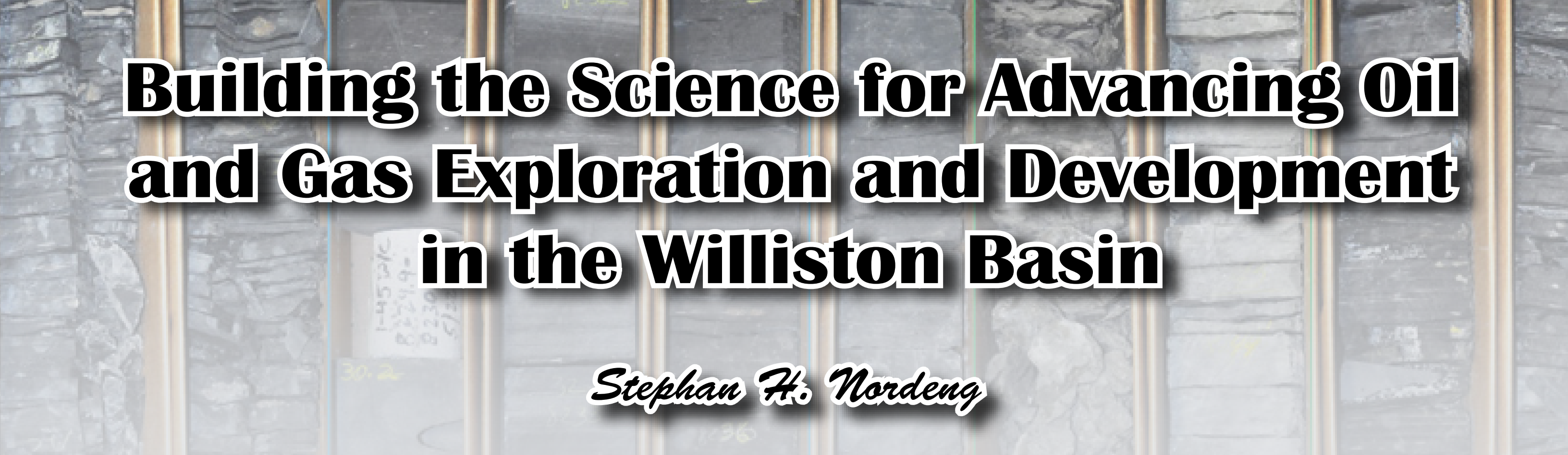

Building the Science for Advancing Oil and Gas Exploration and Development in the Williston Basin

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Oil and gas development within the Bakken source system illustrates a revolutionary change in how petroleum explorationists hunt for new resources. Production from the Bakken is attributed to a combination of factors that include things like the climate and geography of North Dakota 350 million years ago as well as the geological processes that have, over the intervening years, buried the organic matter contained within the Bakken to depths at which high temperatures are capable of converting the hydrocarbons preserved as solid kerogen into liquid and gaseous hydrocarbons. During hydrocarbon generation, petroleum is expelled from kerogen-bearing shale into very poorly permeable rocks that lie above, below and between the oil-generating source beds. Because the rocks that encase the oil-generating source beds are almost impermeable, the expelled oil must physically "push" pre-existing water from the pore space of these rocks. The force required to do this causes significantly increased fluid pressures in the source beds and neighboring reservoirs. It is the presence of these abnormally high fluid pressures, caused by oil generation and expulsion, that permits substantial oil and, to a lesser degree, gas production to be obtained from the horizontally drilled and hydraulically stimulated reservoirs surrounding the Bakken source rocks. Understanding the processes that cause overpressurized reservoirs may provide insights that can be used to explore for other similar petroleum accumulations.

At its simplest level, petroleum accumulations within the Bakken owe their existence to the interaction of two processes. The first involves the generation of petroleum from organic-rich source beds. Fundamentally, this is a chemical process in which the rate of petroleum generation depends upon the chemistry of the organic matter involved, and temperature. The second process, permeability, involves the ease with which fluids migrate through rocks. Permeability is controlled by a variety of things including the size, shape, and interconnectedness of the pore space present in the reservoir rock next to the petroleum-generating source beds. In general, well-connected, large pores resist the flow of fluids much less than microscopic and poorly connected pore space. Most traditional oil and gas exploration efforts sought out highly permeable reservoirs. However, resource plays such as the Bakken not only contain poorly permeable reservoirs but it is the poor permeability of the reservoirs that assist in forming the accumulation in the first place. The reason for this is that even at temperatures beyond the boiling point of water (212°F, 100°C) the decomposition of solid organic matter into petroleum is very slow. Therefore, if the rock that surrounds the source bed is too permeable then little, if any, pressure is needed for newly formed oil to migrate through the bounding rock and escape. However, if the rocks next to the source bed are sufficiently impermeable then the expulsion of even a small amount of generated oil will be resisted resulting in increased fluid pressures within the reservoir. Overpressures characteristic of these accumulations arise when oil generation rates exceed the rate that oil is capable of freely migrating through the surrounding water-saturated pore space. The oil generation component is controlled by chemical kinetics and the migration component is a physical property of the reservoir and fluids (oil, gas and water) involved.

In an effort to better understand the key processes, the North Dakota Geological Survey is conducting research into two fundamental components that control oil generation rates in source beds. Because oil generation rates are related to chemical reactions that occur in organic matter, these studies are focused on defining the relevant physical and chemical properties of the petroleum generating systems within the Williston Basin. These include the chemical properties of source bed kerogen (preserved organic solids) and the physical properties of the stratigraphic section that controls subsurface temperatures.

Following deposition at Earth's surface and preservation during burial, organic matter undergoes a series of chemical reactions that result in the formation of kerogen. With additional burial and higher temperatures, kerogen begins to decompose into oil and/or gas. At even higher temperatures oil decomposes further into gas. Throughout this process, chemical changes within the kerogen produce new products, such as more "mature" kerogen, oil and gas, in which each step requires application of more heat before further chemical changes can occur. This increasing heat requirement is referred to as the activation energy (E_a) which acts as a barrier that must be overcome before organic matter can chemically evolve. This is important because as kerogen matures up to and through the point of oil generation, activation energies continuously increase. This correspondence between increasing organic maturation and activation energy is directly linked to the petroleum-generating process.

The relationship between oil generation rates and chemical properties driven by temperature are related through the Arrhenius Equation:

$$k = A\,e^{-Ea/RT}$$

In this expression the chemical nature of kerogen is described by the activation energy and frequency factor (A). These two terms numerically represent a process in which, for a fixed period of time, there are a number of "attempts" (given by A) for a small amount of kerogen to convert to petroleum. The number of these attempts that succeed is determined by the temperature (T) and the activation energy (E_a). The Arrhenius equation predicts that higher activation energies will be, at the same temperature, associated with slower reaction rates while higher temperatures will be associated with, for the same activation energy, higher reaction rates.

The Arrhenius equation provides a way for combining the kinetic properties of kerogen (different E_a and to a much lesser degree A) with temperature that defines a reaction rate constant (k) that bears directly on how fast petroleum may be generated. This can be done using experiments to determine the kinetic properties of the kerogen (E_a and A) which together with the current formation temperature of the source bed can be used to estimate the current petroleum generation potential. Multiplying the reaction rate by the amount of hydrocarbon-generating carbon that is present in the source bed provides an estimate as to the mass/volume of petroleum that is generated per unit time. This is important because without a continuous input of additional petroleum, overpressures that are instrumental to the formation of Bakken-like accumulations could dissipate through time. Therefore, evaluating the current oil generation rate of a given source bed could be used to better define the limits of current resource plays as well as aid in the search for new resources. The NDGS is currently engaged in studies to characterize the kinetic properties of potential source beds and to better our ability to predict subsurface temperature.

Kinetics

The study of chemical kinetics involves measuring how chemical reaction rates change when experimental temperatures change. Determining the kinetic behavior of oil-generating kerogen can be challenging. This is because petroleum forms at infinitesimally small rates at the subsurface temperatures that drive petroleum generating chemical reactions. Obtaining measurable reaction rates requires temperatures that are at least three to four hundred degrees Celsius higher than the temperatures associated with natural oil generation. Furthermore, most of the commonly employed experimental methods use source rock samples that are dry. Because these experiments do not account for source rock - kerogen - water interactions that could alter the kinetic parameters sought, questions arise concerning the applicability of the results. Another issue with these methods is the fact that small temperature measurement errors generate significantly different kinetic parameters.

Determining the Kinetic Properties of Kerogen

The chemical reaction rate that describes how fast solid organic matter (kerogen) decomposes into oil and/or gas is defined by an activation energy or energies and a frequency factor. These variables can be obtained from laboratory pyrolysis experiments in which small samples are subjected to constantly increasing temperatures while a recording device measures the temperature and corresponding mass of hydrocarbons that are released. When several different heating rates are used, the temperature that corresponds with the maximum amount of hydrocarbon generation (T_p) shifts depending upon the activation energy (E_a) and frequency factor (A) (see fig. 1 for an example).

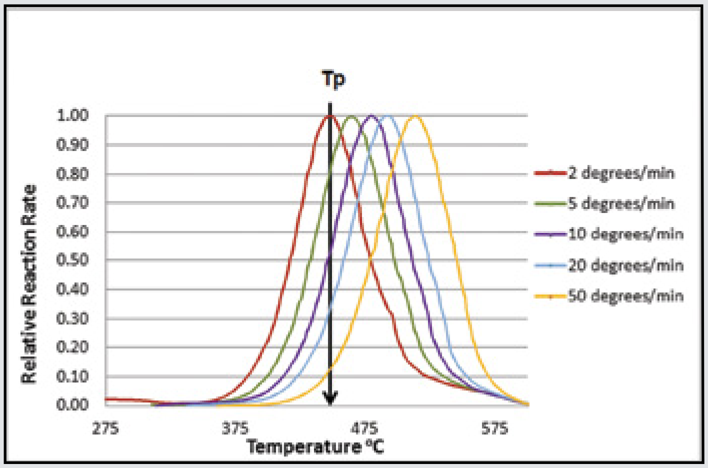

Figure 1. Pyrograms illustrating the shift to higher maximum reaction rate temperatures (T_p) as the heating rate (β) increases. The pyrograms are from a sample of the Bakken Formation collected from the Federal DG-1; API # 33-053-01536-00-00, SE¼SE¼, sec. 34, T. 145 N., R. 100 W. (from Nordeng, 2012).

As a result these variables can be determined by plotting the peak temperature (as $1/T_p$) against a function of heating rate (β) and peak temperature (i.e. figs. 2 and 3). When experimental data is so plotted the results form a straight line from which the activation energy and frequency factor are obtained. Unfortunately this

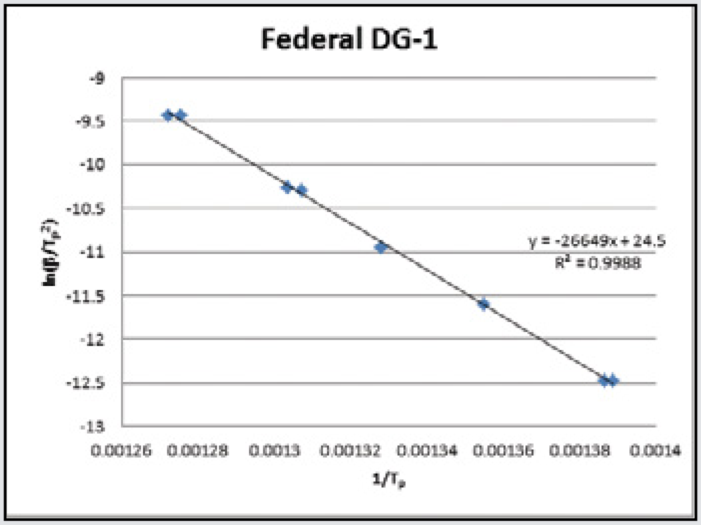

Figure 2. Peak reaction rate temperatures (T_p) and corresponding heating rates (β) plotted in accordance with the Kissinger method (Kissinger, 1957). The slope and intercept of a linear regression is used to find the activation energy (E_a) and frequency factor (A). In this example, the activation energy is 209 kJ/mole and the frequency factor is 5.3 x 10^{14} min^{-1} (see Nordeng, 2012 for details).

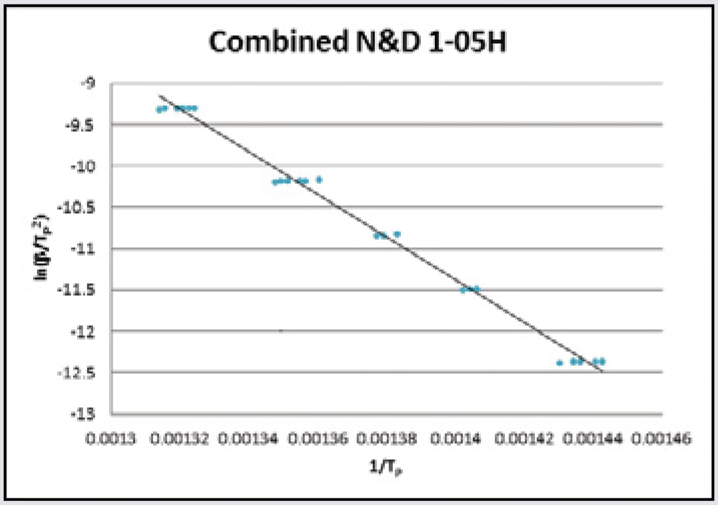

Figure 3. A Kissinger plot showing the variation in experimental results for five source bed samples from the Bakken Formation in the N&D 1-05H.

method is very sensitive to small errors in temperature. These errors translate into compensating errors in both the activation energy and frequency factor. Frequently these errors are quite significant and in some cases result in physically impossible answers (Waples, 2013). In spite of these difficulties, this type of data can be corrected to obtain useful kinetic parameters. This is possible because temperature errors cause a linear variation between activation energy and the natural logarithm of the frequency factor (fig. 4). Making use of the error induced "line" provides a way to correct or at least standardize kinetic data obtained from these pyrolysis experiments. This is accomplished by noting that, from a theoretical perspective, the frequency factor is essentially a constant value. The measured activation energies can be corrected by matching it to the best-fitting error line that corresponds to a given activation energy and a fixed, theoretically reasonable, frequency factor (see fig. 4). When this is done the variation in activation energies is significantly reduced.

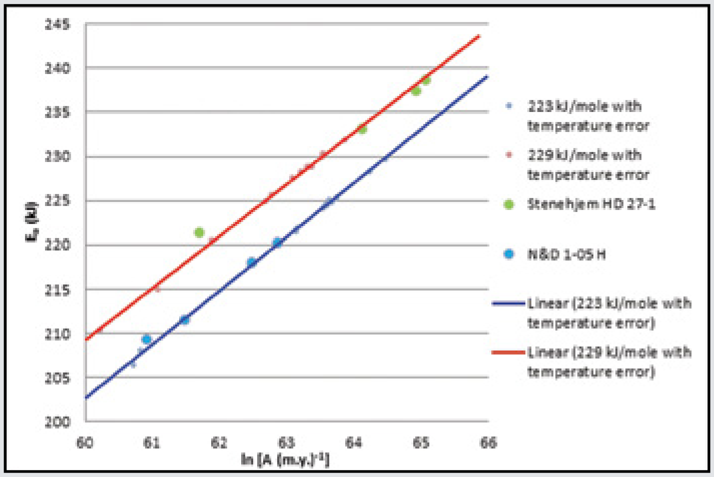

Figure 4. The small pink and purple data points show the "compensation" effect that arises when Kissinger plots contain 2 to 10 °C of normally distributed error in the determination of peak reaction temperature (T_p). These points were generated using a "virtual" kerogen that has a frequency factor of 1 X 10^{14} (sec^{-1}) and an activation energy of either 223 kJ/mole (pink points) or 229 kJ/mole (purple points). Experimentally determined activation energy (E_a) and frequency factors (A) from the Stenehjem HD 27 1; API# 33-053-02357-00-00, NE¼SE¼, sec. 27, T. 150 N., R. 97 W. (larger green points) and N&D 1-05 H; API# 33-061-00521-00-00, sec. 5, T. 152 N., R. 90 W. (larger blue points) are included for comparison.

Temperature

The NDGS is currently developing a program to map the heat flow within the Williston Basin. The primary impetus for this project is the realization that accurate estimates of subsurface temperatures are needed before any estimate of oil generation rates can be made.

The flow of heat from the interior of Earth to the surface is one of the fundamental contributors to planetary plate tectonic processes that cause continents to move and Earth's surface to warp into mountain ranges and depositional basins (Roy et al., 1972). Much of the heat sourced from the deeply buried core and surrounding mantle is distributed in a relatively uniform fashion across Earth's surface. However, locally important variations in heat flow exist within the upper few miles of Earth's crust. These localized heat anomalies, on the scale of tens of miles across, are caused by the decay of naturally occurring radioactive elements that are unevenly distributed throughout the igneous and metamorphic rocks that form Earth's outer crust beneath the thin veneer of sedimentary rocks near the surface. It is the flow of heat and the resulting subsurface temperatures that play important roles that influence exploration, stimulation and completion of oil and gas wells as well as defining the basic resource that is exploited by geothermal energy systems. Understanding the distribution of heat in the subsurface is important, and because the variation in heat flow occurs over large areas, a broad regional approach is needed in mapping out this resource. Furthermore the change in temperature that accompanies this flow of heat is not a simple linear function of depth. Even though it is common practice to assume that temperatures increase at a constant rate with depth, the measured temperatures in figure 6 show that this is clearly not appropriate. A more accurate approach takes into account the temperature changes that occur when heat flows through a sedimentary section consisting of rocks with varying thermal properties.

Existing heat flow maps (fig. 5) all suffer from the fact that the basic data, temperature and depth, are rarely measured in wells that have achieved thermal equilibrium with the surrounding rock. Because of this, potential errors in temperature-depth measurements could translate into significant errors in heat and estimates of subsurface temperatures. To test and, where warranted, correct the current set of heat flow maps the NDGS plans to measure temperature profiles from wells distributed across the Williston Basin in North Dakota.

A detailed basin-scale map of heat flow within the Williston Basin will require a large number of temperature profiles. Based on a preliminary evaluation of the project, the collection of temperature data will be split into two phases. The first phase is designed to provide a coarse regional grid of temperature profiles that will serve as thermal stratigraphic “type” sections distributed over as wide a geographic area as possible. The reason for this is to provide baseline calibration data that will be used to determine heat flow from additional infill temperature profiles that log only the upper portion of the stratigraphic section (< 5,000 ft, 1,520 m).

The purpose of the first phase study is to run temperature logs on twelve or so deep (> 9,000 ft, 2,740 m) wells that can be reasonably assumed to be at thermal equilibrium. From a logistics and operations standpoint the wells that are most likely to provide “easy” access and accurate equilibrium temperature profiles are those that have been temporarily abandoned (TA) and completely inactive for three months or more. Approximately 364 wells are currently listed as temporarily abandoned (TA) wells. To facilitate logging, only those temporarily abandoned wells in which all production tubing and rods have been removed will be considered. Twenty-two of the 364 temporarily abandoned wells have been identified as either having no tubing installed or the tubing extends deep enough so that a sufficiently long temperatures profile may be measured from within the tubing. In order to obtain precise temperature data calibration of the temperature probe will be done prior to logging with the temperature profile measured as the probe is lowered into the well at a rate of approximately 10 feet/minute. Measuring temperatures while slowly lowering the tool will minimize the amount of water that is mixed by the passing tool and help guarantee accurate temperature measurements (Blackwell, pers. comm.)

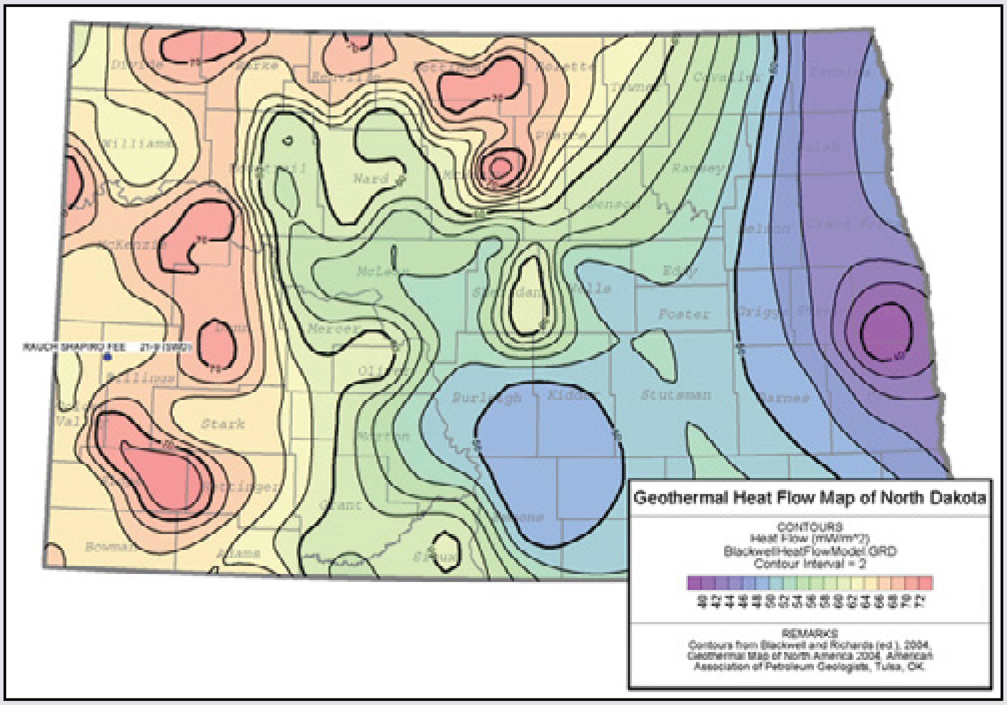

Figure 5. A current map of the conductive heat flow in North Dakota (from Blackwell and Richards, 2004).

The amount of heat flow passing from the crystalline basement into a stack of sedimentary rocks is measured by recording how temperature changes with regard to depth and the types of rock through which heat flows (fig. 6, for example). The following discussion illustrates the relationship between heat flow, subsurface temperatures, and the thermal properties of sedimentary rocks that forms the theoretical underpinning for this study.

Determination of subsurface temperatures within the Rauch Shapiro Fee #21-9

The Rauch Shapiro Fee #21-9 was spudded on June 11, 1980 and reached a total depth of 12,741 feet (3,833 m) on September 7, 1980. Problems with the cementation of the production string resulted in additional cementing operations that ended prior to running a cement bond (CBL) and a temperature log on November 2, 1980. The well was initially completed in the Bakken and Three Forks Formations and had an initial production of 264 bbls. of oil/day. The well was subsequently converted into a salt water disposal well and was plugged and abandoned in August 2008. Even though the example given here is probably one of the best temperature-depth profiles available, it suffers from the fact that the length of time between the end of cementation and logging is unknown. This is important because as cement cures it releases heat. Excess heat increases the temperature around the well bore and because rock acts as an excellent insulator it may take weeks to months for temperatures in the well bore to return to the natural pre-cementation temperature. Therefore, the expectation that the temperatures measured in the Rauch-Shapiro are truly those of the adjacent rock cannot be confidently assumed.

Subsurface temperatures are frequently estimated using Fourier’s law of heat conduction. For a single layer, the following expression predicts that the change in temperature (ΔT) over some thickness (L) is proportional to the ratio between the conductive heat flow (Q) and thermal conductivity of the rock (λ) involved:

Eq. 1 $$\Delta T = Q\,L/\lambda$$

Estimates of the temperature at depth (T_n) are found by adding the temperature changes ($\Delta T_i = QL_i/\lambda_i$) associated with each deeper stratigraphic unit (i=1…n) to the “average” surface temperature (T_o) as follows:

Eq. 2 $$T_n = T_o + Q(\ L_1/\lambda_1 + L_2/\lambda_2 + \dots + L_n/\lambda_n)$$

Where:

Q is the geothermal heat flow (W/m^2)

n is the number of overlying stratigraphic units in the section where i=1…n (the deepest layer)

T_n is the temperature at the base of the nth unit (°C)

T_o is the average surface temperature (°C)

L_i is the thickness of the i^{th} unit (m)

λ_i is the thermal conductivity of the i^{th} layer (W/m K)

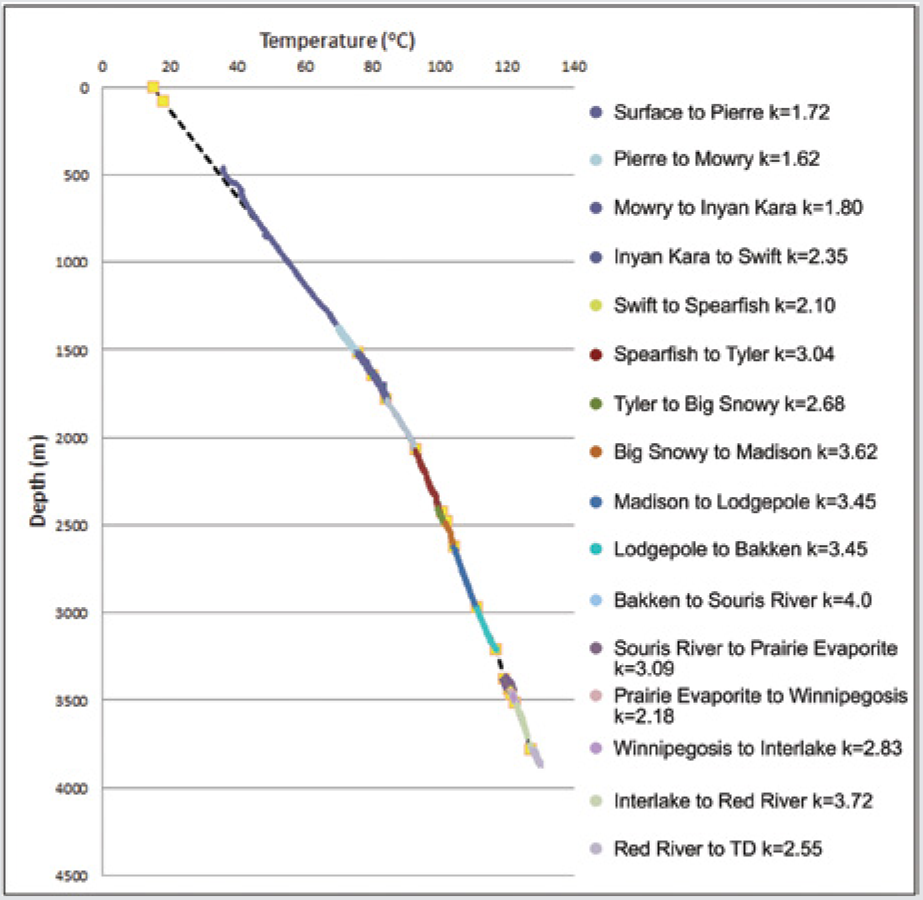

Figure 6. Temperature-Depth profile from the Rauch Shapiro Fee #21-9, API# 33-007-00526-00-00, NE¼NW¼, sec. 9, T. 142 N., R. 102 W., Billings County, North Dakota. The various colored intervals correspond to various stratigraphic intervals. The yellow-filled squares are the predicted temperatures using the thermal conductivities (denoted by k) and a heat flow of 61.5 mW/m^2 (Nordeng and Nesheim, 2011).

Estimating a given formation temperature using Fourier's law requires that the thermal conductivity of each layer together with the conductive heat flow and average surface temperature be known. These values can be found by plotting subsurface temperature against depth. If the temperatures measured are from a section that contains a single thermal conductivity then Fourier's law predicts that the steady state temperature will increase linearly with depth.

The slope of the temperature gradient is a function of the thermal conductivity of the formation and conductive heat flow. Under steady state (constant) heat flow, the slope of the temperature gradient is proportional to the thermal conductivity. Thermally conductive formations have steeper thermal gradients (degrees per foot or meter) than do thermally less conductive formations, with the difference in the temperature gradient being proportional to the difference in thermal conductivity. Therefore, if one knows or assumes an appropriate set of thermal conductivities then it is possible to find a conductive heat flow that can be used to reconstruct an observed temperature profile. An example of this is presented in figure 6 where the calculated temperature, (shown by yellow squares) corresponds well with the observed temperature profile.

The studies detailed here are designed to extend the concepts learned so far from the development of the Bakken Formation. With the Bakken as a guide, the basic science related to the kinetics of potential source beds and increasingly detailed maps of conductive heat flow in the Williston Basin should be valuable in effectively developing the Bakken source system as well as formulating new exploration plays.

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