Thermal history model of the Williston Basin

Yue-Chain Huang

University of North Dakota

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THERMAL HISTORY MODEL OF THE WILLISTON BASIN

by

Yue-Chain Huang

Bachelor of Science

National Taiwan College of Marine Science & Technology

A Thesis

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of the

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for the degree of

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This thesis submitted by Yue-Chain Huang in partial fulfillment of the requirements for the degree of Master of Science from the University of North Dakota has been read by the faculty Advisory Committee under whom the work has been done, and is hereby approved.

W. J. Doane
(Chairman)

E. R. Adams

H. L. Federman

This thesis meets the standards for appearance and conforms to the style and format requirements of the graduate school of the University of North Dakota, and is hereby approved.

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Title       **Thermal History Model of the Williston Basin**
Department  Geology
Degree      Master of Science

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ABSTRACT

The factors that affect the subsurface temperature of a sedimentary basin were investigated by empirical and analytical methods. A review of thermal-mechanical models suggests that the Williston Basin was formed by more than one mechanism. The Williston Basin may have been initiated by a thermal event followed by thermo-flexural or phase-transition subsidence.

The heat that initiated the formation of the Basin was significant to the thermal history of the Basin at its very beginning stage. However, most of the anomalous heat would have dissipated before the deposition of Bakken Formation 363 Ma ago. The heat flow history of the Basin was probably a steady-state condition after the Bakken was deposited.

Compaction is the major factor that affected the thermal structure of the Williston Basin after deposition of the Bakken Formation. Application of a decompaction scheme indicates higher paleotemperatures for the Williston Basin than would be calculated without decompaction.

Calculation of depth-porosity relationships for the Bakken Formation for four wells in the North Dakota portion of the Williston Basin shows a predictable correspondence between compaction and burial depths. The thickness of the Bakken Formation at each location changed proportionally with time as porosity decreased.
The decrease in porosity and thickness of the entire sedimentary section reduced the temperature of the rocks due to the increase in thermal conductivity and thinning of the thermal blanket.

The temperature history of the Bakken Formation shows a four-stage development. The different rates of temperature change reflect variations in rates of deposition and diagenesis of the overlying sediments. The temperature of the Bakken Shale increased slowly in its early history but rapidly in its late history.

Analysis of the thermal history of a sedimentary basin must consider the following:

1. time, temperature, and depth dependency of thermal conductivity
2. burial history
3. time-dependency in heat flow
4. surface temperature history

The time-temperature index (TTI) is an accurate measurement of thermal maturity if the above factors are included in the thermal history analysis.
INTRODUCTION

General

Interest in the thermal histories of sedimentary basins has increased since Waples's (1980) application of Lopatin's (1971) method for predicting thermal maturity. In concept, the thermal maturity of petroleum source rocks should be calculable if one can accurately predict the temperature profile for the source rocks throughout time. A number of workers including Waples (1980) approached this problem by using present day geothermal gradients to determine paleotemperatures (Lopatin, 1971; Schmoker and Hester, 1983; Price, Ging, Daws, Love, Pawlewicz and Anders, 1984; Webster, 1984). Other workers have proposed thermo-mechanical models for basin formation and have projected temperatures as a function of subsidence rate and an exponential decrease in heat flow (McKenzie, 1978; Turcotte and Ahern, 1977; Haxby, Turcotte and Bird, 1976; Ahern and Mrkvicka, 1984; Nunn, Sleep and Moore, 1984; Garner and Turcotte, 1984).

Each of these approaches has provided insight into important aspects of the thermal evolution of sedimentary basins. However, in some cases these models produce conflicting results. For example, estimates of the thermal maturity of Bakken Formation in the Williston Basin based
on temperature gradients derived from bottom-hole tempera-
tures (Webster, 1984; Schmoker and Hester, 1983) conflict
with the interpretation of geochemical data by Price et al.
(1984) who suggest that the Bakken reached thermal maturity
levels that exceed those predicted using estimates of
present-day basin temperatures.

A fundamental problem in this type of analysis is
obtaining a valid estimate of present-day temperatures.
The common technique of analyzing basin temperatures, i.e.,
projecting linear temperature gradients based on bottom-
hole temperatures of oil wells (Fig. 1) has been applied to
the Williston Basin by Nixon (1973) and Meissner (1978) and
has been used for paleotemperature estimates by Webster
(1984) and Price et al. (1984). However, the present-day
temperatures obtained by this analysis disagree with
temperatures actually measured using thermal probes. The
temperature gradients measured with thermistor probes
reveal a complex temperature-gradient profile (Fig. 2) that
is non-linear and, in a single profile, may range from 20
°C km⁻¹ to 60 °C km⁻¹ (Gosnold, 1985).

Another fundamental problem arises from using present-
day temperatures as paleotemperatures. This problem has
been recognized for the Williston Basin by Price et al.
(1984) whose geochemical data indicate significantly higher
paleotemperatures than would be obtained from the present-
day geothermal gradients given by Meissner (1978). Another
Figure 1. Schematic illustration of two methods for calculating formation temperature, (1) Thermal resistance method, (2) Linear gradient method. $T_n$ is temperature of nth layer of sediment. $L_n$ is the thickness of nth layer, $Q_0$ is surface heat flow, $K_n$ is thermal conductivity of nth layer.
(1) THERMAL RESISTANCE METHOD

\[ T_n = T_0 + Q \frac{n}{\sum_{i=1}^{n} \frac{\Delta L_i}{K_i}} \]

(2) SIMPLE GRADIENT METHOD

\[ T_n = T_0 + \left( -\frac{\partial T}{\partial Z} \right) \Delta L \]
Figure 2. Thermal profile of the Williston Basin (from Gosnold, 1985). Curve A shows that the thermal gradient of the Williston Basin is a non-linear type. The non-linear feature of thermal gradient is attributed to various lithologies that are of different thermal conductivities. The slope is steep in the Paleozoic due to the high-conductivity carbonate rocks, and is flatter in the late Mesozoic due to the lower conductivity clastics.
example was given by Naeser and Naeser (1985) who also found disagreement between present-day temperature gradients and paleotemperature gradients in several Tertiary basins in the Western United States.

We address these problems in modeling a basin's thermal history by analyzing the factors that control present and past temperature profiles. It will be shown that the assumption that linear temperature gradients can be used to estimate basin temperatures may be invalid in the general case and is particularly inappropriate for the Williston Basin. We also examine the assumption that the present-day gradients may be used to determine paleotemperatures and suggest explanations for inference of high paleotemperatures in some basins. The essential elements of our approach were discussed by Sclater and Christie (1980) as applied to the North Sea Basin.

Factors Controlling the Present Subsurface Temperature

Quantitative analysis of the thermal structures of the subsurface requires determination of several thermal properties of the strata and the local heat flow. In the simplest case, application of Fourier's law of heat conduction would allow determination of surface temperature by:

\[ Q = \left( \frac{dT}{dZ} \right) \times K \]  

(1)
where $Q$ is heat flow in mW m$^{-2}$, $K$ is thermal conductivity in W m$^{-1}$K$^{-1}$, $dT$ is the increment of temperature change in a vertical length, dZ. The temperature at any point, $Z$ can be calculated by:

$$T_n = T_0 + Q \sum_{n=1}^{n} \frac{L_i}{K_i}$$  \hspace{1cm} (2)

where $T_0$ is surface temperature, $Q$ is the conductive heat flow, $L_i$ is the thickness of the ith layer, and $K_i$ is the conductivity of the ith layer (Fig. 1).

The gross thermal conductivity structure of the subsurface in the Williston Basin comprises two distinct components: a high-conductivity Paleozoic carbonate section and a low-conductivity Mesozoic and Cenozoic clastic section (Gosnold, 1985). For normal continental heat-flow values of about 60 mW m$^{-2}$, a gradient of about 50 K km$^{-1}$ characterizes the carbonates and a gradient of about 20 K km$^{-1}$ characterizes the clastics (Fig. 2).

The data necessary to characterize the present thermal structure in a sedimentary basin according to Equation 2 are surface temperature, heat flow, formation conductivities, and formation thicknesses.
Paleo-heat Flow and Thermal Mechanical Models

Continental Heat Flow

In a conductive regime, heat flow and thermal conductivity are the major parameters governing subsurface temperatures. Rewriting and integrating equation 1 gives:

\[
\int_0^T dT = Q \int_0^z \frac{1}{K(z)} d(z)
\]

Thus, subsurface temperatures are directly proportional to heat flow and inversely proportional to thermal conductivity.

In the Williston Basin, which has a thick, low-conductivity shale-rich layer overlying a thick, high-conductivity carbonate-rich lower layer, the effects of a change in heat flow are complex. A change in heat flow after deposition of the Mesozoic shale units would have a significantly greater effect on subsurface temperatures than would a change in heat flow prior to the Mesozoic. Consequently, an understanding of the factors that control continental heat flow are crucial to this study.

Surface heat flow on the continents was described by Roy, Blackwell and Birch (1968) as:

\[
Q_s = Q_0 + DA
\]
where $Q_s$ is surface heat flow, $A$ is radioactive heat generation in the upper crust, $D$ is a parameter having units of length that was empirically found to be characteristic of a physiographic province (Fig. 3) and $Q_0$ is reduced heat flow. The quantity, $Q_0$, has been taken by a number of workers to represent heat flow from the mantle, or heat flow from below a radioactive upper crust (Birch and others, 1968; Roy et al., 1968; Lachenbruch, 1968; Roy, Beck and Touloukian, 1981).

Vitorello and Pollack (1980) suggest that $Q_0$ varies within certain limits depending on the tectonic age of the province in which heat flow is measured. Thus, they suggest a quantitative method of estimating values for $Q_0$, $Q_s$, and $DA$ where the tectonic age and one or more of the other values are known.

The trend of declining continental heat flow with terrane age (Fig. 4) is caused by declining tectogenic heat with age, a fact observed in the Basin and Range province, where Cenozoic intrusions were active (Roy and others, 1968). Hence, tectogenic heat for basin formation (Ahern and Mrkvicka, 1984; Ahern and Ditmars, 1985) would be significant in the early history of the Williston Basin.

However, by the time of deposition of Bakken Shale, about 363 Ma, and certainly by the time the Bakken was buried to depths greater than about 1 km, about 180 Ma, the thermal effects associated with basin formation would have dissipated.
Figure 3. Surface heat flow versus heat production (Roy et al, 1968). A, B and C represent different heat flow values that observed in three different physiographic provinces in the U.S. $Q_s$ is surface heat flow, $Q_o$ is reduced heat, $D$ is the thickness of radioactive block with units of kilometer and $A$ is heat production.
\[ Q_s = Q_0 + DA \]
Figure 4. Secular decrease of continental heat flow with age and its three components (Vitorello and Pollack, 1980).
HEAT FLOW VERSUS TECTONIC AGE

I = Radiogenic Heat Production
II = Tectogenic Residual Heat
III = Background Heat
Heat generation measurements in North Dakota show a wide range of scatter (Scatollini, 1977) and until more heat generation data are available, the reduced heat flow can only be estimated. Fifteen recent heat flow measurements in the Williston Basin, based on Pierre Shale conductivity of 1.2 Wm\(^{-1}\)K\(^{-1}\), average about 55 ± 6 mW m\(^{-2}\) (Gosnold, 1988). This heat flow value is assumed to represent the steady-state heat flow in the Williston Basin since the deposition of the Bakken Formation.

**Thermo-mechanical Models**

Three natural mechanisms may cause subsidence of a basin: (1) isostatic subsidence, (2) flexural subsidence, and (3) thermal subsidence. Subsidence of a basin may be caused by a combination of mechanisms and any different mechanism may dominate at a different stage of basin formation. For example, the subsidence of an oceanic basin is initiated by the cooling and thickening of lithosphere with age (Turcotte and Ahern, 1977). Both cooling and thickening of lithosphere cause isostatic imbalance that lead to subsidence. If a load of sediment is placed on the oceanic crust, the lithosphere will bend as an elastic beam, (Heller and Angevine, 1987). The lithosphere is weaker when it is hot than when it is cold. Hence, the basin will be deeper if the load is heavier and the crust is weaker (Fig. 5).
Figure 5. Schematic illustration of thermo-flexural mechanisms.
Several mechanisms and models, similar to the subsidence of oceanic basins, have been proposed to explain continental basin formation. Most of these models require heating events that occurred in the remote past, and heat flow in these basins decreases with time. However, an isostatic mechanism that requires no heating event has been discussed by Wyllie (1970) and has been applied to the Williston Basin by Fowler and Nisbet (1984).

Models requiring a thermal event to initiate basin formation allow projection of heat flow and subsidence as a function of time. Such thermo-mechanical models include: (1) thermal expansion model (Sleep, 1971) (Fig. 6); (2) crustal stretching model (McKenzie, 1978; Keen, 1979); (3) deep crustal metamorphism (Falvey, 1974; Middleton, 1980; Haxby et al., 1976); (4) dike intrusion model (Royden et al., 1980); (5) flexural thermo-mechanical model (Nunn, 1981; Ahern and Mrkvicka, 1984; Nunn et al., 1984).

Mechanisms that may account for the depression of continental basins are illustrated in Fig. 7.

**Stretching Model**

Thermo-mechanical models, such as crustal stretching (McKenzie, 1978), are essentially oceanic models applied to continents. Stretching or thinning of the crust serves as the depressional mechanism of the basin in McKenzie's (1978) model. In this model, the crust is stretched by a
Figure 6. Schematic illustration of a thermal expansion mechanism for subsidence of a basin (after Heller and Angevine, 1987).
THERMO-EXPANSIONAL MODEL

erosion
Figure 7. Mechanisms of subsidence (after Beaumont, 1978).
MECHANISMS OF SUBSIDENCE

A. Thermal Uplift - Erosion - Thermal Contraction

B. Phase Change at Depth

C. Intrusion of Dense Material into Crust
D. Rifting and Spreading of Continental Plates

E. Necking of Lithosphere (Viscoelastic or Plastic Lithosphere)

F. Isostatic Adjustment of a Graben (Brittle Lithosphere)
factor of $\beta$, and is thinned to be $1/\beta$ of its original thickness (Fig. 8). Such stretching events cause upwelling of asthenospheric material which is heavier than crustal material. Displacement of the heavier mantle rock to the shallower depth causes isostatic imbalance and the basin subsides to maintain balance. Subsidence of this type is divided into two phases. The early, fast subsidence is structurally dominated by graben faulting. The later, slow subsidence is characteristic of contractional cooling. The heat flow history of this model type has high heat flow in the beginning with exponentially decreasing heat-flow with time. The original heat flow budget of this model is very dependent on the degree of stretching, $\beta$, the ratio of the area of stretched crust surface to the area of original crustal surface (McKenzie, 1978; McKenzie, 1981; Royden et al., 1980).

Ahern and Ditmars (1985) proposed a thermal model to explain the subsidence of the Williston Basin. As a result of heating at the bottom of a 250 km thick plate during 500 Ma and 450 Ma. The temperature anomaly was attributed to convection of mantle heat which increased from 1333 °C to 1850 °C and then decreased to its present value during a 100 Ma period of time (Fig. 9). The heating event first thinned the plate and was followed by lithospheric cooling that lead to the subsidence.
Figure 8. Schematic illustration of stretching mechanism (after McKenzie, 1978).
STRETCHING MODEL

TIME

TEMP. (°C)

DEPTH

TIME

SUBSIDENCE
Figure 9. Thermal history of the Williston Basin (modified after Ahern and Ditmars, 1985). A temperature anomaly was caused by thermal convection at the upper mantle. The thermal event, which occurred during 500 to 450 Ma, was suggested to account for the subsidence of the Williston Basin.
Deep Crustal Metamorphism

The other most widely discussed model of continental basin formation is deep crustal metamorphism (Falvey, 1974; Haxby et al., 1976; Middleton, 1980; Falvey and Middleton, 1981; Nunn, 1981; Ahern and Mrkvicka, 1984). This model is especially applicable to intracratonic basins, because its heat-flow evolution better fits continental heat flow models.

Basin formation by crustal metamorphism is initiated by vertical displacement of phase boundaries through heating of a subcrustal region. A disc load at the lower crust is, therefore, created by conversion of low-density greenschists into high-density amphibolites (Falvey, 1974; Middleton, 1980) or gabbro to eclogite (Haxby et al., 1976). Such lithologic conversion causes isostatic imbalance that leads to subsidence of the basin.

The lithologic conversion occurs in the very early stage of the basin formation, followed by a thermal contraction stage. Hence, subsidence due to this style of model, is faster in the early stage but slower in the later stage. The two-fold subsidence rates of intracratonic basins in the North America and Australia are interpreted as a result of deep crustal metamorphism (Middleton, 1980). The early, fast observational subsidence rate can be accounted for by contractional cooling of a heated body,
and the later, slow subsidence rate is caused by phase changes.

The heat flow history of this model depends upon the metamorphic grade of rock of the lower crust. If the lower crust is composed of a lower grade of rock, it will allow more potential for conversion from low-grade to high-grade and more heat will be absorbed by chemical reaction at the beginning of subsidence. If the lower crust is old, high-grade metamorphic rock, it has less potential for phase changes and less heat is absorbed by chemical reactions. Therefore, the heat flow history of this type of model evolves nonlinearly and depends on the contrast of density between the facies boundaries. Based on this concept, the heat flow would be small at the early stage, if the crust is young and has higher potentials for phase change, otherwise heat flow would be large if the crust is old and metamorphic grade is high allowing less phase change to occur.

Dike Intrusion Model

In a model similar to the stretching model, Royden, Sclater and Von Herzen (1980) proposed a dike-intrusion model to explain basin subsidence as a result of cooling dikes that displace crust. In this model, the heat flow variation in time differs from the stretching model and relies largely on the volume ratio of the intrusive dike to
the intruded lithosphere. This mechanism applies well to oceanic basins but is less appropriate for intracratonic basins.

Thermo-flexural Model

Using flexural rheology and thermal contraction mechanisms for the crust, Ahern and Mrkvicka (1984) modeled the subsidence of the Williston Basin as a function of time. For the Williston Basin, an intrusive body 89 km thick, 400 km in diameter, 89 km below the surface and having an initial anomalous temperature, $T_i = 153 \, ^\circ C$, is proposed to drive the thermo-flexural subsidence of the Williston Basin from Cambrian through Jurassic (Fig. 10). The flexural rigidity of the lithosphere increased with time due to the cooling of the intrusive. The low-temperature intrusive was modeled at depths that were insulated both from the surface and from the mantle. Due to such insulation, the temperature was apt to keep for 300 Ma. The problem with this thermal model is that it poorly fits the deflection of the basin from the late Cretaceous to the present. The surface heat flow due to this temperature anomaly is given by Haxby et al. (1976):

$$Q_a = \frac{2KT_i}{3d} a_n \exp \left[ -\left( \frac{n}{3d} \right)^2 kt \right]$$ (5)
Figure 10. Schematic diagram of the thermal model for the Williston Basin (after Ahern and Mrkvicka, 1984). The elastic rigidity of the earth crust increases with the decreasing temperature. Based on such concept, Ahern and Mrkvicka modeled an heat perturbation of which temperature was 153 °C, located at a depth of 89 km accounted for the subsidence of the Williston Basin.
THERMO-FLEXURAL MODEL FOR WILLISTON BASIN

400 kms

$T_1 = 153 \, ^\circ C$

LITHOSPHERE

ASTHENOSPHERE
0, when \( n \) is even
\[
a_n = \begin{cases} 
1, & \text{when } n = 1, 5, 7, 11, 13, \ldots \\
-2, & \text{when } n = 3, 9, 15, 21, \ldots 
\end{cases}
\]

where \( K \) is the thermal conductivity, \( d \) is the distance from the surface to the intrusive body, \( T_1 \) is initial temperature, \( k \) is thermal diffusivity. The exception of this thermal model is that it poorly fits the deflection of the Williston Basin during the time of 113 Ma ago and the present. Because the deflection of the Williston Basin was much greater than the deflection predicted by the thermal model after the deposition of Greenhorn Formation.

All of the thermo-mechanical models for evolution of the Williston Basin require an instantaneous heat source in the early Paleozoic. Although geological evidence for a heating event in the Williston Basin is difficult to acquire, the theoretical arguments favoring thermo-mechanical models for basin formation (Ahern and Mrkvicka, 1984; Nunn, Sleep and Moore, 1984; Heidlauf, Hsui and Klein, 1986; and Nunn and Aries, 1988) are sound. Supportive evidence for a thermo-mechanical model for evolution of the Williston Basin was provided by Crowley et al (1985). Crowley et al. (1985) determined fission-track age dates of basement samples from the Williston Basin and suggested that the basement in the center of the Basin has been
hotter than the basement near the northeastern margin of the Basin. Crowley, Ahern and Naeser (1985) suggested that an early-Paleozoic heat source in the center of the Williston Basin caused uplift of about 3 km followed by erosion and subsidence. They concluded that the timing of uplifted isotherms, evidenced by the fission-track age dates, is consistent with a thermo-mechanical model for basin formation.

The subsidence curve for the Williston Basin provided by Ahern and Mrkvicka (1984) applies only to the Paleozoic rocks. Subsequent subsidence in the Mesozoic and Cenozoic represents a rejuvenation of the basin that may be better explained by a phase change model such as that of Fowler and Nisbet (1984), see Fig. 11 also. The interest of this study is the temperature history of kerogen-bearing sediments deposited in the mid-Paleozoic. Thus, the key question is whether different models for basin formation produce different temperature histories for the kerogen-bearing sediments. We address this question in the following section and calculate temperature histories based on models with and without a crustal heating event using both analytical and numerical models.
Figure 11. Subsidence versus time plots for five wells from the Williston Basin (after Fowler and Nisbet, 1984). This figure provides evidence that supports the explanation of the formation of Williston Basin by more than one mechanism.
Subsidence by thermal contraction

Subsidence curve of the Williston Basin
METHODOLOGY

Temperature of a rock formation at a depth, $Z$, is controlled by the surface temperature, heat flow, thermal conductivity of the rock, and the thickness of rock formations (see equation 2).

The variation of heat flow, $Q$, is dependent on the mechanical model and basin character, whereas the variation of thermal conductivity and formation thickness with time are attributed mostly to the sedimentary and diagenetic history of rock. The effect of compaction will cause great change in porosity of rock and is discussed in the following section.

Thermal Conductivity of Sediment

Thermal conductivity of rocks varies with mineral composition, volume ratio of rock matrix and interstitial fluid, and the temperature. Because diagenetic processes and temperature change throughout time, the thermal conductivity of rocks may vary significantly during the history of a basin. Determination of thermal conductivity by correcting for diagenetic and temperature changes throughout time is necessary to calculate accurately the paleothernal history of a sedimentary basin.

Based on empirical data, the thermal conductivity of
rock matrix as a function of temperature is calculated by:

\[ KR = Kr - Kr \times (T - 20) \times .001 \]  

(6)

where, \( Kr \) is the thermal conductivity of rock measured at 20 °C, \( T \) is temperature in degrees C.

The thermal conductivity of water as a function of temperature is expressed by a third degree polynomial as:

\[ KW = KWO + KW1 + KW2 + KW3 \]  

(7)

where \( KWO = 0.56, KW1 = KWO + 0.0019763 \times T, KW2 = KW1 - 8.29 \times 10^{-6} \times T^2, KW3 = KW2 + 5.05 \times 10^{-9} \times T^3. \) The relationships are illustrated in Figs. 12, 13, 14 and 15.

**Decompaction of Sediment**

Thermal conductivity of sediment varies with time as compaction reduces the bulk porosity. A water-saturated sediment compacts as subsequent sediments accumulate during basin subsidence. Compaction of sediment occurs because a saturated sediment tends to reduce the fluid pressure and increase the effective stress to balance the pressure excess from the weight of overlying sediments. A result of compaction is a decrease in porosity and outflow of interstitial water. The deeper the sediment is buried, the
Figure 12. Thermal conductivity versus porosity of sediment.
CONDUCTIVITY VS POROSITY

BAKKEN SHALE, NDGS# 11734

THERMAL K (W/m/K)

POROSITY

- MATRIX
- WATER
- SED
Figure 13. Thermal conductivity of rock matrix versus temperature.
CONDUCTIVITY OF RX. MTRX VS TEMPERATURE

BAKKEN SHALE, NDGS# 11734

THERMAL K (W/m/K)

TEMPERATURE (Deg.C)
Figure 14. Thermal conductivity of interstitial water versus temperature.
Figure 15. Thermal conductivity of sediment versus temperature.
CONDUCTIVITY OF SED. VS TEMPERATURE

BAKKEN SHALE, NDGS# 11734

TEMPERATURE (Deg.C)

THERMAL K (W/m/K)

20 40 60 80 100 120
larger the pressure will be from the overlying weight and the greater the degree of compaction.

Equation 8 is from Hubbert (1960) and shows that the variation of porosity in shale is a simple exponential decrease with increasing depth:

\[ f = f_{o} * z^{-c} \]  

Equation (8)

where \( f_{o} \) is the initial porosity, \( z \) is the depth, and \( c \) is a constant characteristic of lithology and its occurrence (see Fig. 16 and Table 1). Sclater and Christie (1980) extend this concept to various lithologies in the North Sea Basin and their work serves as a model for this study. The expression used by Sclater and Christie (1980) is

\[ z_2' - z_1' = z_2 - z_1 - \left( f_{o}/c \right) \left( \exp(-cz_1') - \exp(-cz_2') \right) \]

\[ + \left( f_{o}/c \right) \left( \exp(-cz_1) - \exp(-cz_2) \right) \]

Equation (9)

where

- \( z_1 \) : top of layer
- \( z_2 \) : bottom of layer
- \( z_1' \) : top after decompaction
- \( z_2' \) : bottom after decompaction
- \( f_{o} \) : surface porosity of layer
- \( c \) : characteristic coefficient

Equation (9) predicts values for the bottom depth of a particular layer for the change of thickness due to
Figure 16. Idealized porosity versus depth curves for different lithologies (after Heller and Angevine, 1987).
Porosity ($\bar{\phi}$)

\[ \bar{\phi} = \phi_0 e^{-cz} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>$\phi_0$</th>
<th>$c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>0.5</td>
<td>$5.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0.4</td>
<td>$3.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Limestone</td>
<td>0.5</td>
<td>$7.0 \times 10^{-4}$</td>
</tr>
</tbody>
</table>
Table 1
Surface Porosity and Characteristic Coefficient for Various Lithologies

<table>
<thead>
<tr>
<th>Lithology</th>
<th>C, ( \times 10^{-5} ) cm</th>
<th>( f_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>.51</td>
<td>.63</td>
</tr>
<tr>
<td>Sand Stone</td>
<td>.27</td>
<td>.49</td>
</tr>
<tr>
<td>Lime Stone</td>
<td>.71</td>
<td>.50</td>
</tr>
<tr>
<td>Silt Stone</td>
<td>.39</td>
<td>.59</td>
</tr>
</tbody>
</table>

(Data are derived from Sclater and Christie, 1980)

Table 2
Temperature Factors for Different Temperature Intervals

<table>
<thead>
<tr>
<th>Temperature Interval (°C)</th>
<th>Index Value ( n )</th>
<th>Temperature Factor ( r^n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>30-40</td>
<td>-7</td>
<td>( r^-7 )</td>
</tr>
<tr>
<td>40-50</td>
<td>-6</td>
<td>( r^-6 )</td>
</tr>
<tr>
<td>50-60</td>
<td>-5</td>
<td>( r^-5 )</td>
</tr>
<tr>
<td>60-70</td>
<td>-4</td>
<td>( r^-4 )</td>
</tr>
<tr>
<td>70-80</td>
<td>-3</td>
<td>( r^-3 )</td>
</tr>
<tr>
<td>80-90</td>
<td>-2</td>
<td>( r^-2 )</td>
</tr>
<tr>
<td>90-100</td>
<td>-1</td>
<td>( r^-1 )</td>
</tr>
<tr>
<td>100-110</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>110-120</td>
<td>1</td>
<td>( r )</td>
</tr>
<tr>
<td>120-130</td>
<td>2</td>
<td>( r^2 )</td>
</tr>
<tr>
<td>130-140</td>
<td>3</td>
<td>( r^3 )</td>
</tr>
<tr>
<td>140-150</td>
<td>4</td>
<td>( r^4 )</td>
</tr>
<tr>
<td>150-160</td>
<td>5</td>
<td>( r^5 )</td>
</tr>
</tbody>
</table>

(reproduced from Waple, 1980)
compaction. The examples in Table 1 are the values of characteristic coefficient and surface porosity used in applying this calculation to the Williston Basin.

Fig. 17 is a simplified example illustrating the decompaction of a sedimentary column of which are composed of five layers of various lithologies.

The lithologies of Fig. 17, from top to the bottom, are shale, shaly sand, sandstone, limestone and shale. The bottom depth of each layer is indicated by $d_1$, $d_2$, $d_3$, $d_4$ and $d_5$.

An example of initial porosity, $f_0$, and characteristic coefficient, $c$ for various lithologies, is shown in Table 1. Decompaction of a layer of sediment is calculated by removing the overlying layers of sediment (Fig. 17). For example, layer 2 is decompacted by removing layer 1. As layer 1 is removed, it is assumed that the physical and diagenetic conditions of layer 2, are as they were the time when layer 2 was deposited. At that time, the top of layer 2 is assumed to be at sea level and its surface depth, $d_1'$, is equal to zero.

The calculated effects of decompaction are that the basement will uplift and the thickness of layer 2, as well as the layers below layer 2 will expand (Fig. 17). The bottom depth of layer 2, $d_2'$, due to the removal of layer 1 becomes:
Figure 17. Schematic illustration of a five-layer lithologic section showing decompaction of sediment by back-strip method (after Sclater and Christie, 1980).
### Schematic Illustration of a Five-layer Lithologic Section

<table>
<thead>
<tr>
<th>Litho.</th>
<th>Temp.</th>
<th>Depth</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale</td>
<td>T1</td>
<td>d0</td>
<td>AX1</td>
</tr>
<tr>
<td>Shalysand</td>
<td>T2</td>
<td>d1</td>
<td>AX2</td>
</tr>
<tr>
<td>Sandstone</td>
<td>T3</td>
<td>d2</td>
<td>AX3</td>
</tr>
<tr>
<td>Limestone</td>
<td>T4</td>
<td>d3</td>
<td>AX4</td>
</tr>
<tr>
<td>Shale</td>
<td>T5</td>
<td>d4</td>
<td>AX5</td>
</tr>
<tr>
<td></td>
<td>T6</td>
<td>d5</td>
<td>AX6</td>
</tr>
</tbody>
</table>

### Decompaction of Sediment by Backstrip

- **Sea level**
- **T2'**

<table>
<thead>
<tr>
<th>Temp.</th>
<th>Depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>d0</td>
</tr>
<tr>
<td>T2</td>
<td>d1</td>
</tr>
<tr>
<td>T3</td>
<td>d2</td>
</tr>
<tr>
<td>T4</td>
<td>d3</td>
</tr>
<tr>
<td>T5</td>
<td>d4</td>
</tr>
<tr>
<td></td>
<td>d5</td>
</tr>
<tr>
<td>T3'</td>
<td>d2'</td>
</tr>
<tr>
<td>T4'</td>
<td>d3'</td>
</tr>
<tr>
<td>T5'</td>
<td>d4'</td>
</tr>
<tr>
<td></td>
<td>d5'</td>
</tr>
</tbody>
</table>
\[ d_{2}' = d_2 - d_1 - \left( \frac{f_0}{c} \right) (\exp(-cd_1) - \exp(-cd_2)) + \left( \frac{f_0}{c} \right) (1 - \exp(-cd_2')) \quad (10) \]

where, \( d_2 \) is the bottom depth of layer 2, before decompaction, \( d_1 \) is the bottom depth of layer 1 before it is removed, \( f_0 \) is the surface porosity of layer 2.

By applying \( d_{2}' \) to equation 9 as the top of layer 3, the bottom of layer 3, \( d_{3}' \), is obtained, and so on.

Due to decompaction, the thickness of layer 2 expands to be:

\[ L_{2}' = d_{2}' - d_{1}' = d_{2}' - 0 = d_2 \quad (11) \]

A general expression of the thickness of each layer expanded due to decompaction (see Fig. 17) is:

\[ L_n' = d_n' - d_{n-1}' \quad (12) \]

Porosity is defined as the ratio of the pore volume to the total volume of sediment. Therefore, the new porosity of each layer after decompaction is calculable if the top and bottom positions of that layer are known. Equation (8) shows that porosity is a function of depth, so the void volume for any layer with top depth, \( z_1 \), and bottom depth, \( z_2 \), is:
where $f_0$ is surface porosity of layer 2. The total void volume for the decompacted layer 2 (Fig. 17) is:

$$V_w = \int_{z_1}^{z_2} \exp (-cz) \, dz$$

(13)

The porosity of layer 2, after decompaction becomes:

$$f = \frac{V_w}{V} = \frac{V_w2'}{L2'}$$

(15)

where, $V_w$ is the void volume before compaction, $V$ is the total volume of rock, $V_w2'$ is the void volume after compaction $L2'$ is the thickness of rock after compaction.

**Paleothermal Conductivity**

Porosity and temperature are the critical factors in determining paleothermal conductivity. The composition of sediment is essentially constant throughout geological ages, however, the temperature and the volume ratio of the rock matrix is not. Thermal conductivity as a function of porosity can be obtained by using the relation for thermal conductivity measurements on crushed rocks samples (Sass, 1971) i.e.
\[ KS = (Kw)^f (Kr)^{(1-f)} \] (16)

where, KS is the thermal conductivity of saturated sediment, Kr is the thermal conductivity of rock matrix, Kw is the thermal conductivity of water. Conductivity values for a typical section of the Williston Basin are given in appendix.

**Paleo-temperature**

The temperature at the top of each layer after decompaction can be obtained by equation 2. For the previous decompaction example (see Fig. 17) the surface temperature of each layer, \( T_n \), is calculated by the equation:

\[ T_n = T_{n-1} + \left( \frac{Q}{k_{n-1}} \right) \times L_{n-1} \] (17)

where, \( T_n \) is the surface temperature of the nth layer, \( T_{n-1} \) is the surface temperature of (n+1)th layer, Q is heat flow which is 60 mW m\(^{-2}\) in this study, \( k_{n-1} \) is the formational thermal conductivity of the (n-1)th layer and \( L_{n-1} \) is the thickness of the (n-1)th layer.

To calculate the temperature effect on thermal conductivity, only the surface temperature of each layer \( T_n \) is used. This method of approximation underestimates the temperature change, particularly for those layers wherein thicknesses are great; because within the same layer,
surface temperature is lower than the temperature at deeper levels. However, the temperature effect on the thermal conductivity is not so great as to invalidate this method.

**Time Temperature Index, (TTI)**


Lopatin (1971) related the temperature and time to the thermal maturity of organic material in the sediment. The thermal alteration rate of organics changes by a factor of 2 for every 10 °C increase of temperature; therefore, the thermal alteration rate can be extrapolated up or down within a certain temperature interval.

Every 10 °C interval of temperature is equal to a power number, n, with a base of 2 (see Table 2). The factor of $2^n$ is the temperature weighting factor. The maturation of organic material is calculated by multiplying the temperature weighting factor by the residence time as:

$$\text{TTI} = \sum_{n_{\text{min}}}^{n_{\text{max}}} T_n \cdot r^n$$  \hspace{1cm} (18)

where $T_n$ is the time span the organic material resides in the temperature interval of which weighting factor is $r^n$, $n_{\text{min}}$ and $n_{\text{max}}$ are the minimum and maximum power number, n,
corresponding to every 10 °C increment.

The following is the algorithm used in a BASIC computer program designed to calculate equation 18. Assuming that layer 5 exposed to temperature T1, T2, T3, T4, at ages of AX1, AX2, AX3 and AX4 respectively. AX1 is younger than AX4 and T1 is lower than T4. The TTI can be obtained by summing up the multiple of the time interval between two successive layers with their corresponding temperature weighting factor, equation 19.

\[
TTI = \sum_{n=2}^{4} (AX(N) - AX(N-1)) \times (r^n)
\]  

(19)

However, an accurate dating of sediment and an estimation of sedimentation rate is always difficult. Hence, it becomes difficult to evaluate the exact residence time for the sediment or to determine at which time a certain temperature occurred. If the temperature of T1 is considered as the temperature throughout the time between AX1 and AX2, the TTI will be underestimated. If the temperature of T2 is considered as the temperature throughout the time between AX1 and AX2, the TTI will be overestimated.

Since precise estimates of residence time of any layer are not possible, the TTI value is better estimated by a moderate method that will avoid extreme values. The power of the weighting factor changes by a factor of 1 for every
10 °C temperature change, and there may be several 10 °C increments between T1 and T2 that correspond to several different temperature factors. Hence a method that will avoid extreme estimates of TTI is as follows:

\[ IN = \frac{(T_n - T_{n-1})}{10} \]  

(20)

The span of time for which every 10 °C increment of temperature resides is derived by dividing the time interval between AX(N) and AX(N-1) into IN units as:

\[ TM = \frac{(AX(N) - AX(N-1))}{IN} \]  

(21)

The weighting factor, \( r^n \), is determined according to every 10 °C increment of temperature begins from Tn-1 to Tn. The computer program in the Appendix D, avoids repeating temperatures and superposition of times. Also, we have considered that the power of weighting factor is proportional to every degree of temperature unlike the ten degrees in Waples's (1980). Finally, the TTI of layer 5 is:

\[ TTI = \sum_{n=1}^{4} TM \times (r^n) \]  

(22)

where \( r^n \) is corresponding to every 10 °C change between Tn-1 and Tn.
RESULTS

Porosity

Application of the depth-porosity relation to the Bakken Shale of four wells in the North Dakota portion of the Williston Basin shows various degrees of compaction due to different burial depths at each location. The porosities of Bakken Shale at locations NDGS 11734, NDGS 6684, NDGS 4918, NDGS 893 have decreased 72%, 56%, 49%, 39% from their original porosities from the Paleozoic until the present time respectively (Tables 3, 4, 5, 6 and Figs. 18, 19). The thickness of Bakken shale at each location also shows a value which is proportional to the decreasing porosity throughout geological time (Tables 3, 4, 5, 6 and Fig. 20).

Both changes in porosity and thickness by decompaction will have effects on the thermal structure of the Williston Basin. The decrease of porosity and the thinning of Formations will reduce the temperature of the rocks due to the increase of thermal conductivity and the decrease of blanket effect.

Thermal Conductivity

The thermal conductivities of the Bakken Shale, which are corrected by compaction and temperature effects, show
### Table 3
Compaction History of the Bakken Formation for the NDGS well number 11734

<table>
<thead>
<tr>
<th>AGE (Ma)</th>
<th>POROSITY</th>
<th>THICKNESS (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.6189</td>
<td>0.070</td>
</tr>
<tr>
<td>21</td>
<td>0.4520</td>
<td>0.048</td>
</tr>
<tr>
<td>24</td>
<td>0.4513</td>
<td>0.048</td>
</tr>
<tr>
<td>28</td>
<td>0.4245</td>
<td>0.046</td>
</tr>
<tr>
<td>29</td>
<td>0.4163</td>
<td>0.045</td>
</tr>
<tr>
<td>30</td>
<td>0.4133</td>
<td>0.045</td>
</tr>
<tr>
<td>31</td>
<td>0.4034</td>
<td>0.044</td>
</tr>
<tr>
<td>223</td>
<td>0.3010</td>
<td>0.038</td>
</tr>
<tr>
<td>237</td>
<td>0.2828</td>
<td>0.037</td>
</tr>
<tr>
<td>263</td>
<td>0.2668</td>
<td>0.036</td>
</tr>
<tr>
<td>271</td>
<td>0.2551</td>
<td>0.036</td>
</tr>
<tr>
<td>291</td>
<td>0.1739</td>
<td>0.032</td>
</tr>
</tbody>
</table>

### Table 4
Compaction History of the Bakken Formation for the NDGS Well Number 4918

<table>
<thead>
<tr>
<th>AGE (Ma)</th>
<th>POROSITY</th>
<th>THICKNESS (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.6099</td>
<td>0.128</td>
</tr>
<tr>
<td>1</td>
<td>0.6079</td>
<td>0.127</td>
</tr>
<tr>
<td>8</td>
<td>0.5313</td>
<td>0.107</td>
</tr>
<tr>
<td>9</td>
<td>0.5109</td>
<td>0.102</td>
</tr>
<tr>
<td>19</td>
<td>0.4808</td>
<td>0.096</td>
</tr>
<tr>
<td>20</td>
<td>0.4803</td>
<td>0.096</td>
</tr>
<tr>
<td>28</td>
<td>0.4724</td>
<td>0.095</td>
</tr>
<tr>
<td>33</td>
<td>0.4715</td>
<td>0.095</td>
</tr>
<tr>
<td>163</td>
<td>0.4463</td>
<td>0.090</td>
</tr>
<tr>
<td>223</td>
<td>0.3927</td>
<td>0.082</td>
</tr>
<tr>
<td>237</td>
<td>0.3710</td>
<td>0.079</td>
</tr>
<tr>
<td>263</td>
<td>0.3627</td>
<td>0.078</td>
</tr>
<tr>
<td>291</td>
<td>0.3103</td>
<td>0.072</td>
</tr>
<tr>
<td>363</td>
<td>0.3103</td>
<td>0.072</td>
</tr>
</tbody>
</table>
Table 5
Compaction History of the Bakken Formation for the NDGS well number 6684

<table>
<thead>
<tr>
<th>AGE (Ma)</th>
<th>POROSITY</th>
<th>THICKNESS (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.6290</td>
<td>0.006</td>
</tr>
<tr>
<td>3</td>
<td>0.6211</td>
<td>0.006</td>
</tr>
<tr>
<td>19</td>
<td>0.6211</td>
<td>0.006</td>
</tr>
<tr>
<td>28</td>
<td>0.4750</td>
<td>0.004</td>
</tr>
<tr>
<td>33</td>
<td>0.4740</td>
<td>0.004</td>
</tr>
<tr>
<td>163</td>
<td>0.4486</td>
<td>0.004</td>
</tr>
<tr>
<td>223</td>
<td>0.3865</td>
<td>0.004</td>
</tr>
<tr>
<td>237</td>
<td>0.3680</td>
<td>0.004</td>
</tr>
<tr>
<td>263</td>
<td>0.3519</td>
<td>0.004</td>
</tr>
<tr>
<td>271</td>
<td>0.3375</td>
<td>0.003</td>
</tr>
<tr>
<td>291</td>
<td>0.2744</td>
<td>0.003</td>
</tr>
<tr>
<td>363</td>
<td>0.2744</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Table 6
Compaction History of the Bakken Formation for the NDGS well number 893

<table>
<thead>
<tr>
<th>AGE (Ma)</th>
<th>POROSITY</th>
<th>THICKNESS (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.6292</td>
<td>0.005</td>
</tr>
<tr>
<td>8</td>
<td>0.6231</td>
<td>0.005</td>
</tr>
<tr>
<td>9</td>
<td>0.5997</td>
<td>0.005</td>
</tr>
<tr>
<td>18</td>
<td>0.5711</td>
<td>0.005</td>
</tr>
<tr>
<td>20</td>
<td>0.5688</td>
<td>0.005</td>
</tr>
<tr>
<td>21</td>
<td>0.5473</td>
<td>0.004</td>
</tr>
<tr>
<td>163</td>
<td>0.5292</td>
<td>0.004</td>
</tr>
<tr>
<td>223</td>
<td>0.4571</td>
<td>0.004</td>
</tr>
<tr>
<td>237</td>
<td>0.4415</td>
<td>0.004</td>
</tr>
<tr>
<td>263</td>
<td>0.4276</td>
<td>0.004</td>
</tr>
<tr>
<td>291</td>
<td>0.3846</td>
<td>0.003</td>
</tr>
<tr>
<td>363</td>
<td>0.3846</td>
<td>0.003</td>
</tr>
</tbody>
</table>
Figure 18. Compaction history of Bakken Formation at NDGS well number 11734.
COMPACTIONAL HISTORY OF BAKKEN FM.
NDGS# 11734

POROSITY

0.65
0.6
0.55
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0
100
200
300
400
AGE (Ma)
Figure 19. Compaction history of Bakken Formation at four locations: NDGS 11734, NDGS 4918, NDGS 6684 and NDGS 893.
COMPACTIONAL HISTORY FOR THE BAKKEN

![Graph showing compactional history with various data points for different samples.](image)
Figure 20. Compaction history of Bakken Formation at NDGS well number 11734 location.
COMPACTIONAL HISTORY OF BAKKEN

NDGS# 11734

THICKNESS (km)

0.03 0.035 0.04 0.045 0.05 0.055 0.06 0.065 0.07

AGE (Ma)

0 100 200 300 400
values different from the values estimated by a model without compaction and temperature effects. The thermal conductivities of the Bakken Shale increase by as much as a 46%, 39%, 33% and 30% of the values before compaction, at locations of NDGS well number 11734, 6684, 4918 and 893 respectively (Tables 7, 8, 9, 10; Figs. 12, 15, 21).

**Temperature**

The temperature history of the Bakken Shale generally shows a four-stage curve. The different stages reflect varying deposition rates and lithologic characters of the overlying sediments (Table 7, 8, 9, 10 and Figs. 22, 23). The temperature increase of the Bakken Shale throughout time is caused by the overlying sediments that blanket the heat from the deep crust. The temperature of Bakken Shale increased more slowly in its early history and increased faster in its late history. For the Bakken Shale at NDGS# 11734, the fastest rate of temperature increase occurred due to the rapid deposition of Mesozoic clastic sediments, whereas the second fastest rate occurred due to the clastic blanket deposited during the late Paleozoic (Figs. 24, 25, 26). Because the thermal conductivity of carbonates is higher than that of clastics, heat dissipates faster through carbonates than through clastics. Hence the blanket effect caused by the deposition of carbonates is smaller in magnitude than by the deposition of clastics.
<table>
<thead>
<tr>
<th>AGE (Ma)</th>
<th>DECOMPACTION MODEL</th>
<th>CONSTANT CONDUCTIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>T (°C)</td>
<td>K</td>
</tr>
<tr>
<td>0</td>
<td>20.00</td>
<td>0.93</td>
</tr>
<tr>
<td>21</td>
<td>38.63</td>
<td>1.08</td>
</tr>
<tr>
<td>24</td>
<td>39.18</td>
<td>1.08</td>
</tr>
<tr>
<td>28</td>
<td>39.31</td>
<td>1.11</td>
</tr>
<tr>
<td>29</td>
<td>41.38</td>
<td>1.12</td>
</tr>
<tr>
<td>30</td>
<td>41.89</td>
<td>1.13</td>
</tr>
<tr>
<td>31</td>
<td>42.94</td>
<td>1.14</td>
</tr>
<tr>
<td>223</td>
<td>62.21</td>
<td>1.26</td>
</tr>
<tr>
<td>237</td>
<td>68.19</td>
<td>1.28</td>
</tr>
<tr>
<td>263</td>
<td>73.36</td>
<td>1.29</td>
</tr>
<tr>
<td>271</td>
<td>76.81</td>
<td>1.30</td>
</tr>
<tr>
<td>291</td>
<td>113.03</td>
<td>1.36</td>
</tr>
<tr>
<td>363</td>
<td>113.03</td>
<td>1.36</td>
</tr>
</tbody>
</table>

AGE (Ma) is formation age. T (°C) is formation temperature. K, KW and KR (W/m/K) are thermal conductivity of formation, thermal conductivity of interstitial fluid and thermal conductivity of matrix rock respectively.
Table 8
Conductivity-dependent Thermal History of the Bakken Formation at NDGS Well Number 4918

<table>
<thead>
<tr>
<th>AGE (Ma)</th>
<th>T (°C)</th>
<th>K (W/m/K)</th>
<th>KW (W/m/K)</th>
<th>KR (W/m/K)</th>
<th>T (°C)</th>
<th>K (W/m/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20</td>
<td>0.94</td>
<td>0.63</td>
<td>1.74</td>
<td>20</td>
<td>1.5</td>
</tr>
<tr>
<td>1</td>
<td>20.25</td>
<td>0.91</td>
<td>0.60</td>
<td>1.74</td>
<td>20.07</td>
<td>1.5</td>
</tr>
<tr>
<td>8</td>
<td>26.91</td>
<td>0.99</td>
<td>0.61</td>
<td>1.73</td>
<td>23.17</td>
<td>1.5</td>
</tr>
<tr>
<td>9</td>
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<td>0.62</td>
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<td>1.5</td>
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<td>0.62</td>
<td>1.71</td>
<td>25.84</td>
<td>1.5</td>
</tr>
<tr>
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<td>36.08</td>
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<td>0.62</td>
<td>1.71</td>
<td>25.84</td>
<td>1.5</td>
</tr>
<tr>
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<td>1.06</td>
<td>0.62</td>
<td>1.71</td>
<td>26.62</td>
<td>1.5</td>
</tr>
<tr>
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<td>36.26</td>
<td>1.06</td>
<td>0.62</td>
<td>1.71</td>
<td>26.68</td>
<td>1.5</td>
</tr>
<tr>
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<td>40.40</td>
<td>1.09</td>
<td>0.63</td>
<td>1.70</td>
<td>28.25</td>
<td>1.5</td>
</tr>
<tr>
<td>223</td>
<td>49.06</td>
<td>1.15</td>
<td>0.64</td>
<td>1.69</td>
<td>33.05</td>
<td>1.5</td>
</tr>
<tr>
<td>237</td>
<td>54.03</td>
<td>1.18</td>
<td>0.64</td>
<td>1.68</td>
<td>35.74</td>
<td>1.5</td>
</tr>
<tr>
<td>263</td>
<td>55.84</td>
<td>1.19</td>
<td>0.65</td>
<td>1.68</td>
<td>36.99</td>
<td>1.5</td>
</tr>
<tr>
<td>291</td>
<td>58.09</td>
<td>1.25</td>
<td>0.65</td>
<td>1.67</td>
<td>57.48</td>
<td>1.5</td>
</tr>
<tr>
<td>363</td>
<td>58.09</td>
<td>1.25</td>
<td>0.65</td>
<td>1.67</td>
<td>57.48</td>
<td>1.5</td>
</tr>
</tbody>
</table>

AGE (Ma) is formation age. T (°C) is formation temperature. K, KW and KR (W/m/K) are thermal conductivity of formation, thermal conductivity of interstitial fluid and thermal conductivity of matrix rock respectively.
### Table 9

Thermal History of the Bakken Formation at NDGS Well Number 6684

<table>
<thead>
<tr>
<th>AGE (Ma)</th>
<th>T (°C)</th>
<th>K</th>
<th>KW</th>
<th>KR</th>
<th>T (°C)</th>
<th>K</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>20.00</td>
<td>0.92</td>
<td>0.63</td>
<td>1.74</td>
<td>20.00</td>
<td>1.5</td>
</tr>
<tr>
<td>3</td>
<td>20.89</td>
<td>0.90</td>
<td>0.60</td>
<td>1.74</td>
<td>20.26</td>
<td>1.5</td>
</tr>
<tr>
<td>19</td>
<td>20.88</td>
<td>0.90</td>
<td>0.60</td>
<td>1.74</td>
<td>20.26</td>
<td>1.5</td>
</tr>
<tr>
<td>28</td>
<td>36.41</td>
<td>1.06</td>
<td>0.62</td>
<td>1.74</td>
<td>26.93</td>
<td>1.5</td>
</tr>
<tr>
<td>33</td>
<td>36.57</td>
<td>1.06</td>
<td>0.62</td>
<td>1.71</td>
<td>26.98</td>
<td>1.5</td>
</tr>
<tr>
<td>163</td>
<td>40.77</td>
<td>1.09</td>
<td>0.63</td>
<td>1.70</td>
<td>28.51</td>
<td>1.5</td>
</tr>
<tr>
<td>223</td>
<td>50.72</td>
<td>1.16</td>
<td>0.64</td>
<td>1.69</td>
<td>33.93</td>
<td>1.5</td>
</tr>
<tr>
<td>237</td>
<td>54.81</td>
<td>1.18</td>
<td>0.64</td>
<td>1.68</td>
<td>35.82</td>
<td>1.5</td>
</tr>
<tr>
<td>263</td>
<td>58.60</td>
<td>1.20</td>
<td>0.65</td>
<td>1.67</td>
<td>38.98</td>
<td>1.5</td>
</tr>
<tr>
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<td>1.67</td>
<td>42.28</td>
<td>1.5</td>
</tr>
<tr>
<td>291</td>
<td>83.20</td>
<td>1.28</td>
<td>0.67</td>
<td>1.63</td>
<td>68.03</td>
<td>1.5</td>
</tr>
<tr>
<td>363</td>
<td>83.20</td>
<td>1.28</td>
<td>0.67</td>
<td>1.63</td>
<td>68.03</td>
<td>1.5</td>
</tr>
</tbody>
</table>

AGE (Ma) is formation age. T (°C) is formation temperature. K, KW and KR (W/m/K) are thermal conductivity of formation, thermal conductivity of interstitial fluid, and thermal conductivity of matrix rock respectively.
Table 10
Thermal History of the Bakken Formation at NDGS well number 893

<table>
<thead>
<tr>
<th>DECOMPACTION MODEL</th>
<th>CONSTANT CONDUCTIVITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>AGE (Ma)</td>
<td>T (°C)</td>
</tr>
<tr>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>8</td>
<td>21.11</td>
</tr>
<tr>
<td>9</td>
<td>23.34</td>
</tr>
<tr>
<td>16</td>
<td>26.48</td>
</tr>
<tr>
<td>20</td>
<td>26.77</td>
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<tr>
<td>21</td>
<td>29.13</td>
</tr>
<tr>
<td>163</td>
<td>31.56</td>
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<tr>
<td>223</td>
<td>42.49</td>
</tr>
<tr>
<td>237</td>
<td>44.88</td>
</tr>
<tr>
<td>263</td>
<td>47.35</td>
</tr>
<tr>
<td>291</td>
<td>58.22</td>
</tr>
<tr>
<td>363</td>
<td>58.22</td>
</tr>
</tbody>
</table>

AGE (Ma) is formation age. T (°C) is formation temperature. K, KW and KR (W/m/K) are thermal conductivity of formation, thermal conductivity of interstitial fluid and thermal conductivity of matrix rock respectively.
Figure 21. Temperature-dependent thermal conductivity of interstitial water, rock matrix and sediment versus temperature for Bakken Formation.
CONDUCTIVITY VS TEMPERATURE

BAKKEN SHALE, NDGS# 11734

THERMAL K (W/m/K)

20 40 60 80 100 120
TEMPERATURE (Deg.C)

□ MATRIX    + WATER    ○ SED
Figure 22. Thermal history of Bakken Formation by constant-conductivity model.
THERMAL HISTORY OF BAKKEN FORMATION

CONSTANT CONDUCTIVITY

TEMPERATURE (Deg. C)

AGE (Ma.)

NDGS# 11734
Figure 23. Thermal history of Bakken Formation by decompaction model.
THERMAL HISTORY OF BAKKEN FORMATION

DECOMPACTIONAL MODEL

TEMPERATURE (Deg. C.)

AGE (Ma.)

NDGS# 11734
Figure 24. Thermal history of Bakken Formation by constant conductivity model.
Thermal History For The Bakken Fm.

CONSTANT CONDUCTIVITY

TEMPERATURE (Deg. C.)

0 100 200 300 400

ACE (Ma.)

#11734 + 6684 ◦ 893 Δ #4918
Figure 25. Thermal history of Bakken Formation by decompaction model.
THERMAL HISTORY OF THE BAKKEN FM.

DECOMPACTION MODEL

TEMPERATURE (°C)

AGE (Ma.)

# 11734 + # 6684 ○ # 893 △ # 4918
Figure 26. Thermal history of Bakken Formation of decompaction and constant conductivity model.
Time Temperature Index

Application of the decompaction method reveals a higher paleotemperature of the Williston Basin than a temperature calculated without decompaction. Compaction affects the thermal structure of the Williston Basin, and the thermal maturity of a primary petroleum source rock, the Bakken Shale. The TTI estimations for the Bakken Shale evaluated by a model without correction of porosity and estimations evaluated by a decompaction model are shown in Table 11. Waples (1980) suggested that the onset of oil generation starts from a TTI value of 15, peaks at a value of 75 and continues to an end value of 160 (see Table 12); the TTI values of the Bakken Shale of the four studied wells show contrasting values that are within or beyond these ranges of oil generation.

The significance of the TTI values of the four studied wells, are that TTI values may be within or beyond the range of oil generation due to decompaction or without decompaction of the sediment. The first obvious example is the TTI values of the Bakken Shale at NDGS# 11734, which are 84.65 for the constant conductivity model and 199.82 for the decompaction model. The TTI value of 84.65 is around the value of peak oil generation, whereas the TTI value of 199.82 is over the end of oil generation. The second example is the TTI values of NDGS 6684, which are 10 for the model of constant conductivity and 30.40 for the
Table 11
TTI values of Bakken Shale in the North Dakota portion of the Williston Basin

<table>
<thead>
<tr>
<th>Well number</th>
<th>TTI (1)</th>
<th>TTI (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NDGS 11734</td>
<td>84.65</td>
<td>199.82</td>
</tr>
<tr>
<td>NDGS 6684</td>
<td>10.00</td>
<td>30.40</td>
</tr>
<tr>
<td>NDGS 4918</td>
<td>5.90</td>
<td>9.56</td>
</tr>
<tr>
<td>NDGS 893</td>
<td>2.89</td>
<td>7.24</td>
</tr>
</tbody>
</table>

TTI(1) is Time Temperature Index of thermal maturity derived from a constant conductivity model, whereas, TTI(2) is from a decompaction model.

Table 12
Threshold values of Lopatin's time-temperature index of maturity (TTI)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Onset of oil generation</td>
</tr>
<tr>
<td>75</td>
<td>Peak oil generation</td>
</tr>
<tr>
<td>160</td>
<td>End oil generation</td>
</tr>
</tbody>
</table>
decompaction model. The TTI value of 10 is beyond the range of oil generation, and the TTI of 30.40 is within the range of oil generation. The other results of TTI values of NDGS 4918 and NDGS 893 also show a higher TTI value in decompaction model and a lower value in a constant conductivity model. However, all the TTI values of NDGS# 4918 and NDGS 893 are lower than 15.
DISCUSSION

Because the lithologies of each basin have their own characters, the depth-porosity curve is not constant for the same lithology in different basins. To obtain a more accurate compaction history, a measurement of characteristic coefficient, c (see Fig. 16 and Table 1) for each lithology of the studied basin is strongly suggested.

Data on local unconformities and thicknesses of sediments eroded are critically important for they may significantly affect both compaction and temperature history of a basin. A method of reestablishing thickness of erosion will add to the accuracy of this study.

More accurate dating of each formation is also important to obtain accurate temperature and compaction history, especially, when TTI is considered as an important method of estimating oil generation.

The TTI values of this study provide another possibility of extrapolating the sedimentary history of the Williston Basin. Some of the sediments have shallow burial depths but high observed maturity index. Such phenomenae imply that there were certain thicknesses of overburden that were eroded away in the past. By applying such a concept and a linear thermal gradient to the Michigan Basin, Cercone (1984) deduced that 1,000 meters of sediment

90
were eroded away in the past. It is suggested by this study that by using a nonlinear thermal gradients, an rees-
tablishment of the sedimentary history of the Williston Basin is not only plausible, but it is also expected to have a better result than a model using a simple thermal gradient.
CONCLUSION

Studies of the thermal history of the Williston Basin show significant differences between a constant conductivity model and a decompaction model. Most of the change of the thermal conductivity of sediment arises from changes of porosity. The compaction of sediment reduces the volume ratio of the interstitial water and consequently increases the thermal conductivity of the sediment.

Decompaction allows us to calculate the thermal conductivity of sediment before it is compacted. Both a thick blanket and lower conductivity will retard the dissipation of heat, and vice versa. The carbonate rocks have higher conductivities than clastic rocks, hence the blanket effect from carbonate is smaller than the blanket effect from clastics of the same thickness.

The decompaction model reveals that the thermal maturity of the Bakken Shale would have been above the end values of oil generation, if the overlying sediments of the Bakken Shale were thicker, or the clastic rock were dominant and thick enough to blanket the heat flow from the deep crust of the Williston Basin. The locations where the depth of the Bakken Shale are shallower than the depth of NDGS well number 4918 and 893, would presumably generate no oil. The Bakken Shale at places where its burial depth
is deeper than these two wells would potentially generate oil.

The results of decompaction model of this study, reveal a way of rough estimation of the thermal maturation. If the burial depth of the Bakken Formation was deeper than the burial depth of Bakken Shale at NDGS 11734, then Bakken Shale would have passed its end value of oil generation. If the burial depth of the Bakken Shale was within the burial depths between the NDGS 11734 and 4918, then the Bakken Shale would be still within the range of oil generation, such as that of NDGS 6684.

For the case of constant heat flow of this study, the thermal maturity of petroleum source rock is greatly controlled by the burial depth. However, other factors such as lithology of the overlying sediment as well as the local heat flow history also affect the thermal maturity of the petroleum source rock.

Estimation of Time Temperature Index of organic sediments will be correct if the factors: surface temperature, surface heat flow, time-dependent thermal conductivity and formation thickness, have been considered in calculating subsurface temperature of a basin.
Appendix A1

Input Data

Table 13.
Input Data for NDGS Well Number 4918

<table>
<thead>
<tr>
<th>Fm.</th>
<th>Depth</th>
<th>Age</th>
<th>K</th>
<th>T1</th>
<th>C</th>
<th>Fo</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pierre</td>
<td>1090</td>
<td>70</td>
<td>1.2</td>
<td>16</td>
<td>.51</td>
<td>.63</td>
<td>2.13</td>
</tr>
<tr>
<td>Greenhorn</td>
<td>2500</td>
<td>92</td>
<td>1.2</td>
<td>17</td>
<td>.51</td>
<td>.63</td>
<td>2.13</td>
</tr>
<tr>
<td>Inyan Kara</td>
<td>2648</td>
<td>126</td>
<td>1.6</td>
<td>20</td>
<td>.39</td>
<td>.56</td>
<td>1.585</td>
</tr>
<tr>
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<td>140</td>
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<td>20</td>
<td>.56</td>
<td>.587</td>
<td>3.678</td>
</tr>
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<td>3793</td>
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<td>3.1</td>
<td>20</td>
<td>.51</td>
<td>.63</td>
<td>4.14</td>
</tr>
<tr>
<td>Big Snowy</td>
<td>4060</td>
<td>330</td>
<td>3.1</td>
<td>20</td>
<td>.39</td>
<td>.56</td>
<td>3.37</td>
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<tr>
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<td>.71</td>
<td>.5</td>
<td>4.417</td>
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<td>.71</td>
<td>.5</td>
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<td>4515</td>
<td>354</td>
<td>3.5</td>
<td>20</td>
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<td>.5</td>
<td>4.417</td>
</tr>
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<td>4708</td>
<td>355</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
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<td>362</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
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<td>363</td>
<td>1.5</td>
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<td>4.417</td>
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<td>.565</td>
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<td>.5</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

T161R82
Depth (ft) is the distance from KB to formation. Age (Ma) is formation age. K (W/m/K) is thermal conductivity of formation. T1(°C) is surface temperature. C (m⁻¹) is characteristic coefficient. Fo is original porosity. α (W/m/K) is thermal conductivity of rock matrix measured at 20 °C.
Appendix A2

Input Data

Table 14.

Input Data for NDGS Well Number 6684

<table>
<thead>
<tr>
<th>Fm.</th>
<th>Depth (ft)</th>
<th>Age (Ma)</th>
<th>K (W/m/K)</th>
<th>T (°C)</th>
<th>C (m⁻¹)</th>
<th>Fo</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
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<td>72</td>
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<td>16</td>
<td>.51</td>
<td>.63</td>
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<td>92</td>
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<td>.63</td>
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<td>.63</td>
<td>2.13</td>
</tr>
<tr>
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<td>3095</td>
<td>126</td>
<td>1.6</td>
<td>20</td>
<td>.39</td>
<td>.56</td>
<td>1.585</td>
</tr>
<tr>
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<td>20</td>
<td>.56</td>
<td>.587</td>
<td>3.678</td>
</tr>
<tr>
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<td>3.1</td>
<td>20</td>
<td>.51</td>
<td>.63</td>
<td>4.14</td>
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<tr>
<td>Big Snowy</td>
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<td>.39</td>
<td>.56</td>
<td>3.37</td>
</tr>
<tr>
<td>Madison Gr.</td>
<td>4534</td>
<td>335</td>
<td>3.0</td>
<td>20</td>
<td>.71</td>
<td>.125</td>
<td>4.576</td>
</tr>
<tr>
<td>Frobish Al.</td>
<td>4651</td>
<td>343</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
<td>Madison Bs.</td>
<td>5791</td>
<td>360</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
<td>Bakken</td>
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<td>363</td>
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<td>20</td>
<td>.51</td>
<td>.63</td>
<td>1.74</td>
</tr>
<tr>
<td>Three Forks</td>
<td>5850</td>
<td>366</td>
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<td>20</td>
<td>.39</td>
<td>.56</td>
<td>2.13</td>
</tr>
<tr>
<td>Birdbear</td>
<td>6000</td>
<td>371</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.01</td>
</tr>
<tr>
<td>Duperow</td>
<td>6108</td>
<td>380</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
<td>Souris Riv.</td>
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<td>.586</td>
<td>.565</td>
<td>4.01</td>
</tr>
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<td>6840</td>
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<td>20</td>
<td>.586</td>
<td>.565</td>
<td>4.01</td>
</tr>
<tr>
<td>Prairie</td>
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<td>3.0</td>
<td>20</td>
<td>.71</td>
<td>.125</td>
<td>4.576</td>
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<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.01</td>
</tr>
<tr>
<td>U. Winnip.</td>
<td>7458</td>
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<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
<td>L. Winnip.</td>
<td>7530</td>
<td>402</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
<td>Ashern</td>
<td>7540</td>
<td>403</td>
<td>3.2</td>
<td>20</td>
<td>.586</td>
<td>.565</td>
<td>4.01</td>
</tr>
<tr>
<td>Total Depth</td>
<td>7550</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

T161R85

Depth (ft) is the distance from KB to formation. Age (Ma) is formation age. K (W/m/K) is thermal conductivity of formation. T1(°C) is surface temperature. C (m⁻¹) is characteristic coefficient. Fo is original porosity. α (W/m/K) is thermal conductivity of rock matrix measured at 20 °C.
## Appendix A3

### Input Data

### Table 15.

Input Data for NDGS Well Number 11734

<table>
<thead>
<tr>
<th>Fm.</th>
<th>Depth</th>
<th>Age</th>
<th>K</th>
<th>T</th>
<th>C</th>
<th>F</th>
<th>α</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pierre</td>
<td>750</td>
<td>72</td>
<td>1.2</td>
<td>16</td>
<td>.51</td>
<td>.63</td>
<td>2.13</td>
</tr>
<tr>
<td>Greenhorn</td>
<td>3955</td>
<td>92</td>
<td>1.2</td>
<td>17</td>
<td>.51</td>
<td>.63</td>
<td>2.13</td>
</tr>
<tr>
<td>Mowry</td>
<td>4232</td>
<td>100</td>
<td>1.2</td>
<td>18</td>
<td>.51</td>
<td>.63</td>
<td>2.13</td>
</tr>
<tr>
<td>Inyan Kara</td>
<td>4581</td>
<td>126</td>
<td>1.6</td>
<td>20</td>
<td>.39</td>
<td>.56</td>
<td>1.585</td>
</tr>
<tr>
<td>Jurassic</td>
<td>5000</td>
<td>140</td>
<td>2.8</td>
<td>20</td>
<td>.56</td>
<td>.587</td>
<td>3.678</td>
</tr>
<tr>
<td>Kibbey Ss.</td>
<td>6496</td>
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<td>20</td>
<td>.27</td>
<td>.4</td>
<td>3.802</td>
</tr>
<tr>
<td>Kibbey Lm.</td>
<td>6659</td>
<td>333</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.01</td>
</tr>
<tr>
<td>Kibbey Si.</td>
<td>6691</td>
<td>334</td>
<td>1.6</td>
<td>20</td>
<td>.39</td>
<td>.56</td>
<td>2.13</td>
</tr>
<tr>
<td>Charles</td>
<td>6789</td>
<td>335</td>
<td>3.0</td>
<td>20</td>
<td>.71</td>
<td>.125</td>
<td>4.576</td>
</tr>
<tr>
<td>Charles Bs.</td>
<td>7261</td>
<td>339</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
<td>Ratcliffe</td>
<td>7271</td>
<td>342</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
<td>Bakken</td>
<td>8618</td>
<td>363</td>
<td>1.5</td>
<td>20</td>
<td>.51</td>
<td>.63</td>
<td>1.74</td>
</tr>
<tr>
<td>Three Forks</td>
<td>8722</td>
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<td>1.6</td>
<td>20</td>
<td>.39</td>
<td>.56</td>
<td>2.13</td>
</tr>
<tr>
<td>Birdbear</td>
<td>8905</td>
<td>371</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.01</td>
</tr>
<tr>
<td>Duperow</td>
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<td>380</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

T161R100

Depth (ft) is the distance from KB to formation. Age (Ma.) is formation age. K (W/m/K) is thermal conductivity of formation. T1(°C) is surface temperature. C (m⁻¹) is characteristic coefficient. Fo is original porosity. α (W/m/K) is thermal conductivity of rock matrix measured at 20 °C.
Appendix A4

Input Data

Table 16.
Input Data for NDGS Well Number 893

<table>
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<tr>
<th>Fm.</th>
<th>Depth</th>
<th>Age</th>
<th>K</th>
<th>T</th>
<th>C</th>
<th>F</th>
<th>a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pierre</td>
<td>1250</td>
<td>72</td>
<td>1.2</td>
<td>16</td>
<td>.51</td>
<td>.63</td>
<td>2.13</td>
</tr>
<tr>
<td>Mowry</td>
<td>1995</td>
<td>100</td>
<td>1.2</td>
<td>18</td>
<td>.51</td>
<td>.63</td>
<td>2.13</td>
</tr>
<tr>
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<td>2192</td>
<td>126</td>
<td>1.6</td>
<td>20</td>
<td>.39</td>
<td>.56</td>
<td>1.585</td>
</tr>
<tr>
<td>Jurassic</td>
<td>2432</td>
<td>140</td>
<td>2.8</td>
<td>20</td>
<td>.56</td>
<td>.587</td>
<td>3.678</td>
</tr>
<tr>
<td>Spearfish</td>
<td>3220</td>
<td>200</td>
<td>3.1</td>
<td>20</td>
<td>.39</td>
<td>.56</td>
<td>4.14</td>
</tr>
<tr>
<td>Ratcliffe</td>
<td>3402</td>
<td>342</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
<td>Frobish.Al.</td>
<td>3592</td>
<td>343</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
<td>State &quot;A&quot;</td>
<td>3611</td>
<td>345</td>
<td>3.0</td>
<td>20</td>
<td>.71</td>
<td>.125</td>
<td>4.576</td>
</tr>
<tr>
<td>Tilston</td>
<td>3831</td>
<td>354</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
<td>Lodgepole</td>
<td>3995</td>
<td>355</td>
<td>3.5</td>
<td>20</td>
<td>.71</td>
<td>.5</td>
<td>4.417</td>
</tr>
<tr>
<td>Bakken</td>
<td>4035</td>
<td>363</td>
<td>1.5</td>
<td>20</td>
<td>.51</td>
<td>.63</td>
<td>1.74</td>
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<tr>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

T158R24
Depth (ft) is the distance from KB to formation. Age (Ma) is formation age. K (W/m/K) is thermal conductivity of formation. T1(°C) is surface temperature. C (m⁻¹) is characteristic coefficient. Fo is original porosity. a (W/m/K) is thermal conductivity of rock matrix measured at 20 °C.
## Appendix B1

Output Data

### Table 17.

Thermal Profile of the Williston Basin at NDGS Well Number 11734 Location

<table>
<thead>
<tr>
<th>fm/period</th>
<th>age (Ma)</th>
<th>temp (°C)</th>
<th>therm. cond. (W/m/K)</th>
<th>sed. water</th>
<th>matrix thick.</th>
<th>porosity (decimal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pierre</td>
<td>0</td>
<td>16.00</td>
<td>1.2</td>
<td>0.56</td>
<td>2.14</td>
<td>0.977</td>
</tr>
<tr>
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<td>20</td>
<td>64.84</td>
<td>1.2</td>
<td>0.65</td>
<td>2.03</td>
<td>0.084</td>
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<td>69.07</td>
<td>1.2</td>
<td>0.66</td>
<td>2.03</td>
<td>0.106</td>
</tr>
<tr>
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<td>54</td>
<td>74.38</td>
<td>1.6</td>
<td>0.66</td>
<td>1.49</td>
<td>0.128</td>
</tr>
<tr>
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<td>68</td>
<td>79.17</td>
<td>2.8</td>
<td>0.67</td>
<td>3.46</td>
<td>0.456</td>
</tr>
<tr>
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<td>260</td>
<td>88.94</td>
<td>3.2</td>
<td>0.67</td>
<td>3.54</td>
<td>0.050</td>
</tr>
<tr>
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<td>261</td>
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<td>0.67</td>
<td>3.73</td>
<td>0.010</td>
</tr>
<tr>
<td>Kibbey Si.</td>
<td>262</td>
<td>90.04</td>
<td>1.6</td>
<td>0.67</td>
<td>1.98</td>
<td>0.030</td>
</tr>
<tr>
<td>Charles</td>
<td>263</td>
<td>91.16</td>
<td>3.0</td>
<td>0.68</td>
<td>4.25</td>
<td>0.144</td>
</tr>
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<td>267</td>
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<td>3.5</td>
<td>0.68</td>
<td>4.09</td>
<td>0.003</td>
</tr>
<tr>
<td>Ratcliffe</td>
<td>270</td>
<td>94.09</td>
<td>3.5</td>
<td>0.68</td>
<td>4.09</td>
<td>0.411</td>
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<td>0.68</td>
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<td>0.032</td>
</tr>
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<td>0.68</td>
<td>1.96</td>
<td>0.056</td>
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<td>104.49</td>
<td>3.5</td>
<td>0.68</td>
<td>3.67</td>
<td>0.029</td>
</tr>
<tr>
<td>Duperow</td>
<td>308</td>
<td>104.99</td>
<td>3.5</td>
<td>0.68</td>
<td>4.04</td>
<td>0.003</td>
</tr>
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</table>
### Table 18.
**Thermal Profile of the Williston Basin at NDGS Well Number 4918 Location**

<table>
<thead>
<tr>
<th>fm/period</th>
<th>age (Ma)</th>
<th>temp (°C)</th>
<th>sed. water</th>
<th>matrix thick.</th>
<th>porosity (decimal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pierre</td>
<td>0</td>
<td>16.00</td>
<td>1.2</td>
<td>0.56</td>
<td>2.14</td>
</tr>
<tr>
<td>Mowry</td>
<td>28</td>
<td>37.49</td>
<td>1.2</td>
<td>0.62</td>
<td>1.20</td>
</tr>
<tr>
<td>Inyan kara</td>
<td>54</td>
<td>39.74</td>
<td>1.6</td>
<td>0.63</td>
<td>1.55</td>
</tr>
<tr>
<td>Jurassic</td>
<td>68</td>
<td>44.43</td>
<td>2.8</td>
<td>0.63</td>
<td>3.59</td>
</tr>
<tr>
<td>Spearfish</td>
<td>128</td>
<td>49.23</td>
<td>3.1</td>
<td>0.64</td>
<td>4.02</td>
</tr>
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<td>Big Snowy</td>
<td>258</td>
<td>50.81</td>
<td>3.1</td>
<td>0.64</td>
<td>3.27</td>
</tr>
<tr>
<td>Madison Gr.</td>
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<td>50.86</td>
<td>3.0</td>
<td>0.64</td>
<td>4.43</td>
</tr>
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<td>3.5</td>
<td>0.64</td>
<td>4.28</td>
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<td>3.5</td>
<td>0.64</td>
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<td>3.5</td>
<td>0.64</td>
<td>4.27</td>
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<td>0.65</td>
<td>4.25</td>
</tr>
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<td>0.65</td>
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<td>66.90</td>
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</table>
## Appendix B3

Output Data

### Table 19.

**Thermal Profile of the Williston Basin at NDGS Well Number 6684 Location**

<table>
<thead>
<tr>
<th>fm/period</th>
<th>age (Ma)</th>
<th>temp (°C)</th>
<th>therm. cond. (W/m/K)</th>
<th>sed. water</th>
<th>matrix</th>
<th>thick. porosity (km)</th>
<th>(decimal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pierre</td>
<td>0</td>
<td>16.00</td>
<td>1.2</td>
<td>0.56</td>
<td>2.14</td>
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</tr>
<tr>
<td>Greenhorn</td>
<td>20</td>
<td>41.76</td>
<td>1.2</td>
<td>0.63</td>
<td>2.08</td>
<td>0.086</td>
<td>0.6300</td>
</tr>
<tr>
<td>Mowry</td>
<td>28</td>
<td>46.05</td>
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<td>0.63</td>
<td>2.07</td>
<td>0.083</td>
<td>0.3978</td>
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<td>Inyan Kara</td>
<td>54</td>
<td>50.21</td>
<td>1.6</td>
<td>0.64</td>
<td>1.53</td>
<td>0.104</td>
<td>0.3799</td>
</tr>
<tr>
<td>Jurassic</td>
<td>68</td>
<td>54.10</td>
<td>2.8</td>
<td>0.64</td>
<td>3.55</td>
<td>0.253</td>
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<td>Spearfish</td>
<td>128</td>
<td>59.52</td>
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<td>0.65</td>
<td>3.98</td>
<td>0.079</td>
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<td>Big Snowy</td>
<td>258</td>
<td>61.05</td>
<td>3.1</td>
<td>0.65</td>
<td>3.98</td>
<td>0.079</td>
<td>0.3268</td>
</tr>
<tr>
<td>Madison Gr.</td>
<td>263</td>
<td>61.11</td>
<td>3.0</td>
<td>0.65</td>
<td>4.39</td>
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<td>0.0463</td>
</tr>
<tr>
<td>Frobisher</td>
<td>271</td>
<td>61.82</td>
<td>3.5</td>
<td>0.65</td>
<td>4.23</td>
<td>0.347</td>
<td>0.1619</td>
</tr>
<tr>
<td>Madison Bs.</td>
<td>288</td>
<td>67.78</td>
<td>3.5</td>
<td>0.66</td>
<td>4.21</td>
<td>0.015</td>
<td>0.1420</td>
</tr>
<tr>
<td>Bakken</td>
<td>291</td>
<td>68.03</td>
<td>1.5</td>
<td>0.66</td>
<td>1.66</td>
<td>0.003</td>
<td>0.2539</td>
</tr>
<tr>
<td>Three Forks</td>
<td>294</td>
<td>68.16</td>
<td>1.6</td>
<td>0.66</td>
<td>2.03</td>
<td>0.046</td>
<td>0.2769</td>
</tr>
<tr>
<td>Birdbear</td>
<td>299</td>
<td>69.87</td>
<td>3.5</td>
<td>0.66</td>
<td>3.81</td>
<td>0.033</td>
<td>0.1349</td>
</tr>
<tr>
<td>Duperow</td>
<td>301</td>
<td>70.43</td>
<td>3.5</td>
<td>0.66</td>
<td>4.19</td>
<td>0.013</td>
<td>0.1273</td>
</tr>
<tr>
<td>Souris Riv.</td>
<td>308</td>
<td>72.66</td>
<td>3.2</td>
<td>0.66</td>
<td>3.80</td>
<td>0.094</td>
<td>0.1711</td>
</tr>
<tr>
<td>Dawson Ba.</td>
<td>314</td>
<td>74.41</td>
<td>3.2</td>
<td>0.66</td>
<td>3.79</td>
<td>0.052</td>
<td>0.1639</td>
</tr>
<tr>
<td>Prairie</td>
<td>317</td>
<td>75.39</td>
<td>3.0</td>
<td>0.66</td>
<td>4.32</td>
<td>0.133</td>
<td>0.0261</td>
</tr>
<tr>
<td>Winnepogo</td>
<td>326</td>
<td>78.05</td>
<td>3.5</td>
<td>0.67</td>
<td>4.16</td>
<td>0.003</td>
<td>0.0996</td>
</tr>
<tr>
<td>Upper Winn.</td>
<td>328</td>
<td>78.10</td>
<td>3.5</td>
<td>0.67</td>
<td>4.16</td>
<td>0.022</td>
<td>0.0987</td>
</tr>
<tr>
<td>Lower Winn.</td>
<td>330</td>
<td>78.48</td>
<td>3.5</td>
<td>0.67</td>
<td>4.16</td>
<td>0.003</td>
<td>0.0978</td>
</tr>
<tr>
<td>Ashern</td>
<td>331</td>
<td>78.53</td>
<td>3.2</td>
<td>0.67</td>
<td>3.78</td>
<td>0.050</td>
<td>0.1467</td>
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</table>
### Table 20.
Thermal Profile of the Williston Basin at NDGS Well Number 893 Location

<table>
<thead>
<tr>
<th>fm/period</th>
<th>age (Ma)</th>
<th>temp (°C)</th>
<th>therm.cond. (W/m/K)</th>
<th>thick. (m)</th>
<th>porosity (decimal)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>sed.</td>
<td>water</td>
<td>matrix</td>
</tr>
<tr>
<td>Pierre</td>
<td>0</td>
<td>16.00</td>
<td>0.97</td>
<td>0.56</td>
<td>2.14</td>
</tr>
<tr>
<td>Mowry</td>
<td>28</td>
<td>33.31</td>
<td>1.09</td>
<td>0.62</td>
<td>2.10</td>
</tr>
<tr>
<td>Inyan kara</td>
<td>54</td>
<td>37.22</td>
<td>1.00</td>
<td>0.62</td>
<td>1.55</td>
</tr>
<tr>
<td>Jurassic</td>
<td>68</td>
<td>42.08</td>
<td>1.71</td>
<td>0.63</td>
<td>3.60</td>
</tr>
<tr>
<td>Spearfish</td>
<td>128</td>
<td>51.50</td>
<td>1.85</td>
<td>0.64</td>
<td>4.01</td>
</tr>
<tr>
<td>Ratcliffe</td>
<td>270</td>
<td>53.45</td>
<td>2.49</td>
<td>0.64</td>
<td>4.27</td>
</tr>
<tr>
<td>Frobisher</td>
<td>271</td>
<td>54.94</td>
<td>2.52</td>
<td>0.64</td>
<td>4.26</td>
</tr>
<tr>
<td>State A</td>
<td>273</td>
<td>55.08</td>
<td>2.62</td>
<td>0.64</td>
<td>4.42</td>
</tr>
<tr>
<td>Tilston</td>
<td>282</td>
<td>56.71</td>
<td>2.61</td>
<td>0.65</td>
<td>4.25</td>
</tr>
<tr>
<td>Lodgepole</td>
<td>283</td>
<td>57.93</td>
<td>2.64</td>
<td>0.65</td>
<td>4.25</td>
</tr>
<tr>
<td>Bakken</td>
<td>291</td>
<td>58.22</td>
<td>1.16</td>
<td>0.65</td>
<td>1.67</td>
</tr>
</tbody>
</table>
Appendix C

"STRIP" BASIC Computer Program

For Calculating Time-dependency of Thermal Conductivity

10 CLS
20 DEF SNG A-V,X,Z
30 DIM PRT(22),PT(22),MT(22),IKT(22),JT(22),SPT(22),BST(22)
40 DIM MGT(22),TT(22),FAT(22),FRT(22),BT(22),MST(22)
50 DIM DDT(22),DWT(22),DAT(22),IT(22),AX(22),TOTDT(22),TTI(22)
60 CONST
70 LOCATE 1,5
80 PRINT "program to determine temperature history of Williston Basin strata based on depth-dependent thermal conductivity: well# 4918"
90 E=2.7182818#
100 GOTO 320
110 LOCATE 6,S:INPUT "enter well number =" ; WN
120 LOCATE 8,5:INPUT "enter present surface temperature (°C) =" ; APRT
130 LOCATE 9,5:INPUT "enter Pierre data: depth (ft) =" ; PD
140 LOCATE 10,5:INPUT "enter Mowry data: depth (ft) =" ; MD
150 LOCATE 11,5:INPUT "enter Inyan Kara data: depth (ft) =" ; IKD
160 LOCATE 12,5:INPUT "enter Spearfish data: depth (ft) =" ; SPD
170 LOCATE 13,5:INPUT "enter Big Snowy data: depth (ft) =" ; BSD
180 LOCATE 14,5:INPUT "enter Madison group data: depth (ft) =" ; MGD
190 LOCATE 15,5:INPUT "enter Frobisher alida intv. data: depth (ft) =" ; FAD
200 LOCATE 16,5:INPUT "enter Rival subintv. data: depth (ft) =" ; FRD
210 LOCATE 17,5:INPUT "enter Rival intv. data: depth (ft) =" ; RDI
220 LOCATE 18,5:INPUT "enter Boisneau intv. data: depth (ft) =" ; BD
230 LOCATE 19,5:INPUT "enter Madison base data: depth (ft) =" ; MBD
240 LOCATE 20,5:INPUT "enter Bakken data: depth (ft) =" ; BD
250 LOCATE 21,5:INPUT "enter Duperow data: depth (ft) =" ; DDD
260 LOCATE 22,5:INPUT "enter Winnepo data: depth (ft) =" ; DWD
270 LOCATE 23,5:INPUT "enter Ashern data: depth (ft) =" ; DAD
280 LOCATE 24,5:INPUT "enter Interlake data: depth (ft) =" ; ID
290 LOCATE 25,5:INPUT "enter total depth: depth (ft) =" ; TOTDP
300 CLS:LOCATE 10,5:INPUT:"to decompact sed. press return. else 1"; WRCN
310 CLS
320 CLS: LOCATE 6,5:INPUT;"enter heat flow for tejas-zuni sequence " ; QZ
330 LOCATE 7,5:INPUT;"enter heat flow for abasaroka sequence " ; QA
340 LOCATE 8,5:INPUT;"enter heat flow for kaskaskia sequence " ; QK
350 LOCATE 9,5:INPUT;"enter heat flow for tippecanoe sequence " ; QT
360 LOCATE 10,5:INPUT;"enter heat flow for sauk sequence " ; QS
370 DO PRINT=0
380 FM=0.003048
390 MD=MD*FM:IKD=IKD*FM:JD=JD*FM:SPD=SPD*FM:BSD=BSD*FM
400 MGD=MGD*FM:FAD=FAD*FM:FRD=FRD*FM:TD=TD*FM:BID=BID*FM

103
MBD=MBD*FM: BD=BD*FM: DDD=DDD*FM: DWD=DWD*FM: DAD=DAD*FM

ID=ID*FM: PD=PD*FM: TOTDP=TOTDP*FM

PD1=PD: MD1=MD: IKD1=IKD: JD1=JD: SPD1=SPD: BSD1=BSD

MGD1=MGD: FAD1=FAD: FRD1=FRD: TD1=TD: BID1=BID: MBD1=MBD: BD1=BD

DDD1=DDD: DWD1=DWD: DAD1=DAD: ID1=ID: TOTDP1=TOTDP

FOSS=.4: FOSH=.63: FOSSH=.56: FOLM=.5: CSH=.51: CSS=.27: CSSH=.39: CLM=.71

CLS

PRINT "well number = n" ndgs; WN
PRINT "present surface temperature (°C) =": APRT
PRINT "pierre depth (km) =": PD
PRINT "mowry depth (km) =": MD
PRINT "inyan kara depth (km) =": IKD
PRINT "jurassic depth (km) =": JD
PRINT "spearfish depth (km) =": SPD
PRINT "big snow depth (km) =": BSD
PRINT "madison group depth (km) =": MGD
PRINT "frobiner depth (km) =": FAD
PRINT "rival subintv. depth (km) =": FRD
PRINT "clinton intv. depth (km) =": TD
PRINT "bottineau intv. depth (km) =": BID
PRINT "madison base depth (km) =": MBD
PRINT "bakken depth (km) =": BD
PRINT "duperon depth (km) =": DDD
PRINT "winnepego depth (km) =": DWD
PRINT "ashern depth (km) =": DAD
PRINT "interlake depth (km) =": ID
PRINT "total depth (km) =": TOTDP

FOR Y=1 TO 18 STEP 1

IF Y=1 THEN G=PD: Tl=APRT: AX(1)=72: Q=QZ
IF Y=2 THEN G=MD: Tl=17: AX(2)=100: Q=QZ
IF Y=3 THEN G=IKD: Tl=18: AX(3)=126: Q=QZ
IF Y=4 THEN G=JD: Tl=20: AX(4)=140: Q=QZ
IF Y=5 THEN G=SPD: Tl=20: AX(5)=200: Q=QA
IF Y=6 THEN G=BSD: Tl=20: AX(6)=330: Q=QK
IF Y=7 THEN G=MGD: Tl=20: AX(7)=335: Q=QK
IF Y=8 THEN G=FAD: Tl=20: AX(8)=343: Q=QK
IF Y=9 THEN G=FARD: Tl=20: AX(9)=344: Q=QK
IF Y=10 THEN G=TD: Tl=20: AX(10)=364: Q=QK
IF Y=11 THEN G=BID: Tl=20: AX(11)=356: Q=QK
IF Y=12 THEN G=MBD: Tl=20: AX(12)=362: Q=QK
IF Y=13 THEN G=BD: Tl=20: AX(13)=363: Q=QK
IF Y=14 THEN G=DDD: Tl=20: AX(14)=380: Q=QK
IF Y=15 THEN G=DWD: Tl=20: AX(15)=398: Q=QK
IF Y=16 THEN G=DAD: Tl=20: AX(16)=403: Q=QK
IF Y=17 THEN G=ID: Tl=20: AX(17)=405: Q=QT
IF Y=18 THEN GOTO 3950

AX=AX(Y)
GOTO 1200

T=0
T=T1+((Z*Q)/(K))+A
A=T-T1

CL
960  CONST(0) = 0.56 : CONST(1) = .0019763 : CONST(2) = -8.29*10^(-6)
970  CONST(3) = 5.05*10^(-9)
980  KW = CONST(0)
990  FOR II = 1 TO 3
1000  KW = KW + CONST(II) * T^II
1010  NEXT
1020  TOTDT(Y) = T1 + A
1030  IF W = 1 GOTO 1380
1040  IF W = 2 GOTO 1460
1050  IF W = 3 GOTO 1570
1060  IF W = 4 GOTO 1680
1070  IF W = 5 GOTO 1790
1080  IF W = 6 GOTO 1890
1090  IF W = 7 GOTO 1990
1100  IF W = 8 GOTO 2100
1110  IF W = 9 GOTO 2210
1120  IF W = 10 GOTO 2320
1130  IF W = 11 GOTO 2420
1140  IF W = 12 GOTO 2520
1150  IF W = 13 GOTO 2640
1160  IF W = 14 GOTO 2740
1170  IF W = 15 GOTO 2840
1180  IF W = 16 GOTO 2940
1190  IF W = 17 GOTO 3030
1200  A = 0
1210  Z4 = 0
1220  PT(Y) = T1 + A : R = GD - G : W = 1 : Z = ZG : PA = 72 - AXY
1230  IF PA < 0 THEN PA = 0 : KP = 0 : PT(Y) = 0 : GOTO 1380
1240  Z1 = PDL : ZZ = MD1
1250  GOSUB 3760
1260  CONST(0) = 0.56 : CONST(1) = .0019763 : CONST(2) = -8.29*10^(-6)
1270  CONST(3) = 5.05*10^(-9)
1280  KW = CONST(0)
1290  FOR II = 1 TO 3
1300  KW = KW + CONST(II) * T^II
1310  NEXT
1320  K = 1.2
1330  KP = K
1340  ZP = Z
1350  KWP = KW : KRP = K
1360  FP = .63
1370  GOTO 930
1380  HT(Y) = T1 + A : R = HD - G : W = 2 : K = 1.2 : MA = 100 - AXY
1390  IF MA < 0 THEN MA = 0 : KH = 0 : HT(Y) = 0 : GOTO 1460
1400  Z1 = MD1 : ZZ = IKD1
1410  GOSUB 3760
1420  KWM = KW : KRM = K : KM = K
1430  ZM = Z
1440  FM = .63
1450  GOTO 930
1460  IKT(Y) = T1 + A : R = IKD - G : W = 3 : IKA = 126 - AXY : C = CSSH : FO = FOSSH
1470  IF IKA < 0 THEN IKA = 0 : IKK = 0 : IKT(Y) = 0 : GOTO 1570
1480 Z1=IDX1:Z2=JD1
1490 GOSUB 3760
1500 KR=1.13-2.13*(IKT(Y)-20)*.001
1510 K=KR*((KW/KR)^F)
1520 IF WRONG=1 THEN K=1.6
1530 KWI=KW:KRI=KR:KIK=K
1540 JD=24:Z2IK=2
1550 FIX=F
1560 GOTO 930
1570 JT(Y)=T1+A:R=JT(Y)-20*.001
1580 IF JA<O THEN JA=0:KJ=0:JT(Y)=0:GOTO 1680
1590 Z1=JD1:Z2=SPD1
1600 GOSUB 3760
1610 KR=3.678-3.678*(JT(Y)-20)*.001
1620 K=KR*((KW/KR)^F)
1630 IF WRONG=1 THEN K=2.8
1640 Z2J=Z:KJ=K
1650 KWJ=KW:KRJ=KR
1660 SPD=Z4:Z2IK=Z
1670 GOTO 930
1680 SPT(Y)=T1+A:R=SPD-G:W=5:SPA=200-AXY:C=.51:FO=.63
1690 IF SPA<0 THEN SPA=0:SPT(Y)=0:GOTO 1790
1700 Z1=SPD1:Z2=BSD1
1710 GOSUB 3760
1720 KR=4.14-4.14*(SPT(Y)-20)*.001
1730 K=KR*((KW/KR)^F)
1740 IF WRONG=1 THEN K=3.1
1750 KSP=K:Z2SP=Z
1760 KWSP=KW:KRSP=KR
1770 SPD=Z4:FSP=F
1780 GOTO 930
1790 BST(Y)=T1+A:R=BSD-G:W=5:BSA=200-AXY:C=.51:FO=.63
1800 IF BSA<0 THEN BSA=0:BST(Y)=0:GOTO 1890
1810 Z1=BSD1:Z2=MGD1
1820 GOSUB 3760
1830 KR=3.37-3.37*(BST(Y)-20)*.001
1840 K=KR*((KW/KR)^F)
1850 IF WRONG=1 THEN K=3.1
1860 KWBS=KW:KRBS=KR:BBS=K
1870 MGD=Z4:Z2BS=Z
1880 GOTO 930
1890 HGT(Y)=T1+A:R=MGD-G:W=7:NGA=335-AXY:C=.71:FO=.125
1900 IF NGA<0 THEN NGA=0:NMG=0:HGT(Y)=0:GOTO 1990
1910 Z1=MGD1:Z2=FA01
1920 GOSUB 3760
1930 KR=4.576-4.576*(HGT(Y)-20)*.001
1940 K=KR*((KW/KR)^F)
1950 IF WRONG=1 THEN K=3
1970 Z2MG=Z:FA=24+XF0:FMG=F
1980 GOTO 930
1990 FAT(Y)=T1+A:R=FAD-G:W=8:FAA=343-AXY:C=CLM:FO=FOML
IF FAA < 0 THEN FAA = 0: KFA = 0: FAT(Y) = 0: GOTO 2100
2010 KR = 4.417001 - 4.417001 * (FAT(Y) - 20) * .001
2020 Z1 = FAD1: Z2 = FRD1
2030 GOSUB 3760
2040 Z = Z + XF1
2050 K = KR * ((KW/KR) * (F))
2060 IF WRONG = 1 THEN K = 3.5
2070 Z2FA = Z + XF2: FRD = FRD - Z2FA
2080 FFA = F
2090 GOTO 2210
2100 PRT(Y) = T1 + A: R = TR - G: W = 6: FRA = 344 - AXY: FO = FOLM: C = CLM
2110 IF FRA < 0 THEN FRA = 0: KFR = 0: PRT(Y) = 0: GOTO 2210
2120 Z1 = FRD1: Z2 = TD1
2130 GOSUB 3760
2140 Z2R = Z2R - D: Z = Z + XF2
2150 K = KR * ((KW/KR) * (F))
2160 Z2FR = Z2FR - D: Z2 = Z
2170 IF WRONG = 1 THEN K = 3.5
2180 Z2FR = Z2FR - D: Z = Z + XF3
2190 K = KR * ((KW/KR) * (F))
2200 GOTO 930
2210 TT(Y) = T1 + A: R = TR - G: W = 10: TA = 354 - AXY: C = CLM: FO = FOLM
2220 IF TA < 0 THEN TA = 0: KT = 0: TT(Y) = 0: GOTO 2230
2230 KR = 4.417001 - 4.417001 * (TT(Y) - 20) * .001
2240 Z1 = TD1: Z2 = BD1
2250 GOSUB 3760
2260 K = KR * ((KW/KR) * (F))
2270 IF WRONG = 1 THEN K = 3.5
2280 KT = K: FT = F: Z = Z + XF2
2290 BD = BD + XF2: Z2 = Z
2300 K = KW * (KW/KR) - F
2310 GOTO 930
2320 BIT(Y) = T1 + A: R = BD - G: W = 11: BIA = 355 - AXY: C = CLM: FO = FOLM
2330 IF BIA < 0 THEN BIA = 0: KBI = 0: BIT(Y) = 0: GOTO 2420
2340 Z1 = BD1: Z2 = MB1
2350 GOSUB 3760
2360 KR = 4.417001 - 4.417001 * (BIT(Y) - 20) * .001
2370 IF WRONG = 1 THEN K = 3.5
2380 Z = Z + XF3
2390 Z2BI = Z2BI + XF3: FBT = F
2400 KBI = K * (KW/KR) - K
2410 GOTO 930
2420 MBT(Y) = T1 + A: R = MB - G: W = 12: MBA = 362 - AXY: C = CLM: FO = FOLM
2430 IF MBA < 0 THEN MBA = 0: KMB = 0: MBT(Y) = 0: GOTO 2520
2440 KR = 4.417001 - 4.417001 * (MBT(Y) - 20) * .001
2450 Z1 = MB1: Z2 = BD1
2460 GOSUB 3760
2470 K = KR * ((KW/KR) * (F))
2480 IF WRONG = 1 THEN K = 3.5
2490 KMB = K: KMB = K: KMB = K
2500 Z2MB = Z2MB = Z: FMB = F
2510 GOTO 930
2520 BT(Y)=T1+A:R=BD-G:W=13:BA=363-AXY:FO=FOSH:C=CSH
2530 IF BA<0 THEN BA=0:KB=0:BT(Y)=0:GOTO 2640
2540 Z1=BD1:22=DDD
2550 GOSUB 3760
2560 Z=Z+XF5
2570 KR=1.74-1.74*(BT(Y)-20)*.001
2580 K=KR*(KW/KR)-F
2590 FB=F:
2600 IF WRONG=1 THEN K=1.5
2610 DDD=24:Z2=Z:KB=K
2620 KWB=KW:KRB=KR:FB=F
2630 GOTO 930
2640 DDT(Y)=T1+A:R=DWD-G:W=14:DDA=380-AXY:CLM:FO=FOLM
2650 IF DDA<0 THEN DDA=0:DDD=0:DDT(Y)=0:GOTO 2740
2660 KR=4.417001-4.417001*(DDT(Y)-20)*.001
2670 Z1=DDD1:22=DDD1
2680 GOSUB 3760
2690 KK=KR*(KW/KR)-F
2700 IF WRONG=1 THEN K=3.5
2710 KDD=K:WD=KD:KRD=K
2720 Z2DD=Z:FWD=F
2730 GOTO 930
2740 DWT(Y)=T1+A:R=DWP-G:W=15:DWA=398-AXY:CLM:FO=FOLM
2750 IF DWA<0 THEN DWA=0:DWD=0:DWT(Y)=0:GOTO 2840
2760 KR=4.01-4.01*(DWT(Y)-20)*.001
2770 Z1=DWD1:22=DWD1
2780 GOSUB 3760
2790 K=KR+(KW/KR)-F
2800 IF WRONG=1 THEN K=3.5
2810 KDV=K:WDV=KD:KRD=K
2820 Z2DV=Z:FWD=F
2830 GOTO 930
2840 DAT(Y)=T1+A:R=DDA-G:W=16:DA=403-AXY:CLM:FO=FOLM
2850 IF DAA<0 THEN DAA=0:DAT(Y)=0:GOTO 2940
2860 KR=4.01-4.01*(DAT(Y)-20)*.001
2870 Z1=DAD1:22=ID1
2880 GOSUB 3760
2890 K=KR+(KW/KR)-F
2900 IF WRONG=1 THEN K=3.2
2910 KDA=F:FDA=F
2920 ID=24:22DAD=Z:KD=KD:KRD=K
2930 GOTO 930
2940 IT(Y)=T1+A:R=ID-G:W=17:IA=405-AXY:CLM:FO=FOLM
2950 IF IACO THEN IA=0:IT(Y)=0:GOTO 3020
2960 KR=4.01-4.01*(IT(Y)-20)*.001
2970 Z1=ID1:22=TOTDP1
2980 GOSUB 3760
2990 K=KR+(KW/KR)-F
3000 IF WRONG=1 THEN K=3.5
3010 K1=F:F=Z+XF8
3020 TOTDP=24:ZT=Z:KWI=KD:KRI=K
3030 CLS
3040 IF Y<5 THEN PRINT "heat flow for tejas-zuni sequence "; QZ
3050 IF Y=5 THEN PRINT "heat flow for absaroka sequence "; QA
3060 IF 5<Y AND Y<17 THEN PRINT "heat flow for kaskaskia sequence "; QK
3070 IF 17=Y THEN PRINT "heat flow for tippecanoe sequence "; QT
3080 CLS:LPRINT CHR$(12)
3090 FS=" \\
	###.###
3100 LOCATE 1.9:PRINT "__therm. cond.(w/m/k)___"
3110 LPRINT "__therm. cond.(w/m/k)___"
3120 LOCATE 4.9:PRINT "fm/period  age  temp sed. water matrix __thick. porosity" x
3130 LPRINT "fm/period  age  temp sed. water matrix __thick. porosity"
3140 LOCATE 5.9:PRINT "(myrbp) (c)"
3150 LPRINT "(myrbp) (c)"
3160 IF Y=1 GOTO 3330
3170 IF Y=2 GOTO 3350
3180 IF Y=3 GOTO 3370
3190 IF Y=4 GOTO 3390
3200 IF Y=5 GOTO 3410
3210 IF Y=6 GOTO 3430
3220 IF Y=7 GOTO 3450
3230 IF Y=8 GOTO 3470
3240 IF Y=9 GOTO 3490
3250 IF Y=10 GOTO 3510
3260 IF Y=11 GOTO 3530
3270 IF Y=12 GOTO 3550
3280 IF Y=13 GOTO 3570
3290 IF Y=14 GOTO 3590
3300 IF Y=15 GOTO 3610
3310 IF Y=16 GOTO 3630
3320 IF Y=17 GOTO 3650
3330 PRINT USING FS: "pierre":PA;PT(Y);KT;KWT;KRT;ZT;FT
3340 LPRINT USING FS: "pierre":PA;PT(Y);KT;KWT;KRT;ZT;FT
3350 PRINT USING FS: "mowry":MA;MT(Y);KM;KWM;KRM;ZM;FM
3360 LPRINT USING FS: "mowry":MA;MT(Y);KM;KWM;KRM;ZM;FM
3370 PRINT USING FS: "inyan kara":IKA;IKT(Y);KIK;KWIK;KRIK;ZIKA;FIK
3380 LPRINT USING FS: "inyan kara":IKA;IKT(Y);KIK;KWIK;KRIK;ZIKA;FIK
3390 PRINT USING FS: "jurassic":JA;JT(Y);KJ;KWJ;KRIJ;ZIKA;FIK
3400 LPRINT USING FS: "jurassic":JA;JT(Y);KJ;KWJ;KRIJ;ZIKA;FIK
3410 PRINT USING FS: "spearfish":SPA;SPT(Y);KSP;KWS;KRSP;ZSP;FPS
3420 LPRINT USING FS: "spearfish":SPA;SPT(Y);KSP;KWS;KRSP;ZSP;FPS
3430 PRINT USING FS: "big snowy":BSA;BST(Y);KBS;KWBS;KRBS;ZBS;FPS

###.###

cond.(w/m/k) ----

---therm. cond.(w/m/k)---

fm/period  age  temp sed. water---matrix thick

porosity

---porosity---

fm/period  age  temp sed. water matrix thick

(km) (decimal) "(myrbp) (c)

(km) (decimal) "(myrbp) (c)
110

3440 LPRINT USING Fs; "big snowy"; BSA; BST(Y); KBS; KWBS; Z2BS; FS
3450 PRINT USING Fs; "madison group"; HGA; HTO(Y); KMG; KWMO; Z2MG; FMG
3460 LPRINT USING Fs; "madison group"; HGA; HTO(Y); KMG; KWMO; Z2MG; FMG
3470 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3480 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3490 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3500 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3510 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3520 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3530 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3540 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3550 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3560 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3570 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3580 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3590 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3600 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3610 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3620 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3630 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3640 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3650 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3660 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3670 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3680 PRINT USING Fs; "frobisher alida"; FAA; FAT(Y); KFA; KWFA; Z2FA; FFA
3690 NEXT Y
3700 CLS
3710 LPRINT CHR$(12)
3720 FOR Y=1 TO 21 STEP 1
3730 NEXT Y
3740 GOTO 3940
3750 REM subroutine
3760 IF WRON=1 THEN Z=Z2-ZI:GOTO 3930
3770 IF W=1 THEN Z3=Z1:Z4=Z2:GOTO 3880
3780 IF W=2 THEN Z3=Z1:Z4=Z2:GOTO 3880
3790 IF W=3 THEN Z3=Z1:Z4=Z2:GOTO 3880
3800 B=Z3-Z2-(FO/C)*((E^(-C*Z1))-(E^(-C*Z2)))-(E^(-C*Z3))-(E^(-C*Z4)))
3810 PRINT Z1:Z2:Z3:Z4
3820 FOR Z4 = Z4 TO TOTDP STEP .001
3830 X=Z4-((FO/C)*((E^(-C*Z4)))-B)/(L-(FO*E^(-C*Z4)))
3840 N=Z4/24
3850 IF N < .0005 THEN GOTO 3870 ELSE 3860
3860 NEXT Z4
3870 F=(FO/C)*((E^(-C*Z3))-(E^(-C*Z4)))/((Z4-23))
3880 PRINT "top footage bottom footage porosity"
3890 PRINT " 23 24 ".0005
3900 PRINT " 24 23 24 23"
3910 Z=24-Z3
3920 Z3=Z4
3930 RETURN
3940 REM**** TTI EVALUATION ********
3950 CLS
LOCATE 5,6: LPRINT "THERMAL MATURITY CALCULATION"
LOCATE 5,6: LPRINT "MODERATE"
LPRINT: LPRINT "THE SEDIMENTS HAVE DECOMPACTED"
FOR Y=O TO 13
Z=Y+1
FOR TEM=BT(Y) TO BT(Z) STEP 10
IF BT(Y)=BT(Z) THEN GOTO 4050
IF TEM=BT(Z) THEN GOTO 4310
IF TEM<30 AND TEM>30 THEN N=-8
TEM=BT(Y)
IF TEM<40 AND TEM>30 THEN N=-7: TXT=(TEM-30)/10: GOTO 4200
IF TEM<50 AND TEM>40 THEN N=-6: TXT=(TEM-40)/10: GOTO 4200
IF TEM<60 AND TEM>50 THEN N=-5: TXT=(TEM-50)/10: GOTO 4200
IF TEM<70 AND TEM>60 THEN N=-4: TXT=(TEM-60)/10: GOTO 4200
IF TEM<80 AND TEM>70 THEN N=-3: TXT=(TEM-70)/10: GOTO 4200
IF TEM<90 AND TEM>80 THEN N=-2: TXT=(TEM-80)/10: GOTO 4200
IF TEM<100 AND TEM>90 THEN N=-1: TXT=(TEM-90)/10: GOTO 4200
IF TEM<110 AND TEM>100 THEN N=0: TXT=(TEM-100)/10: GOTO 4200
IF TEM<120 AND TEM>110 THEN N=1: TXT=(TEM-110)/10: GOTO 4200
IF TEM<130 AND TEM>120 THEN N=2: TXT=(TEM-120)/10: GOTO 4200
IF TEM<140 AND TEM>130 THEN N=3: TXT=(TEM-130)/10: GOTO 4200
IF TEM<150 AND TEM>140 THEN N=4: TXT=(TEM-140)/10: GOTO 4200
IF TEM<160 AND TEM>150 THEN N=5: TXT=(TEM-150)/10: GOTO 4200
TN=ABS(AX(Z)-AX(Y))
IN=ABS((BT(Z)-BT(Y))/10)
IF IN<1 THEN IN=1
IF IN>IN+1
if TN/IN
if 0
if Q=N+TXT
LPRINT "Q": Q
K=TN*Z(Q)
LPRINT "ttt": K
TTI=TTI+K
NEXT
NEXT Y
LPRINT "AGE": TEMP"
FOR Y=0 TO 13
LPRINT AX(Y), BT(Y)
NEXT
LPRINT "THE TIME TEMPERATURE INDEX FOR NDGS# 4918 is": TTI
END
Appendix D

"TTII" BASIC Computer Program
For Calculation of Time Temperature Index

10 CLS:LOCATE 12,5
20 PRINT" MODERATE TTI EVALUATION. PROGRAM TTII BY Y.C.HUANG"
30 DIM AX(20), BT(20)
40 INPUT " NORTH DAKOTA GEOLOGICAL SURVEY WELL NUMBER, WN";WN
50 INPUT" Number of layers above Bakken, nn";NN
60 AX(0)=0:TTI=0
70 FOR Y=0 TO NN
80 PRINT" AGES and TEM of each layer above Bakken.AX(";Y;"),BT(";Y;") ;
90 INPUT AX(Y),BT(Y)
100 NEXT Y
110 CLS:LOCATE 5,5:LPRINT " THERMAL MATURITY CALCULATION"
120 LOCATE 5,6:LPRINT "MODERATE"
130 LPRINT:LPRINT "THE SEDIMENTS HAVE BEEN DECOMPACTED"
140 FOR Y=0 TO NN
150 Z=Y+1
160 TEM=BT(Y)
170 FOR TEM=ST(Y) TO BT(Z) STEP 10
180 IF TEM=BT(Z) THEN GOTO 240
190 IF TEM<30 THEN N=-8
200 IF TEM<40 AND TEM>30 THEN N=-7:TXT=(TEM-30)/10:GOTO 340
210 IF TEM<50 AND TEM>40 THEN N=-6:TXT=(TEM-40)/10:GOTO 340
220 IF TEM<60 AND TEM>50 THEN N=-5:TXT=(TEM-50)/10:GOTO 340
230 IF TEM<70 AND TEM>60 THEN N=-4:TXT=(TEM-60)/10:GOTO 340
240 IF TEM<80 AND TEM>70 THEN N=-3:TXT=(TEM-70)/10:GOTO 340
250 IF TEM<90 AND TEM>80 THEN N=-2:TXT=(TEM-80)/10:GOTO 340
260 IF TEM<100 AND TEM>90 THEN N=-1:TXT=(TEM-90)/10:GOTO 340
270 IF TEM<110 AND TEM>100 THEN N=0:TXT=(TEM-100)/10:GOTO 340
280 IF TEM<120 AND TEM>110 THEN N=1:TXT=(TEM-110)/10:GOTO 340
290 IF TEM<130 AND TEM>120 THEN N=2:TXT=(TEM-120)/10:GOTO 340
300 IF TEM<140 AND TEM>130 THEN N=3:TXT=(TEM-130)/10:GOTO 340
310 IF TEM<150 AND TEM>140 THEN N=4:TXT=(TEM-140)/10:GOTO 340
320 IF TEM<160 AND TEM>150 THEN N=5:TXT=(TEM-150)/10:GOTO 340
330 IF TEM<170 AND TEM>160 THEN N=6:TXT=(TEM-160)/10:GOTO 340
340 TN=ABS(AX(Z)-AX(Y))
350 IN=ABS((BT(Z)-BT(Y))/10)
360 IF IN<1 THEN IN=1
370 IF IN>1 THEN IN=IN+1
380 TN=TN/IN
390 Q=N-TXT
400 LPRINT"Q";Q
410 K=TN*Q(2)Q
420 LPRINT "TTI ";K
430 TTI=TTI+ K
440 NEXT
450 NEXT Y
460 LPRINT
470 LPRINT " AGE  TEMP"
480 FOR Y=O TO NN
490 LPRINT AX(Y), BT(Y)
500 NEXT
510 LPRINT" THE TTI OF BAKKEN AT NDGS";WN:" IS":TTI
REFERENCES CITED


Ahern, J. L., and Ditmars, R. C., 1985, Rejuvenation of continental lithosphere beneath an intracratonic basin: Tectonophysics, v. 120, p. 21-35.


