Temperature Logging in the Williston Basin

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The North Dakota Geological Survey has initiated a temperature logging program in the Williston Basin. Funding for this project has been obtained from the Williston Basin Petroleum Conference and State of North Dakota. We plan to measure temperature profiles in temporarily abandoned wells for the purpose of determining the crustal heat flow at several locales in the Williston Basin. These heat flow values are critical pieces of data that are needed to check and, where needed, update current heat flow maps. Heat flow, together with thermal conductivity values of subsurface rocks, can be used to estimate subsurface temperatures at other locations and depths.

Understanding the thermal history of a basin can result in improved models for use in exploration for oil and natural gas (Prensky, 1992). Insight into the timing of petroleum generation, migration, accumulation and preservation can be gained by determining the thermal maturity of hydrocarbons and/or by using the paleoheat flux of a sedimentary basin (Nuccio and Barker, 1990). Subsurface temperature is important to understanding the origin and evolution of sedimentary basins and can also be used in the determination of important kinetic factors as described by Nordeng and Nesheim (2011) and Nordeng (2012, 2013, 2014), which can ultimately be used to predict the oil generation potential of various geologic formations within the Williston Basin.

A simple example of estimating the depths of oil generation based on differing thermal gradients is presented in figure 1. Oil is typically formed between temperatures of around 150 to 300°F. Three different temperature gradients are plotted on the graph as temperature versus depth. It can be seen that at the higher temperature gradient (35°F/1,000 ft.), 150°F is first reached at a depth of around 4,000 ft. whereas for the lowest temperature gradient shown (18°F/1,000 ft.) it isn't reached until a depth of approximately 8,000 ft. While overly simplistic, the example illustrates how critical it is to have a relatively accurate idea of the thermal gradient.

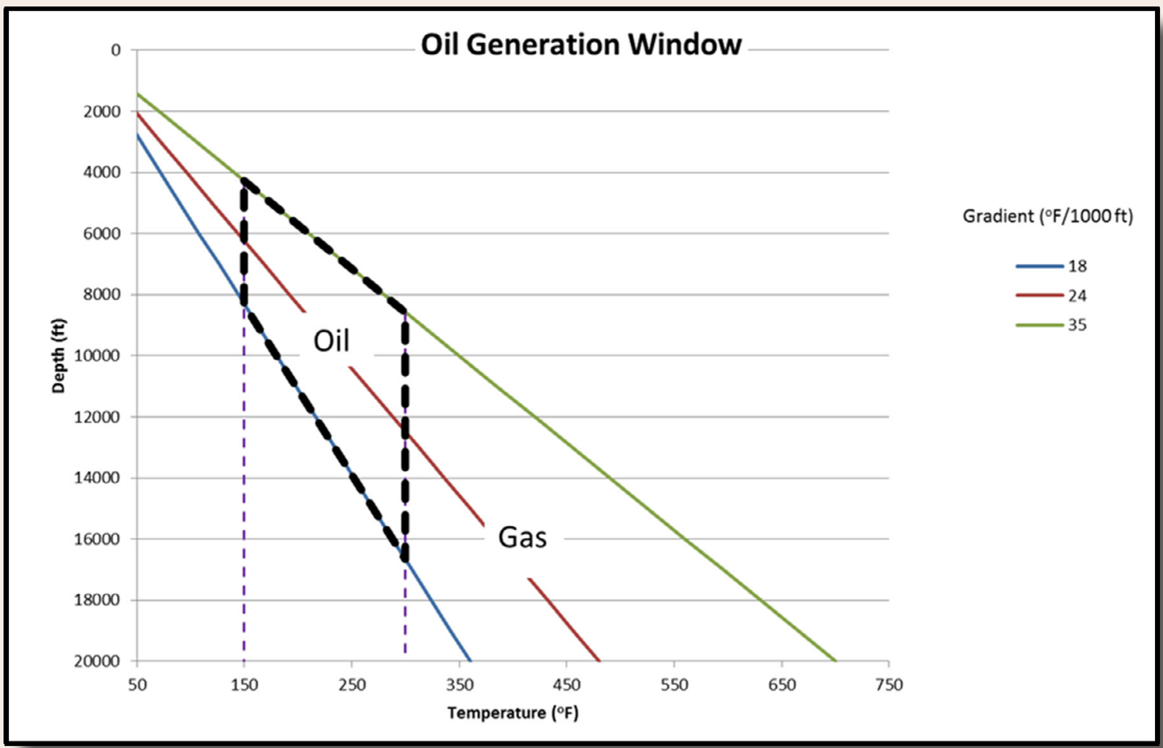

Figure 1. Illustration of the oil generation "window" at various temperature gradients. Assuming that oil is generated at temperatures between 150°F and 300°F, it can be seen that oil will begin forming at much shallower depths for the highest temperature gradient (35°F/1,000 ft.) versus the lowest gradient (18°F/1,000 ft.). The figure assumes a constant thermal conductivity.

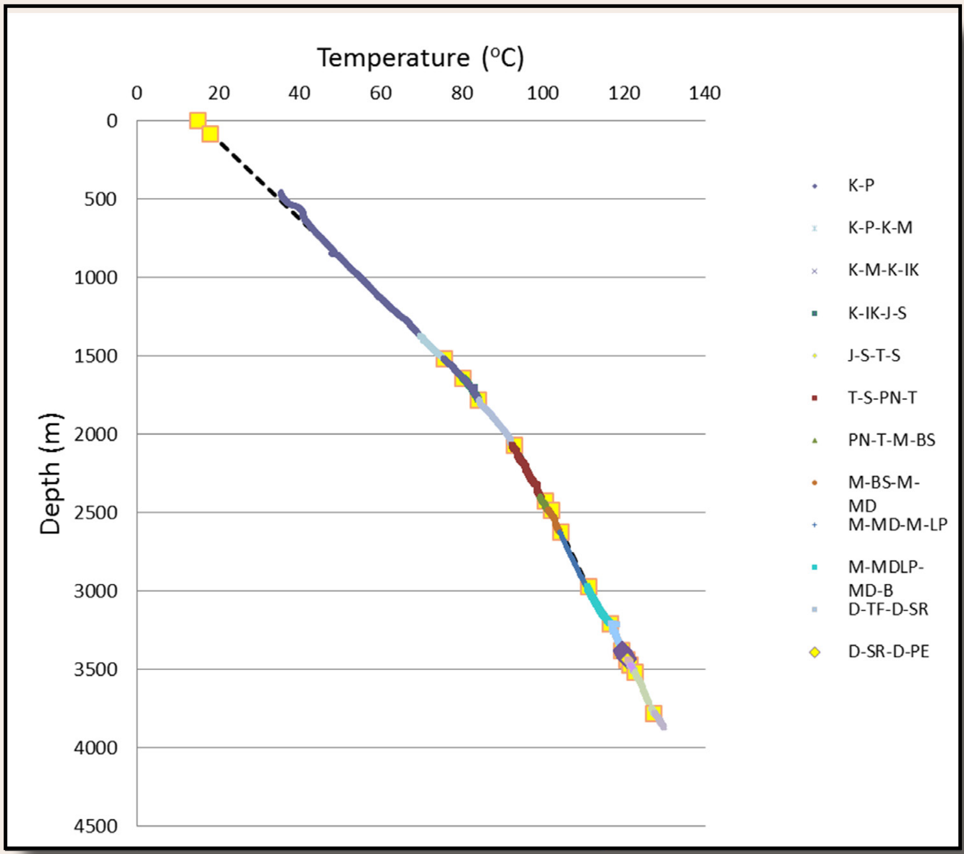

Figure 2. Temperature-depth profile from the Rauch Shapiro Fee #21-9, Billings County, North Dakota. The various colored intervals correspond to various stratigraphic intervals. The yellow-filled squares are the predicted temperatures using thermal conductivities from the literature and direct measurements and a heat flow of 61.5 mW/m^2 (from Nordeng et al., 2011 and Gosnold et al., 2012). Notice that the slope (gradient) changes for the various intervals due to differing thermal conductivities.

So how do we determine the gradient? In the example illustrated in figure 1, the gradients are shown as simply linear relationships of temperature versus depth. Thus, if we knew the temperature at a few depths, we could draw a best-fitting line through those points and obtain our gradient by determining the slope of the line. Unfortunately, it is not quite this simple. In reality, the gradients will change depending upon certain properties of the layers of rock (geologic formations) that heat is travelling through. Specifically, different rock types have different values of thermal conductivity. Thermal conductivity is simply the ease with which heat will travel through an object and different materials have different values of thermal conductivity. For example, if you pour hot coffee into a metal cup and then into a ceramic mug, the outside of the metal cup will heat up much more rapidly than the ceramic one (i.e. it has a higher thermal conductivity). An example of how the gradient is affected by changes in thermal conductivity is shown in figure 2.

The relationship between heat-flow, thermal conductivity, and temperature gradient can be expressed by Fourier's Law:

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

Where: Q = conductive heat flow

λ = thermal conductivity

$\Delta T/\Delta Z$ = temperature gradient (change of temperature over change in depth)

As presented in Nordeng (2014), this equation can be re-arranged as:

Eq. 2: $\Delta T = Q \, \Delta Z/\lambda$

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

Eq. 3: $T_n = T_o + Q\,(Z_1/\lambda_1 + Z_2/\lambda_2 + \ldots + Z_n/\lambda_n)$

Where:

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

T_n = the temperature at the base of the nth unit

T_o = the average surface temperature

Z_i = the thickness of the ith unit

λ_i = the thermal conductivity of the ith layer

Thus, to calculate the temperature at any point, we need to know the average surface temperature (can be obtained from historical weather station data), the thickness of the units (can be obtained from well logs), the thermal conductivities of the formations (can be obtained from the literature or direct measurements, e.g. Gosnold et al., 2012), and the conductive heat flow for the area (obtained from current heat flow maps such as Blackwell and Richards, 2004). As we have a lot of data on the average surface temperature and thicknesses of the formations across the basin, the biggest sources of error are caused by using imprecise thermal conductivities or by assuming incorrect values of heat flow as current maps are based on a relatively small number of data points.

Obviously, the temperature at any depth can be measured directly by logging the wells, but one of our goals is to be able to estimate the temperatures at any point in the Williston Basin without having to expend the time and resources to physically log a well at a given locality. The temperature logging profiles that we hope to generate as part of this program will allow us to obtain better estimates of heat flow across the basin by using Equation 1, thereby reducing potential errors at other locations. In addition, if we have better heat flow values we can, by comparing observed versus predicted temperature profiles, "tweak" the thermal conductivity values for each formation such that the observed versus predicted profiles are more closely aligned thus improving these values. Ideally, it would be highly beneficial to obtain more laboratory measurements of thermal conductivity values for the various formations.

Subsurface temperatures are routinely collected during logging and drill stem tests performed during drilling or completion activities and the question may arise as to why these values can not be used in lieu of embarking on a new logging program. The issue at hand is that true formation temperatures are rarely recorded because drilling, well completion and production operations can cause significant variations in the wellbore from the actual temperature of the neighboring formation. These temperature differences can persist for days or weeks after drilling or production has ceased. For example, during drilling the circulation of drilling mud can cool the rock formations, during completion operations curing of cement and acidizing are exothermic reactions that can increase temperatures, and during production gas entering the wellbore cools by expansion. In order to confidently obtain accurate subsurface temperatures, care must be taken to assure that the well bore and formation temperature are the same, i.e. that the temperatures have equilibrated. While a number of correction schemes have been derived to account for variations between actual formation temperatures and the measured wellbore temperatures obtained during drilling, or while the well is producing, such as that developed by Cooper and Jones (1959) or the Horner Method (Lachenbruch and Brewer, 1959), the best alternative is to make use of well bores that have been idle for months or, if possible, years so that equilibrated temperatures have been reached. Given these constraints and a review of the pertinent literature, the NDGS has concluded that wells temporarily abandoned and undisturbed for at least three months should easily meet the requirements of this study.

The project will consist of lowering a temperature probe to the bottom of the well (depth of the plug) using conventional well logging tools. After setting the equipment up over a well, a dummy or slug will be lowered into the well to verify that there are no obstructions within the well. A period of time will be allowed to elapse after the dummy has been raised out of the well in order that the well fluid temperatures can re-equilibrate before lowering the logging tools. The wells will be logged as the tool is lowered into the well to minimize temperature disturbance or mixing of the fluids arising from the displacement of fluids by the volume of the tool. Disturbance or mixing is more likely to occur if the tool is lowered to the bottom of the well first and then logged on the way up. Pressure measurements will also be obtained to aid in the correlation of the temperature measurements and depth. Other tools may also be used such as a Casing Collar Locator (CCL) or a Gamma Ray probe, again to aid in correlation of the temperature probe with depth or with the geologic formations. We hope to log 12 or more wells during the summer and fall of 2014 and continue the program over the course of the next few years.

A more ambitious by-product of the program may also be achieved. By using the present heat flow, determining the structure of the basin at past times, its compaction history and the total amount of stretching that the lithosphere has undergone (palinspastic restoration), and combining this information with three-dimensional models of the crust and basin architecture, the thermal history of key sequences might be achieved with reasonable accuracy (Beardsmore and Cull, 2001).

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