

Determination of Subsurface Temperatures and the Fraction of Kerogen Converted to Petroleum within the Rauch Shapiro Fee #21-9, Billings County North Dakota

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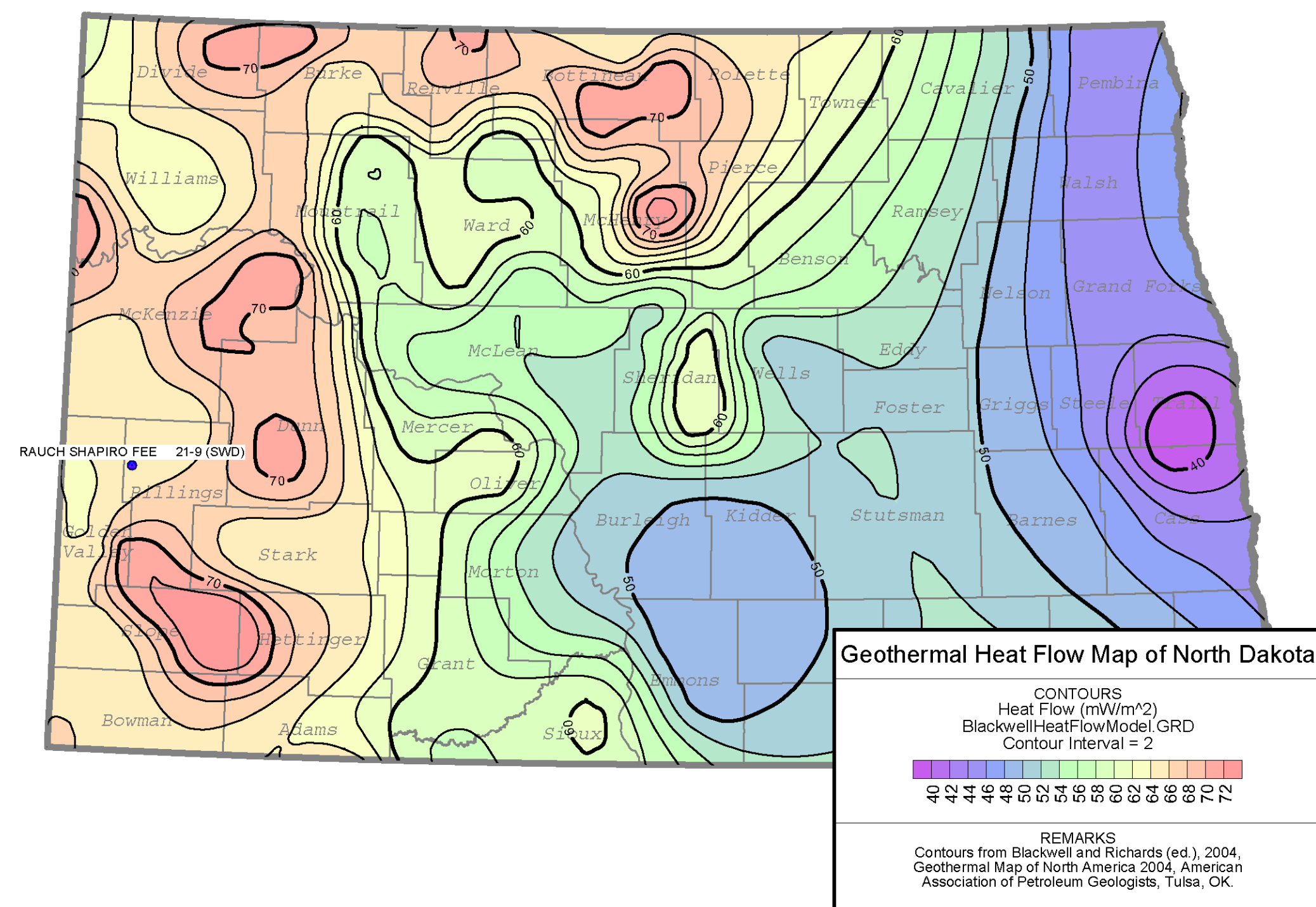


Figure 1. Heat flow map of North Dakota (from Blackwell and Richards (2004) with the location of the Rauch Shapiro Fee 29-1 drilled by Diamond Shamrock Corp. in the NE ¼, NW ¼, Sec. 9, T142N, R102W of Billings County, North Dakota.

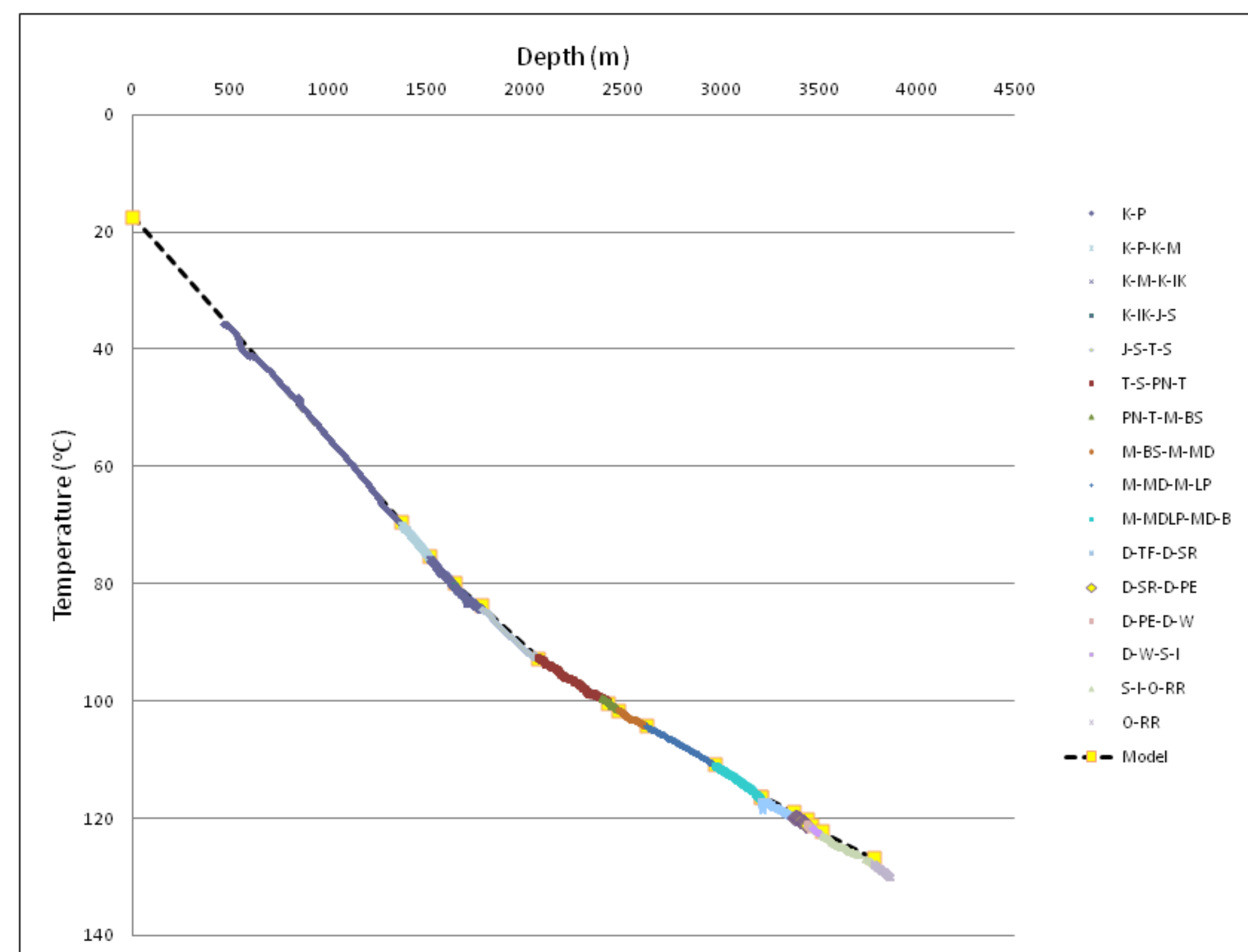


Figure 2. Temperature-Depth profile for the Rauch Shapiro Fee #29-1. The "average" surface temperature, found by extrapolating the temperature-depth trend defined by the section above the Mowry Formation, is 17.45 °C (R² = 0.997). Use the unit code column in Table 1 as a reference to the formation tops that define the thermal stratigraphy used above.

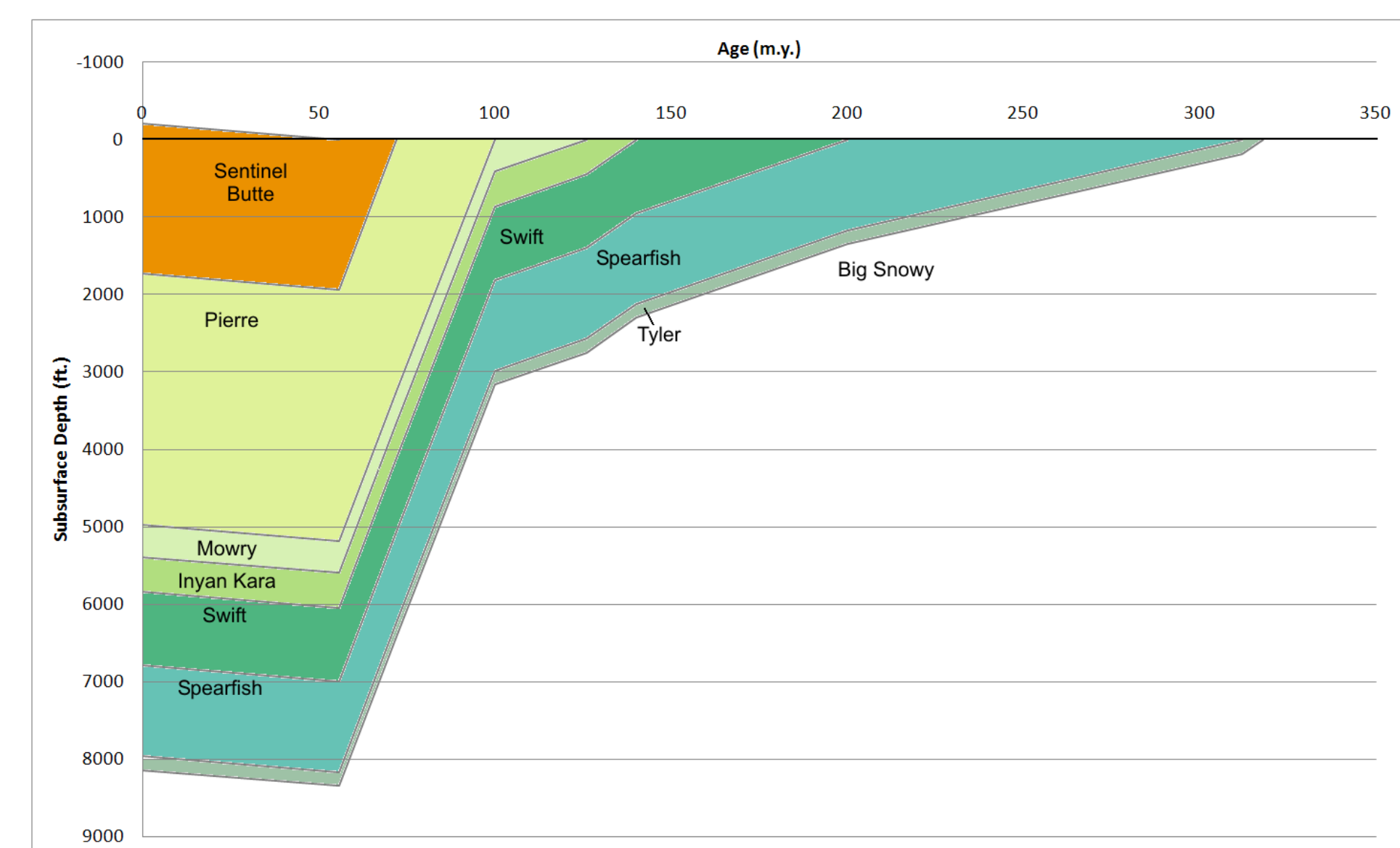


Figure 3. Burial history of the Tyler Formation relative to the modern land surface (Subsurface Depth = 0).

Determination of subsurface temperatures within the Rauch Shapiro Fee #21-9, Billings County North Dakota

The Rauch Shapiro Fee #21-9, spudded on June 11, 1980, reached a total depth of 12741' 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 log (CBL) and a temperature log on November 2, 1980. The well initially completed in the Bakken and Three Forks Formations produced 264 barrels of oil. The well was subsequently converted into a salt water disposal well and was plugged and abandoned in August 2008. Even though the timing of the various cementing operations are not well known, the total depth for which temperature readings are available make this well an attractive subject for the determination of the thermal conductivities for most of the section present in the Williston Basin.

Subsurface temperatures frequently are estimated using Fourier's law of heat conduction that describes the difference in temperature (ΔT) that occurs when heat flows at a constant rate (Q) through some thickness (L) of stratigraphic unit that has a constant thermal conductivity (K). For a single layer, the following expression holds:

$$\text{Eq. 1} \quad \Delta T = Q L / K$$

Estimates of the temperature at depth (T_n) are found by adding the temperature changes (QL/K) associated with each deeper stratigraphic unit ($i=1...n$) to the "mean" surface temperature (T_0) as follows (Blackwell and Richards, 2004):

$$\text{Eq. 2} \quad T_n = T_0 + Q(L_1/K_1 + L_2/K_2 + \dots + L_n/K_n)$$

Where:

- n is the number of stratigraphic units in the section where $i=1...n$
- T_n is the temperature at the base of the n th unit (°C)
- T_0 is the average surface temperature (°C)
- Q is the conductive heat flow (mW/m²)
- L_i is the thickness of the i th unit (m)
- K_i is the thermal conductivity of the i th layer (W/m²·K)

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 can be found by plotting the 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 a conductive heat flow then it is possible to find a set of thermal conductivities that will fit an observed temperature profile. This can be done by subdividing the section into thermal units that exhibit a constant (linear) change in temperature with depth. When this is done the segments that exhibit a linear gradient may be assumed to have a constant thermal conductivity. The thermal conductivities that correspond to these gradients may be determined experimentally under laboratory conditions using known heat flows. In the absence of experimental results, estimates of thermal conductivity may be made from temperature-depth measurements when the geothermal heat flow is known. Rearranging Eq. 1 and using linear regression to find the temperature gradient for the selected stratigraphic intervals in Table 1 results in a solution for the thermal conductivity:

$$\text{Eq. 3} \quad K = Q L / \Delta T$$

Where:

- K is the thermal conductivity of the interval covered by the linear regression (W/m²·K)
- $\Delta T/L$ is the thermal gradient (°C/m) found using linear regression of a Temperature-Depth plot such as the one shown in Figure 2 and
- Q is the geothermal heat flow (W/m²).

In this study, the geothermal heat flow for the Rauch Shapiro #21-9 was estimated from Blackwell and Richards' (2004) heat flow map (Fig. 1) to be 61.5 mW/m². Using this heat flow value and the temperature gradients from the temperature log of the Rauch Shapiro #29-1 the thermal conductivities listed in Table 1 were found with Eq. 3. For example, if the temperature gradient ($\Delta T/L$) through the Tyler Formation is 0.0214°C/m and the geothermal heat flow is .06512 W/m², then solving Eq. 3 yields a thermal conductivity for the Tyler Formation of 3.0 (W/m²·K).

In order to use Eq. 2 to estimate subsurface temperatures, the average surface temperature must also be known. In many instances average surface temperatures are obtained from weather records. However, these records are of short geological duration and may not be a true representation of a geologically meaningful average (Gosnold, pers. com.). A more meaningful average surface temperature might be obtained by extrapolating the temperature gradient that is present in the shallow subsurface at depths beyond 300 feet (~100 m). The relatively shallow temperature profile (<3300 ft., <1000 m) within the Rauch Shapiro is remarkably linear. Extrapolation of this temperature data to the surface (see Figure 2) suggests that the long-term average surface temperature is about 17.45°C. Using this as the surface temperature in Eq. 2 along with the thermal conductivities in Table 1 results in a modeled thermal profile (yellow squares; Figure 2) that correspond well with the entire temperature profile found in the Rauch Shapiro #21-9.

Determination of Maturity of the Tyler Formation in the Rauch Shapiro Fee 21-9

Estimating the thermal maturity of the Tyler Formation requires knowledge of the thermal history of the formation. This is done by reconstructing the burial history and with the information present in Table 1, a reconstruction of the formation's temperature history. The temperature history can be used to estimate, at least from a theoretical standpoint, the level of thermal maturity that organic matter within the Tyler has achieved. Wood (1988) presents a method that expresses a source rock's level of organic maturity in terms of the amount of kerogen that has been converted to petroleum. Wood does this with the Arrhenius equation (Eq. 4) in which the rate of petroleum generation is linked to temperature and parameters that describe the kinetics of the kerogen involved.

$$\text{Eq. 4} \quad k = A e^{-E_a/RT}$$

Where:

- k = reaction rate (mol/m.y)
- A = Frequency at which potential reaction states or collisions occur (1/m.y)
- E_a = Activation energy (kJ)
- R = Gas constant (0.008314 kJ/mol²·K)

Wood's method requires several assumptions. These assumptions typically involve estimating the activation energy (E_a) and frequency factor (A); parameters that define the reaction rate in Eq. 4. Because no better data are available, the average activation energy of the Bakken shale, as reported by Waples (2010), is used here to estimate the maturity of the Tyler Formation. Waples, found that the "average" kerogen in the Bakken Formation has an activation energy of about 212 kJ/mol. According to Wood, the frequency factor (A) varies with the activation energy (E_a) as following:

$$\text{Eq. 5} \quad A = e^{(E_a + 120.83)/5.504}$$

Therefore, given an activation energy of 212 kJ/mol (50.7 kcal/mol) the corresponding frequency factor from Eq. 5 is 1.828×10^{26} m.y.⁻¹. When the activation energy and frequency factor adequately describe a given kerogen's kinetics then the degree of maturation may be found provided an adequate description of the kerogen's thermal history is also known.

The thermal history uses the preserved stratigraphic section to reconstruct the burial history and, using the assumptions mentioned above, result in an estimate of the Tyler Formation's temperature through time. If the geothermal heat flow and thermal conductivity of the various units involved have been constant then the thermal maturation of the Tyler Formation may be estimated by summing the amount of maturation that has occurred during each of the time-stratigraphic intervals used.

The approach used by Wood (1988), is similar to the Lopatin method with one important difference. The kinetics of kerogen maturation, as defined by the Lopatin method, does not account for differences in maturation rates caused by variations in kerogen composition. Wood recognized this problem and developed a maturation model that is capable of taking into account kerogen dependent variations in activation energy. This is done by using the Arrhenius equation to describe the chemical reaction rates that are controlled by the composition of the kerogen and the thermal history of the source bed. The standard Arrhenius equation is only valid for isothermal reactions. However, Wood applied a version of the Arrhenius equation developed by Gorbachev (1975) to solve for the reaction progress that occurs when temperatures change at a constant rate. Wood uses the following expression for this purpose:

$$\text{Eq. 6} \quad TTI_{Arr} (t_n \text{ to } t_{n+1} \text{ where } T_n < T_{n+1}) = A/q \{ [RT_{n+1}^2 / (E_a + 2RT_{n+1})] e^{-E_a/RT_{n+1}} - [RT_n^2 / (E_a + 2RT_n)] e^{-E_a/RT_n} \}$$

Where:

- TTI_{Arr} is a measure of maturation for a kerogen for the time-period t_n to t_{n+1} where the temperature changes from T_n to T_{n+1} .
- t = time (m.y.)
- T = Temperature (°K)
- A = Frequency factor (m.y.⁻¹)
- $q = t/T$ = Heating rate (°K/m.y.)
- R = Gas constant (0.008314 kJ/mol²·K)
- E_a = Activation energy (kJ/mol)

When the temperature history of the source bed is known then estimating the temperature of the source bed before and after each new unit is added (or removed) provides the input needed to solve Eq. 6 for the degree of maturation that occurred within the Tyler Formation as each new unit was added. These temperatures and the associated time intervals when used in Eq. 6 provide the incremental change in kerogen maturation that when summed yields an estimate of the kerogens overall maturation (ΣTTI_{Arr}). When petroleum generation involves a first order reaction then the fraction of the original kerogen that remains is related to the ΣTTI_{Arr} (see Wood, 1988) as follows:

$$\text{Eq. 7} \quad X = e^{-\Sigma TTI_{Arr}}$$

Where:

- X = Fraction of the original kerogen (initially assumed to be 1) that remains.
- ΣTTI_{Arr} = The degree of maturation from Eq. 6

Table 2 presents the Time-Temperature Index and the fraction of the original kerogen reacted using data from the Rauch Shapiro 21-9 in Eq. 3, Eq. 5 and Eq. 6. The results of these calculations suggest that if the kerogen in the Tyler Formation is kinetically similar to the kerogen within the Bakken Formation, then something on the order of 7% of the original kerogen has been converted to petroleum.

References

Blackwell, D. D., Richards, M. C., 2004, Geothermal map of North America 2004, American Association of Geologists, Tulsa OK.

Gorbachev, V. M., 1975, A solution of the exponential integral in non-isothermal kinetics for linear heating: Journal of Thermal Analysis, v. 8, p. 349-350.

Waples, D. W., Leonard, J. E., Coskey, R., Safra, S., Nagdy, R., 2010, A new method for obtaining personalized kinetics from archived Rock-Eval data, applied to the Bakken Formation, Williston Basin: American Association of Petroleum Geologists, abstract Search and Discovery #90108

Wood, D. A., 1988, Relationships between thermal maturity indices calculated using Arrhenius equation and Lopatin method: implications for petroleum exploration: American Association of Petroleum Geologists Bulletin, v. 72, p 115-134.

Unit	Unit Code	Depth (ft)	Depth (m)	Thermal Gradient (°C/m)	Intercept (°C)	R ²	Thermal Conductivity (W/m ² ·K)
Surface		0	0				
Sentinel Butte		-202	-61.570				1.72*
Pierre	K-P	1733	83.184	0.0379	17.446	0.9974	1.72
Mowry	K-M	4980	1517.904	0.0402	14.573	0.9128	1.62
Inyan Kara	K-K	5393	1643.786	0.0362	20.836	0.8469	1.80
Swift	J-S	5844	1781.251	0.0277	35.122	0.969	2.35
Spearfish	T-S	6794	2070.811	0.031	29.183	0.9901	2.10
Tyler	PN-T	7963	2427.122	0.0214	48.41	0.9915	3.04
Big Snowy	M-BS	8146	2482.901	0.0243	41.07	0.98	2.68
Madison	M-MD	8596	2620.061	0.018	57.06	0.967	3.62
Lodgepole	M-LP	9755	2973.324	0.0189	54.71	0.9986	3.45
Bakken	MD-B	10521	3206.801	0.0235	40.842	0.994	2.77
Three Forks	D-TF	10526	3208.325				2.50**
Souris River	D-SR	11083	3378.098	0.0157	66.835	0.8924	4.15
Prairie Evap.	D-PE	11284	3439.363	0.0211	48.489	0.9877	3.09
Winnipegosis	D-W	11380	3468.624	0.0299	18.177	0.9834	2.18
Interlake	S-I	11534	3515.563	0.023	41.862	0.979	2.83
Red River	O-RR	12403	3780.434	0.0175	61.473	0.9938	3.72
TD		12762	3889.858	0.0255	31.45	0.9886	2.55

Table 1. Thermal conductivities of units present in the Rauch Shapiro Fee #21-9 (API#: 33-007-00526-00-00) based on a constant conductive heat flow of 65.12 (mW/m²).

*Assumed thermal conductivity based on linear relationship with underlying Pierre Fm.
** Plausible shale value.

Formation	Depth (ft.)	Age (m.y.)	Thickness (m)	Thermal Conductivity	Δ Temperature (°C)	Temperature at base of the Tyler Fm. (°C)	Temperature at base of the Tyler Fm. (°C)	Heating Rate (°C/m.y.)	TTI Arr	1-X Fraction of Kerogen Converted
Surface	0	0	-61.570	1.720	-2.331	105.2	378.4	-0.042	0.074	0.071
Sentinel Butte	-202	55.7	589.788	1.720	22.330	107.6	380.7	1.370	0.006	0.006
Pierre	1733	72	989.686	1.720	37.470	85.2	358.4	1.338	0.000	0.000
Mowry	4980	100	125.882	1.620	5.060	47.8	320.9	0.195	0.000	0.000
Inyan Kara	5393	126	137.465	1.800	4.973	42.7	315.8	0.355	0.000	0.000
Swift	5844	140	289.560	2.350	8.024	37.7	310.9	0.134	0.000	0.000
Spearfish	6794	200	356.311	2.100	11.049	29.7	302.8	0.099	0.000	0.000
Tyler	7963	312	55.778	3.040	1.195	18.6	291.8	0.199	0.000	0.000
Big Snowy	8146	318	137.160	2.680	3.333	17.5	290.6			

Table 2. Example of applying Eq. 3, Eq. 5 and Eq. 6 to determine the level of thermal maturity within the Tyler Formation using data from the Rauch Shapiro 21-9 contained in Table 1. The column labeled 1-X is the fraction of the available kerogen that has been converted to oil or gas. In Eq. 7, X is the fraction of kerogen remaining so 1-X represents the fraction converted.