Williston Basin Static Temperature Logging Program Continues to Yield Results

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INTRODUCTION

Subsurface temperature measurements have continued to evolve since the first thermometer was developed centuries ago. Measuring subsurface temperatures likely began as a scientific curiosity, but ultimately progressed into a commercial necessity as subsurface mining and petroleum operations required accurate temperature measurements for use in the design and application of subsurface tools. Temperature logs are common in the petroleum industry, but are often collected before the wellbore has time to return to its static temperature due to commercial barriers, resulting in unreliable data. Corrections are often applied to these dynamic logs but, these too, have their limitations. Therefore, static temperature logging, or logging after the productive portion of a well's life cycle and before the permanent abandonment of the well, provides the most accurate temperature measurements. Since 2014, the North Dakota Geological Survey (NDGS) has run temperature logs in 25 wells in the Williston Basin and will continue this program into the foreseeable future.

HISTORY OF TEMPERATURE LOGGING

The first subsurface temperature measurements were made in mine shafts, tunnels, and water wells in the 1700s shortly following the creation of the first thermometers (Jessop, 1990). In the late 1860s, the British Association for the Advancement of Science began systematically using temperature measurements to examine regional geothermal gradients in hopes of reducing temperatures in mines and tunnels to acceptable levels for the labor force (Jessop, 1990). These first measurements were acquired using maximum-reading thermometers and taken at depths up to several hundred feet (Strong, 1933). Ore and coal mining expanded the application of temperature measurements until the latter half of the 1800s when another industry took the lead in the use of temperature logging.

The birth of the petroleum industry in the late 1800s brought many changes to temperature measurements. Electrical-resistance thermometers were developed which increased the accuracy and precision of the temperature measurements. In the 1930s Schlumberger introduced the first continuous temperature survey (Prensky, 1992). Continuous temperature data readings allowed operators to evaluate wellbore temperature anomalies related to completion and production engineering, many techniques of which are still in use.

COMMON APPLICATIONS

Today, the majority of temperature measurements acquired in the petroleum industry are continuous-recorded temperature surveys that are primarily used in engineering (drilling, completions and production) and geology (thermal maturity assessments). The temperature logs produced from these surveys can be used to identify zones that may be either producing formation fluid (kicks) or taking wellbore fluids (losses) as temperature changes (increases or decreases) can provide evidence of cooler drilling mud escaping into the formation or warmer formation fluid flowing into the borehole, for example. If run immediately after a cement job (prior to cement curing), temperature logs can be utilized to evaluate the location of the top of cement or channels within the cement as the curing process is an exothermic reaction (heat release) that is easily identifiable in logs (Prensky, 1992). Temperature logs are also vital in assessing drilling (mud) and completion fluid (acid or frac) composition, as well as in the design of drill bits, drill pipe, casing and logging tools. Production engineering applications include fluid flow (production or injection) assessment. For example, temperature anomalies occur when warmer formation production fluid (oil) flows into a cooler wellbore or, in the case of a gas reservoir, a cooling anomaly is observed as gas is produced which allows the gas to expand and creates an endothermic reaction (heat absorption), known as the Joule-Thompson effect. Temperature surveys are further utilized by geologists when assessing thermal maturity of hydrocarbon source rocks (e.g., Nordeng et al., 2010; Nordeng and Nesheim, 2011; Nordeng and Nesheim, 2012). Although, temperature surveys provide a great deal of data, there are many known errors in these logs.

ACQUIRING AND ANALYZING SUBSURFACE TEMPERATURES

The vast majority of temperature measurements are taken during drilling operations (measured while drilling or MWD) or within a few days of the conclusion of drilling operations (typically via wireline conveyed logs). Acquiring temperature logs during or soon after drilling operations, when cooler drilling fluids are circulated through the wellbore, does not allow temperatures to equilibrate to a static state. This equilibration can take weeks or months and an operator's capital constraints typically don't allow for logging operations post-production. Figure 1 (NDIC: 15593) demonstrates the difference in temperature readings between a well logged immediately after drilling operations ceased (dynamic temperature log) to a log taken several months after a well was temporarily abandoned (static temperature log). The dynamic temperature log (blue line) displays a very different gradient and bottom hole temperature than the static log (red line) due to the effects that fluid circulation has on near-wellbore temperatures.

In order to account for the shortcomings of dynamic temperature logs, corrections are commonly applied to temperature logs in order to estimate the static temperature of the wellbore. The Horner method is the most common technique used in the petroleum industry to correct temperature logs. This method employs an algorithm that uses progressive temperature measurements over time and extrapolates that trend to approximate the bottom hole temperature (Horner, 1951). Though the Horner method, and other similar techniques, can give a more accurate estimation of the bottom hole temperature, the data required for this can often times be problematic to find. For instance, the time elapsed after circulation cessation, a common factor in several bottom hole temperature estimations, is often only available in drilling reports. These drilling reports are rarely publically available so the interpreter must assume the time elapsed which can lead to errors. Although various correction techniques applied to dynamic temperature logs can provide more accurate results, acquiring static temperature measurements is the most accurate method.

NEW DATA

Recognizing the need for more accurate temperature data in the Williston Basin, the NDGS began a wireline program in 2014. Between 2014 and 2015, 23 wells were temperature logged by the NDGS (fig. 2). Wells were strategically selected based on geographic location, wellbore depth, and the amount of time elapsed since production had ceased in order to provide the best possible results. McDonald (2015) published these results, which included a determination of heat flow within the basin.

Two additional wells have been logged post-2015. The Ridl 16-1 was logged in late 2016 to a depth of 7,680 feet below ground level and, most recently, the George Palmer 1-11-141-94 was logged down to 11,000 feet in September 2018 (fig. 1). The geothermal gradients of both the Ridl 16-1 (2.11°F/100 ft.) and the George Palmer 1-11-141-94 (1.63°F/100 ft.) are consistent with the work of McDonald (2015) as the Ridl well is located in an area of higher predicted mean heat flow than the George Palmer well (fig. 2).

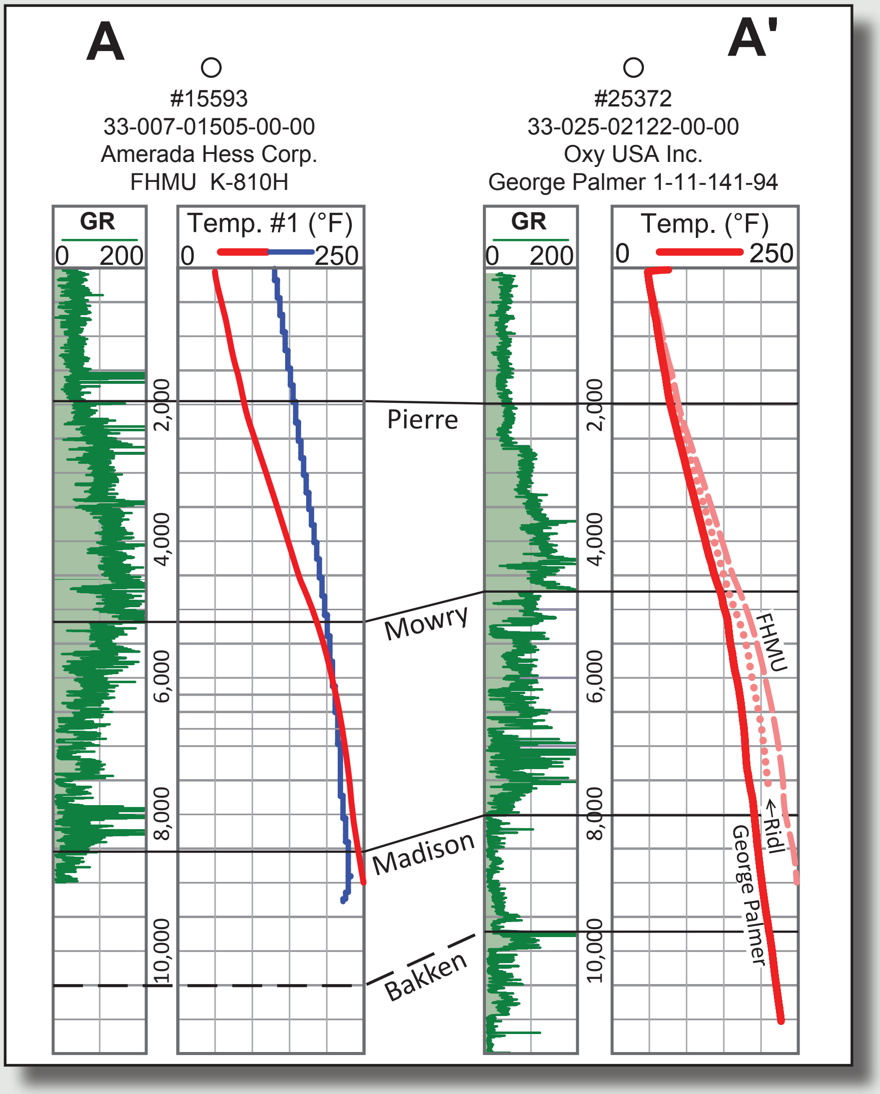

Figure 1. Wireline logs with gamma ray and temperature curves. The FHMU log (left) shows the difference between a dynamic temperature log (blue line) taken immediately after drilling operations ceased and a static temperature log (red line) taken several months after the well was temporarily abandoned. The George Palmer log compares the static temperature logs for the George Palmer (solid red line) to the same from the Ridl (dotted pink line) and FHMU (dashed pink line) wells. Note the ~50° F difference in temperature at around 9,000 feet between the George Palmer and FHMU temperature profiles.

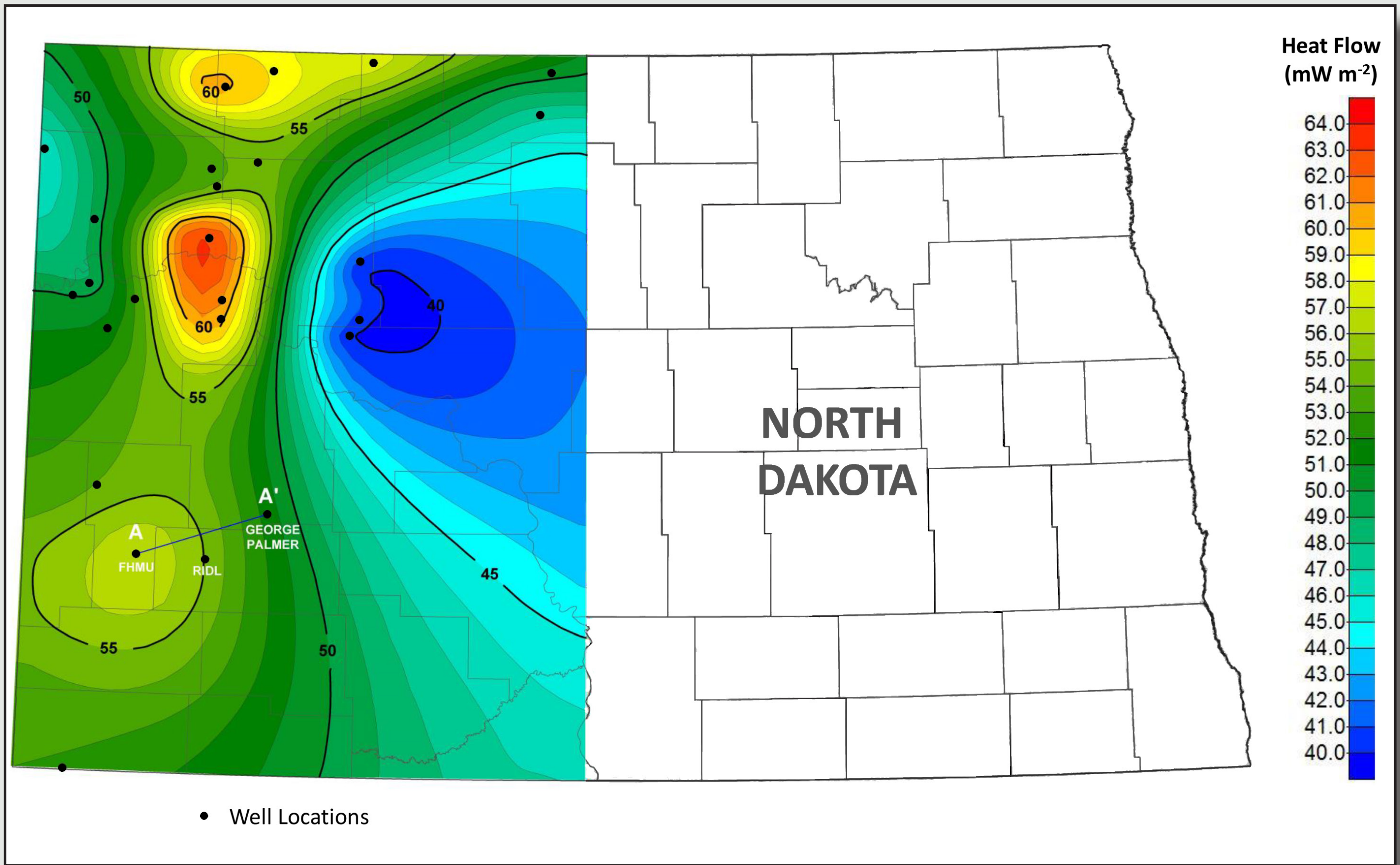

Figure 2. Location map of North Dakota with colored contours representing heat flow within the Williston Basin (modified from McDonald, 2015). Heat flow for the Ridl and George Palmer wells has not been calculated but the well's temperature profiles fit within the previously reported heat flow contours as subsurface temperature gradients decrease (cool) moving eastward from the FHMU towards the George Palmer, which aligns with the decreasing heat flow trend previously modeled/contoured by McDonald (2015).

Although the pace of the logging program has slowed in recent years, the importance of more accurate temperature measurements remains. The NDGS continues to strategically select wells for future temperature logging to provide industry with the most accurate temperature surveys possible. These static temperature measurements will give engineers and geologists a clearer picture of heat flow in the subsurface and provide them with more accurate data to make better, more informed decisions.

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