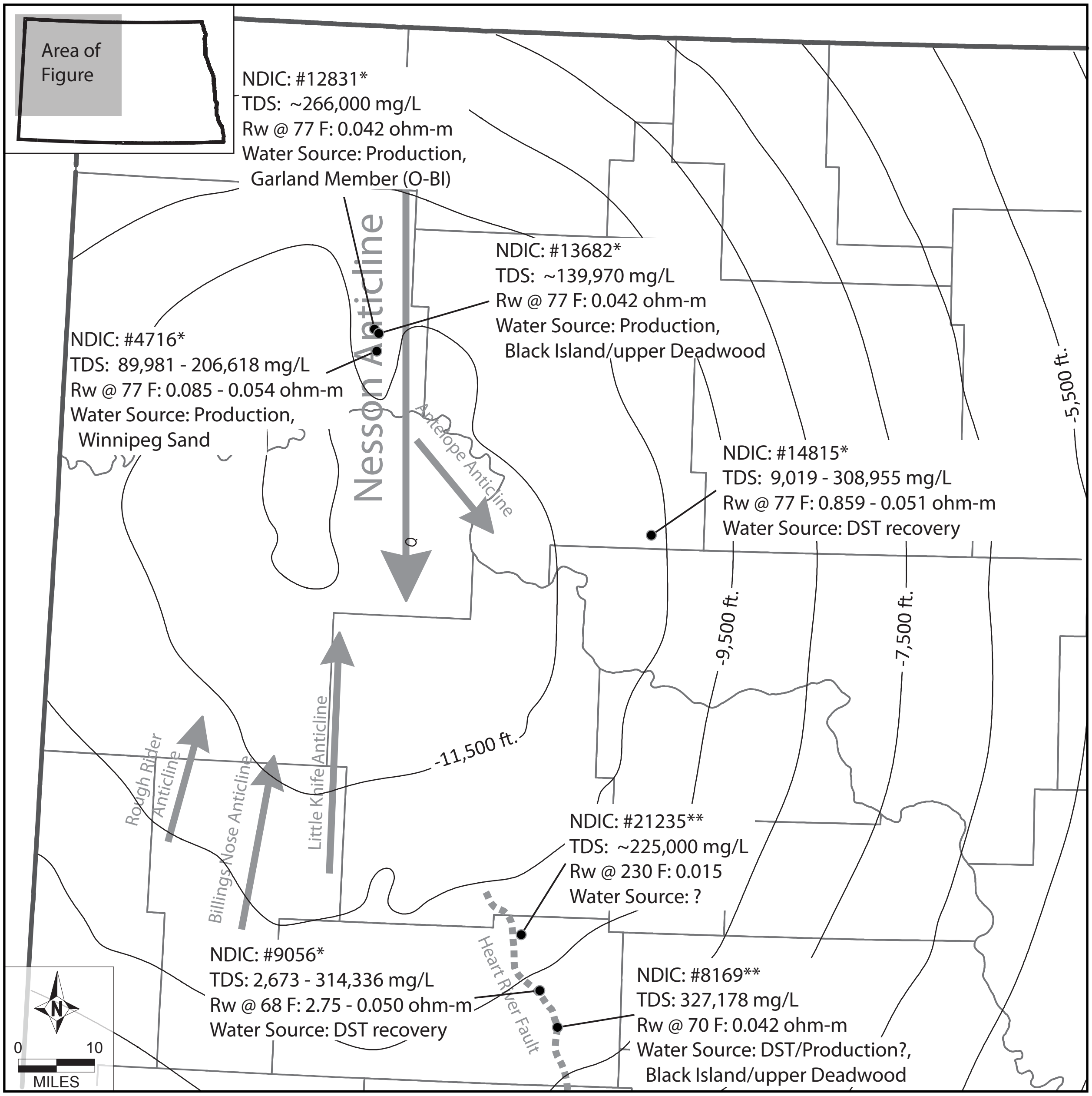
The next component needed for the Archie equation is the porosity (ϕ) of Sandstone A. Being that the Black Island is comprised mostly of sandstone, the density porosity log curve (sandstone matrix) was used for the porosity component. At times the density porosity and the core measured porosity data sets for Sandstone A overlap very well (Fig. 8), and at other times the density porosity is consistently higher than the core porosity values (Fig. 9). One possibility for the difference could be the varying presence of natural fractures in the interval of interest where the log porosity is higher than that of the core porosity. Variations in shale content, and possibly bioturbation, may play a role in the accuracy of the log porosity as well. The quality of the log and/or core data could also play a role. Figure 10 displays the contoured log porosity of Sandstone A.

Using the Archie Equation with components outlined above, water saturations (S_W) were calculated for Sandstone A from 52 wells across western North Dakota. Assuming all of the non-water filled pore space is filled with hydrocarbons, hydrocarbon saturations for Sandstone A were calculated using $1\text{-}S_W$. The calculated hydrocarbon saturations of Sandstone A were averaged by well and contoured to generate Figure 11. In the study area, there were another 92 wells that penetrated Sandstone A, but these wells either did not have a density porosity log or the density porosity log was unreliable due to hole instability indicated by the caliper log.

Interpretations and Discussion

Utilizing the Archie equation, Sandstone A appears to be hydrocarbon charged (S_W averages <50%) across most of western-northwestern North Dakota (Fig. 11). Assuming the overlying Icebox Formation is the source rock interval, and lateral hydrocarbon migration is minimal due to overall low permeability within the reservoir (averages ~0.3 millidarcies), the entire Garland section should be hydrocarbon charged wherever Sandstone A is charged. The high quartz sand content of the Garland Member likely enhances its ability to take on a hydrocarbon charge.

The hydrocarbon saturations displayed in Figure 11 should be viewed cautiously for several reasons. First, there is limited core data away from structure to validate the low calculated water saturations. Second, factors such as changes in bioturbation grade, shale content, and variations in cementation likely occur within Sandstone A across the study area, causing some variation in the accuracy of Archie



* - Data retrieved from a Water Analysis Report (Oil & Gas well file)

** - Data retrieved from a Oil & Gas hearing field file

Figure 6. Map showing information on the Total Dissolved Solids (TDS) content and resistivity (Rw) of formation water collected from the Black Island Formation. Structure contours depict the top of the Icebox Formation. DST = Drill Stem Test

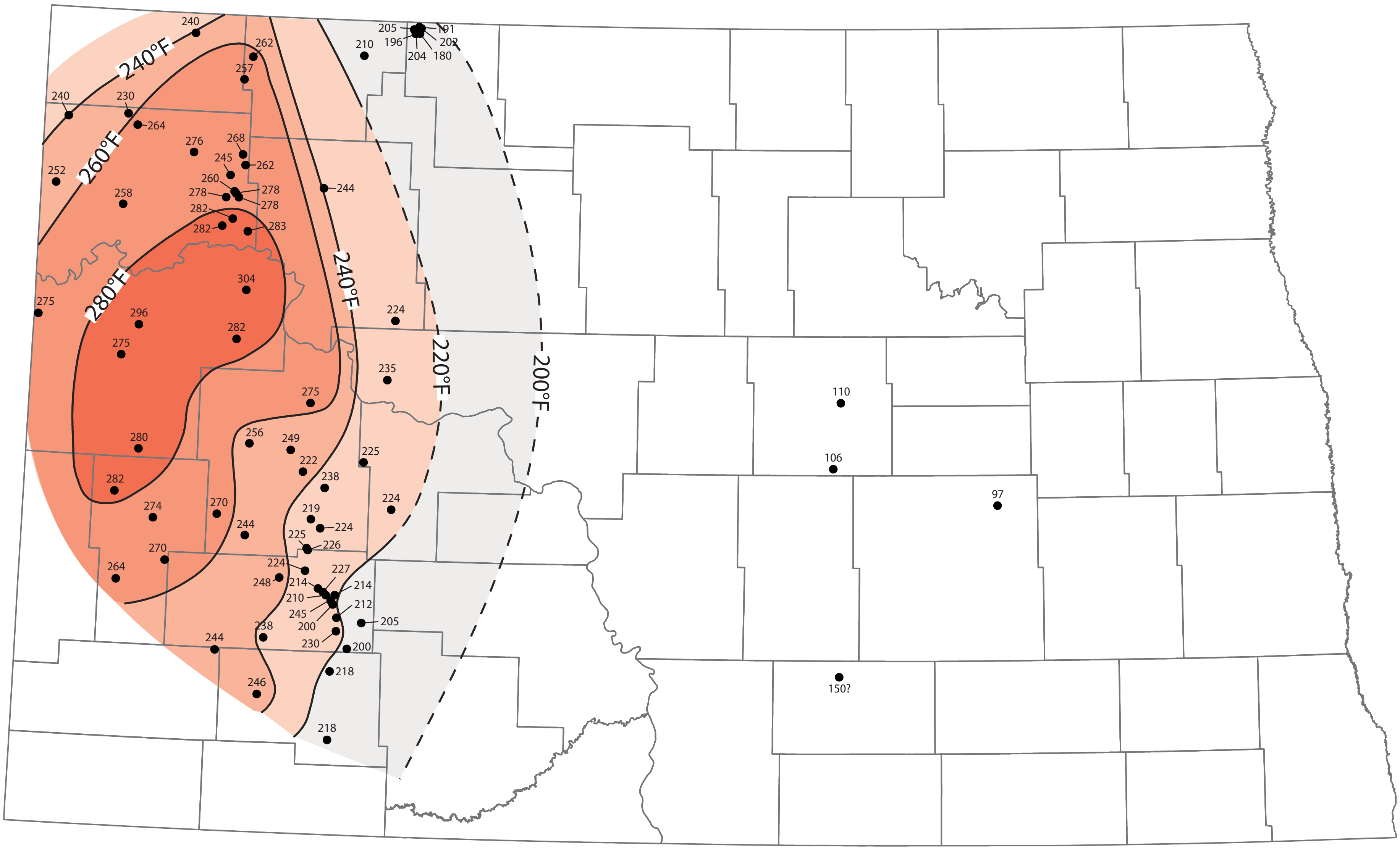


Figure 7. Formation temperature map of the Black Island Formation. The contours displayed are meant to generalize the formation temperatures of the Black Island Formation and are based off of bottom hole temperatures (BHT) measured during Black Island drill stem tests (DST's). BHT's measured during DST's are typically assumed to represent minimum formation temperatures. Black dots show control wells with the BHT listed next to each respective well. Some of the DST's used above tested both the Black Island and the upper Deadwood Formations.

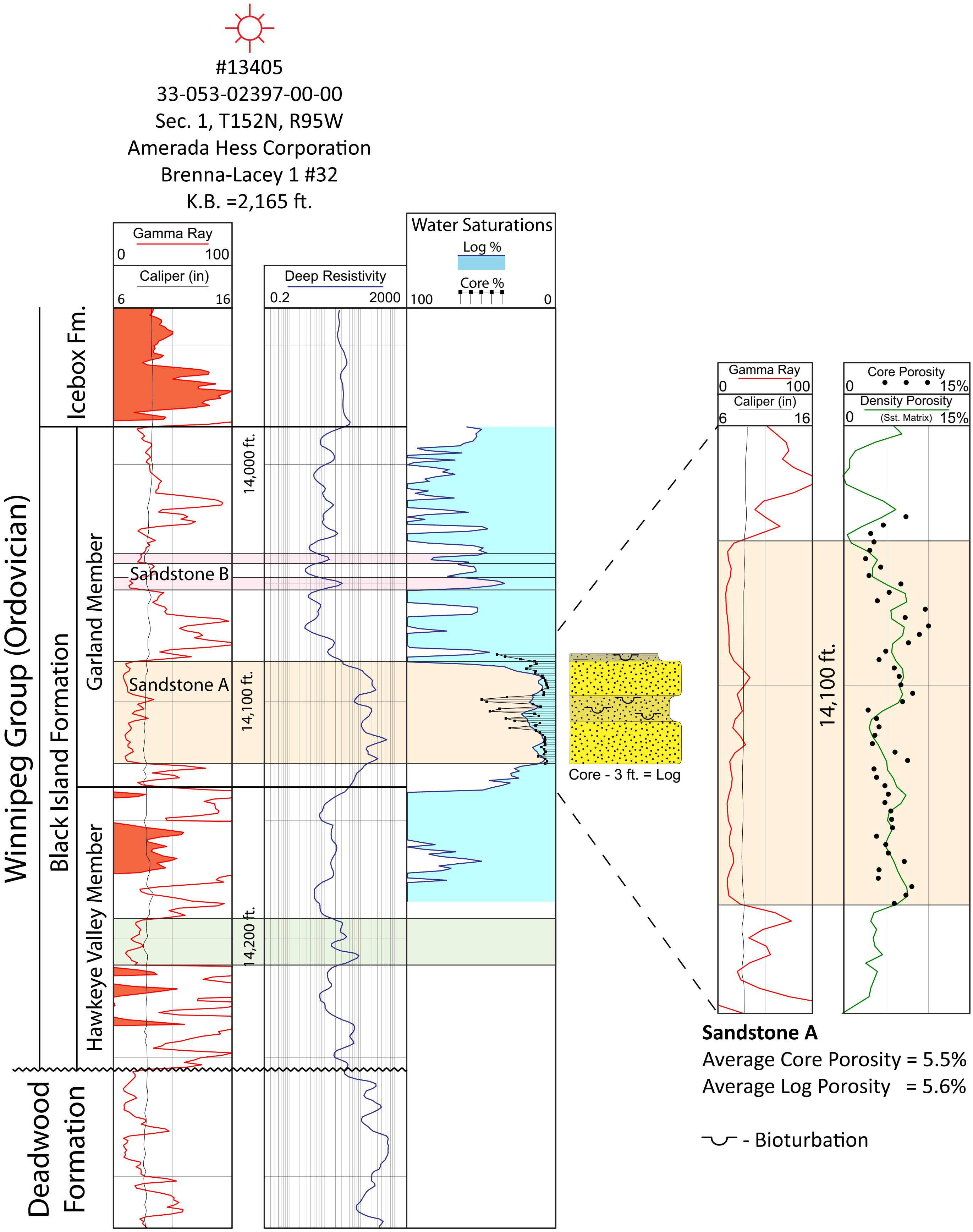


Figure 8. Wireline log of the Black Island Formation from Amerada Hess's Brenna-Lacey 1 #32 comparing core measured and log calculated water saturation (left) as well as core and log porosity (right). Note how well the core and log water saturations overlap for the clean, non-bioturbated sandstone intervals identified in core within Sandstone A but tend to vary more in shaly and/or bioturbated intervals. The core and log porosity of any given point along Sand A differs by 0-3% porosity while the overall porosity averages are approximately the same.

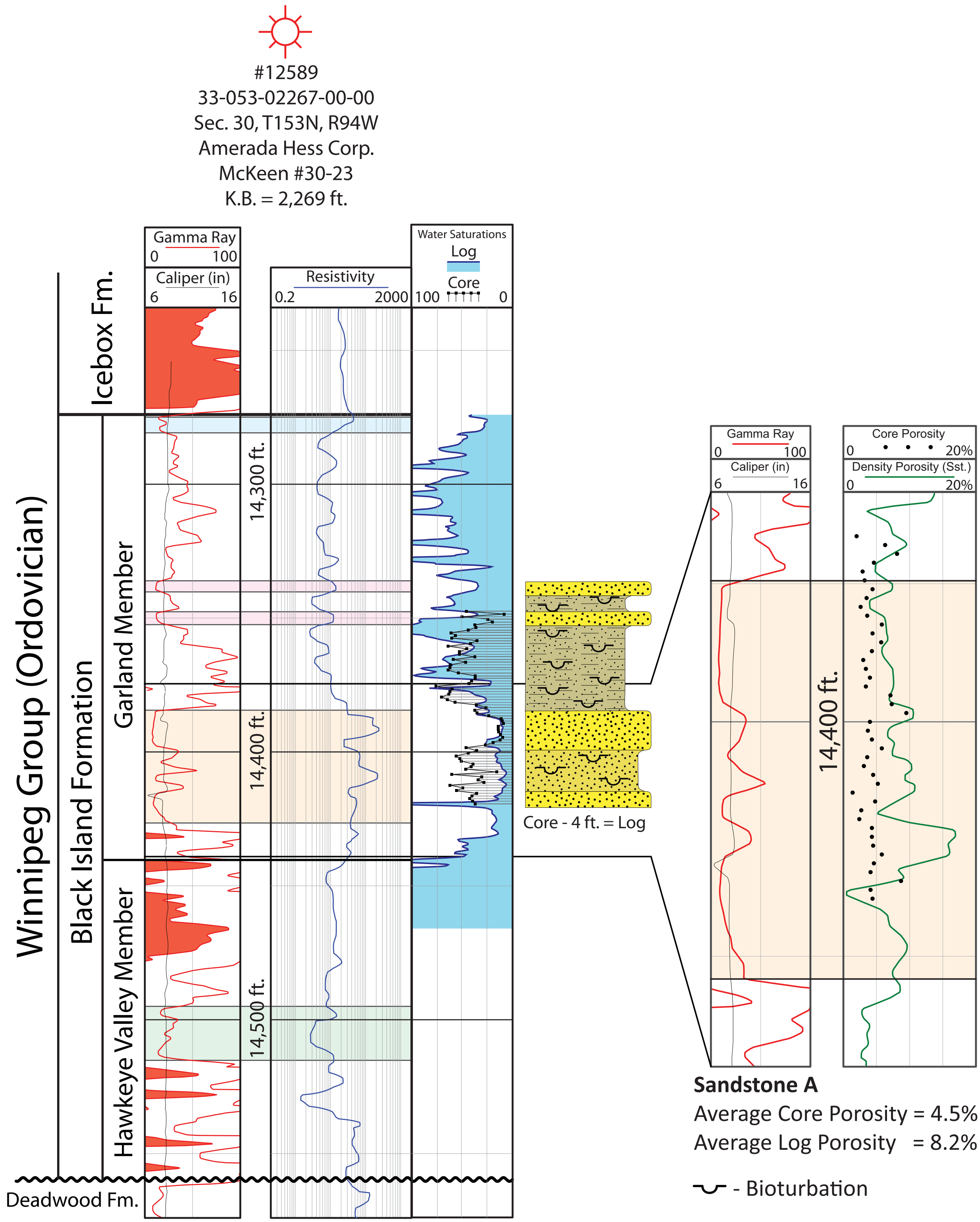


Figure 9. Wireline log of the Black Island Formation from Amerada Hess's McKeen #30-23 comparing core measured and log calculated water saturation (left) as well as core and log porosity (right) of the Garland Member Sandstone A. The core measured porosity values tend to be 2-5% porosity lower than the log porosity curve. The core measured and log calculated water saturations overlap closely for the upper 14 ft. of Sandstone A, where the core and log porosity values trend more closely together.

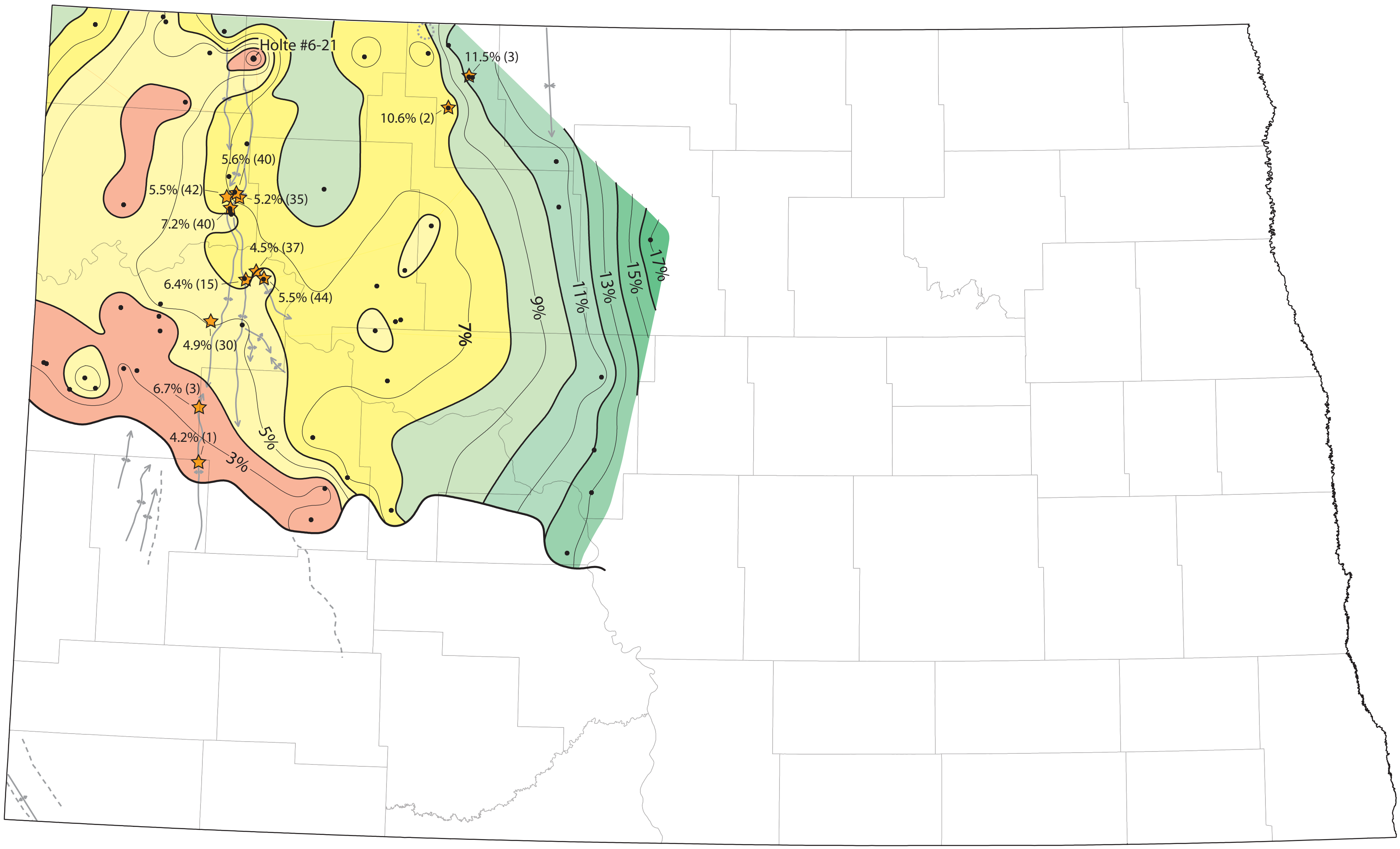


Figure 10. Log (Density Porosity-sandstone matrix) averaged porosity map of Sandstone A"   Black dots show control wells. Orange stars show locations of partial to complete cores of Sandstone A with the average core measured porosity listed and number of core analyzes in paretheses. Note how Sandstone A is more porous east of the Nesson Anticline than to the west. Core measured porosity averages are similiar to the log porosity average, but the core averages vary a little more over short distances. The caliper log of each well was examined to determine if the density porosity curve was reliable or not. The intervals in which the borehole diameter notably increased, based on the caliper log, were removed from the density porosity average.

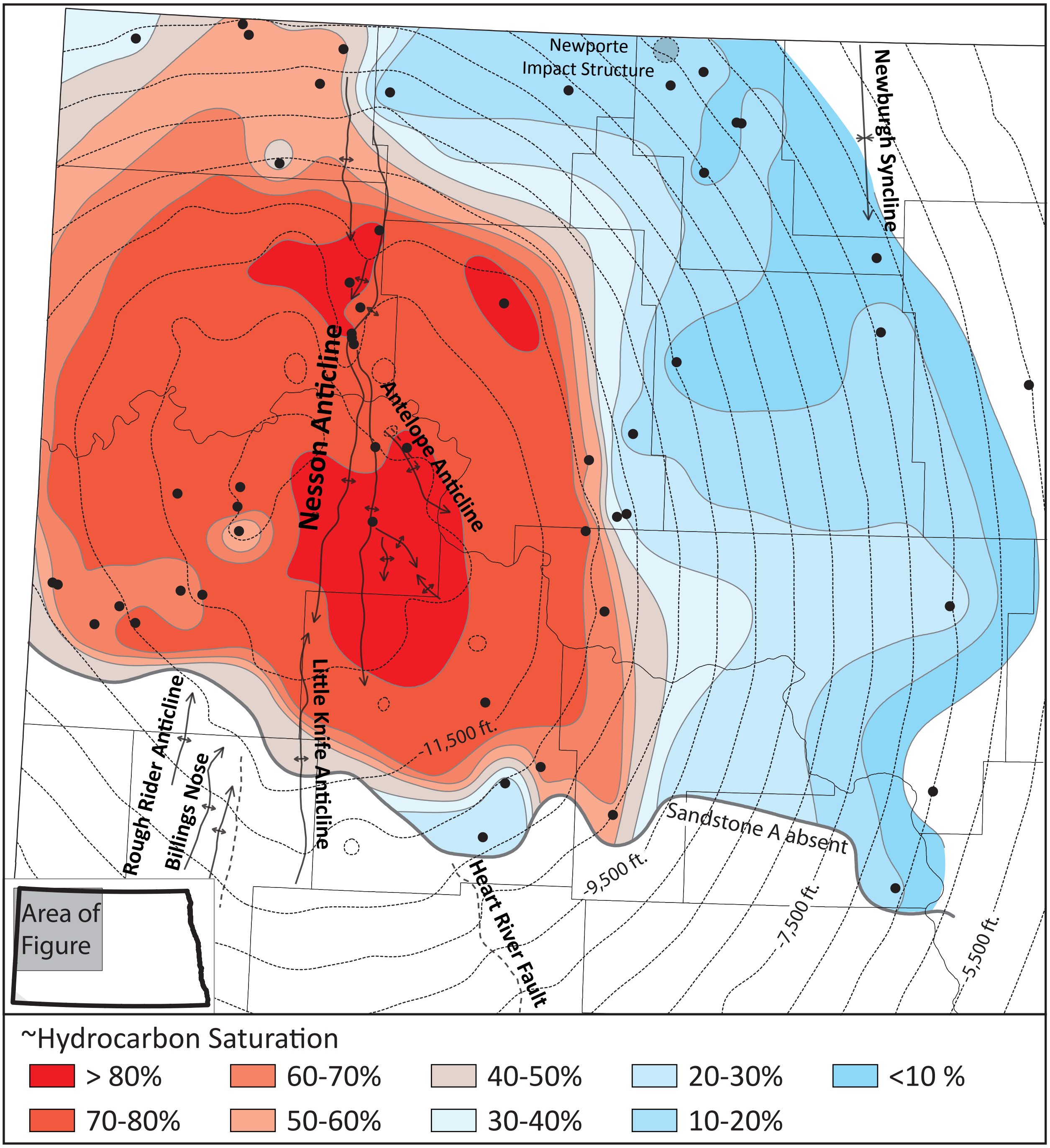


Figure 11. Hydrocarbon saturation map for Sandstone A of the Garland Member (upper Black Island Formation). Contours were initially generated using the map module in Petra and before being modified manually. The dotted lines depict structure contours on the Black Island Formation surface.

Equation calculations. For example, shale content increases an intervals electrical conductivity, which artificially increases the calculated water saturation. Third, non-hydrocarbon gases such as carbon dioxide and nitrogen make up 3-32% of gas produced from Black Island vertical completions across western North Dakota (Nesheim, 2012), and therefore occupy some of the non-water filled pore space within Sandstone A. Across the Nesson and Antelope Anticlines, analyzed Black Island gases have averaged approximately 83.1% methane, 10.8% nitrogen, 3.5% carbon dioxide, 1.4% ethane, and 0.2% propane.

The Sandstone A hydrocarbon charged area correlates well with where the overlying Icebox Formation has been modeled to be near its maximum thermal maturation (Fig. 12). Geochemical data from Icebox samples from southern Saskatchewan (compiled from Osadetz et al., 1992 & Siebel, 2002) average as a good quality source (~1-2% TOC), supporting the idea that the Icebox has sourced the Black Island's hydrocarbons. Sandstone A is located 60-100 ft. below the base of the Icebox throughout most of western North Dakota (Fig. 1, Plate 1 A-A' & B-B'). Therefore, in order to expel enough hydrocarbon volume to adequately charge the underlying Black Island reservoir to include Sandstone A, the Icebox Formation likely needs to be near its peak thermal maturity.

Two anomalous regions of higher water saturation in Sandstone A occur within the area of peak Icebox maturation ($\geq$95% kerogen conversion). Along the southern extent of Sandstone A, calculated water saturations increase to upwards of 75% (Fig. 11 & 12). This southern area, however, is where Sandstone A thins and pinches out (Fig. 2), possibly grading into shaly, bioturbated sandstone. The thinning of Sandstone A along with a possible increase in the reservoir's heterogeneity (bioturbation) and shale content likely both diminishes the reservoir quality of Sandstone A and the accuracy of the Archie Equation. The second anomalous area is located in northwestern North Dakota along the Canadian border (Fig. 11 and 12). Within Jordan Exploration's Holte #6-21 (NDIC: 15137, SENW Sec. 21, T162N, R94W), located in western Burke County (Fig. 10 & 12), Sandstone A's log porosity is anomalously low with an average of only 1.7%. The surrounding wells average 4-8% log porosity for Sandstone A. So either the log porosity of Sandstone A from the Holte #6-21 is inaccurate, making the log calculation inaccurate, or the well was drilled within a zone of extremely low porosity where Sandstone A was unable to take on a significant hydrocarbon charge.

The hydrocarbon potential of the Black Island Formation is not limited to just gas. While Winnipeg (Black Island) production has consisted of wet to dry gas in North Dakota to date, Winnipeg production in southern Saskatchewan has yielded primarily oil (Nesheim, 2012). Geochemical data reported by Siebel (2002) indicates the Icebox Formation contains Type I to Type II kerogen, which is prone to generating oil. With an oil-prone source rock, the hydrocarbon content of the Black Island reservoir likely contains separate dry gas, wet gas, and oil windows depending on the level of maturation of the system. Therefore, oil production from the Black Island Formation is possible at depths shallower than current production in North Dakota.

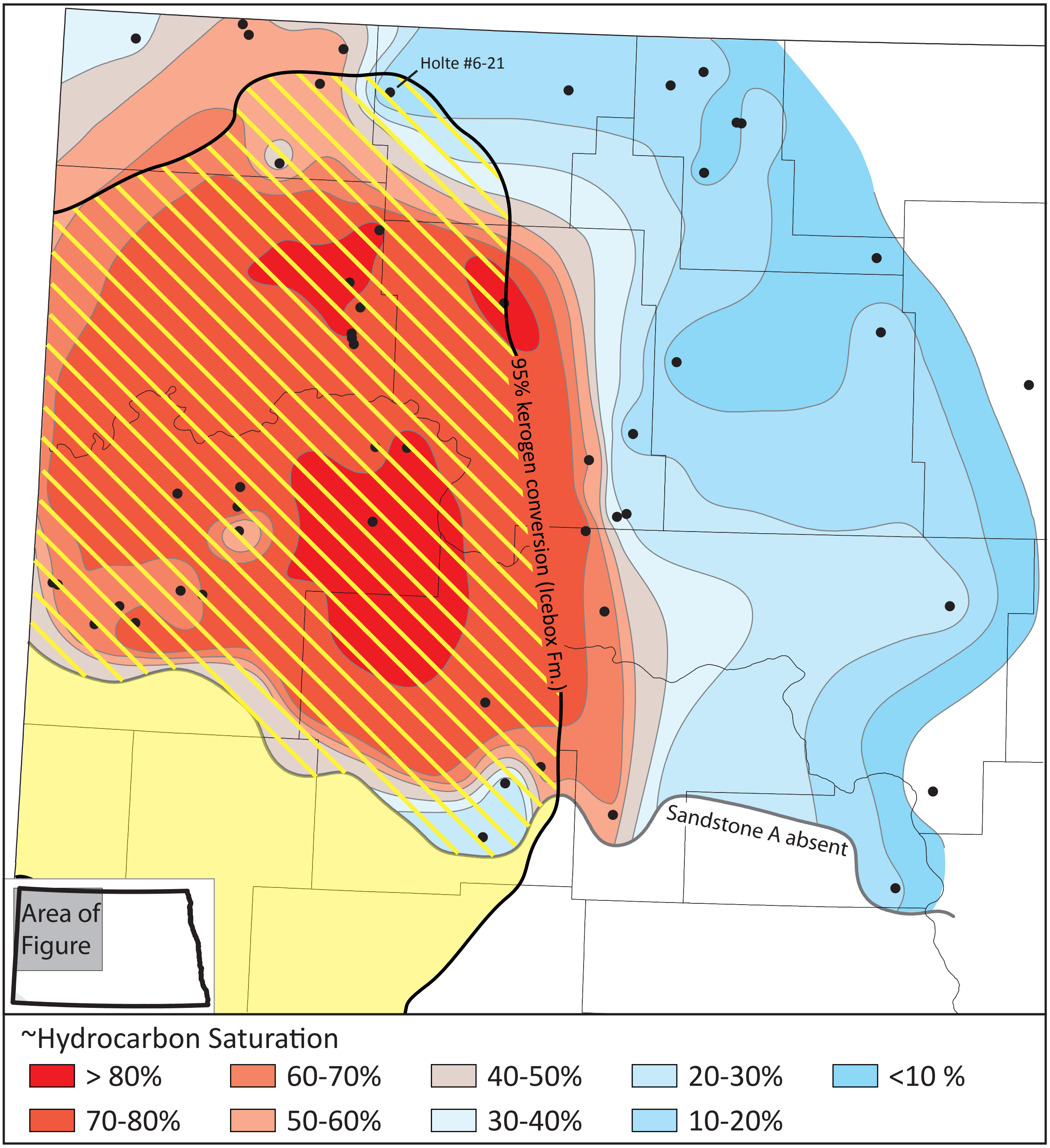


Figure 12. Hydrocarbon saturation map for Sandstone A overlain by the model area of 95% conversion of Icebox kerogen to hydrocarbons (Nesheim and Nordeng, 2013).

Conclusions

The Garland Member (upper Black Island Formation) contains three regionally extensive clean sandstone intervals: Sandstones A, B, and C. In the deeper portions of the Williston Basin, these clean sandstone intervals display high resistivity and neutron porosity crossover signatures indicating significant gas presence. Based on core analysis data, Sandstones A-C average 5-6% porosity, ~0.3 millidarcies permeability, and 10-20% water saturation, indicating they may represent a series of tight gas reservoirs. Using the Archie Equation, the lower most clean sandstone interval, Sandstone A, appears to average ≥60% hydrocarbon saturation in most of western-northwestern North Dakota which suggests the entire Garland section is hydrocarbon charged. The area where Sandstone A appears to be hydrocarbon charged correlates well with where the overlying Icebox Formation has been modeled to be near peak thermally maturity. Based on the Icebox's type I-II oil prone kerogen, and the observed Winnipeg oil production in southern Saskatchewan, the Black Island Formation may transition from a gas to an oil play in portions of North Dakota.

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