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# Time - Temperature Index of the Bakken Formation in North Dakota

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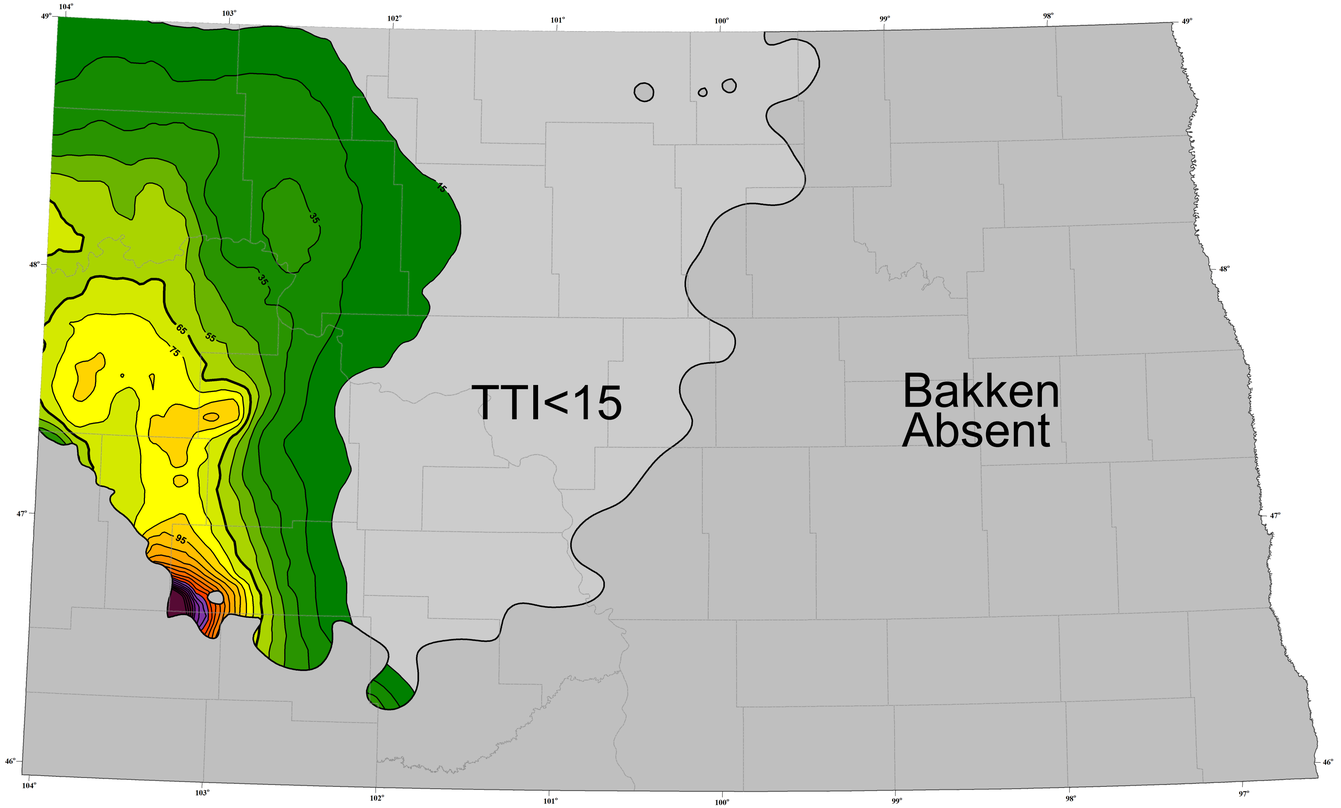



TTI Contour Interval

- 15-25
- 25-35
- 35-45
- 45-55
- 55-65
- 65-75
- 75-85
- 85-95
- 95-105
- 105-115
- 115-125
- 125-135
- 135-145
- 145-155
- 155-165
- 165-175
- 175-185
- 185-195
- 195-205
- 205-215
- 215-225
- 225-235
- 235-245
- TTI < 15
- Bakken Absent

## Explanation

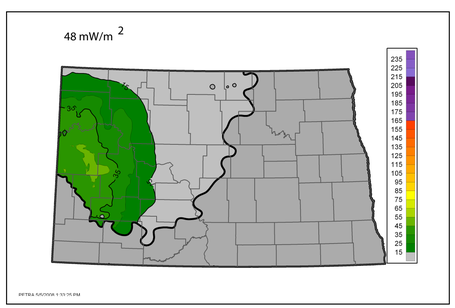
- Contour of the Time-Temperature Index of the Bakken Formation
- Extent of the Bakken Formation
- County Boundaries

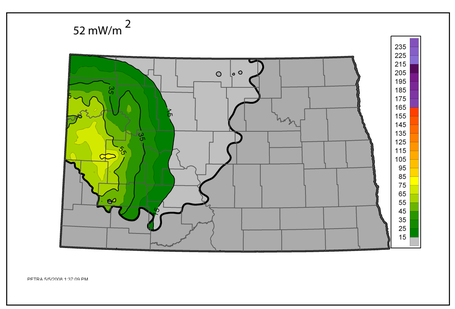
0 20 40 60 80 Miles

0 20 40 60 80 Kilometers

North American Datum 1927 Lambert Conformal Conic

N W E S




The two inset maps illustrate the sensitivity of the TTI calculation to variations in the assumed heat flow. The inset to the left is calculated using a constant heat flow value of 48 mW/m$^2$ whereas the inset to the right is made with a heat flow value of 52 mW/m$^2$. Note that increasing the heat flow forces the onset of oil generation (TTI > 15) towards the east.

## Introduction

The Lopatin (1970) method that produces the Time -Temperature Index (TTI) is used here to evaluate the petroleum generation potential of the Mississisippian/ Devonian aged Bakken Formation. The TTI is based on the realization that the chemical reactions that generate oil and gas are critically dependent upon the temperature history of a hydrocarbon generating source rock.

Because temperatures increase with depth, calculating the TTI requires a reconstruction of a source rock's burial history. Thus, in order to reconstruct the burial history of the Bakken, the overlying stratigraphic section must be subdivided into time equivalent and lithologically equivalent units. Time equivalence is needed in order to correctly reconstruct the burial history and lithologic equivalence is needed to correctly determine the temperature history. In this study the stratigraphic section overlying the Bakken is divided into the units listed in Table 1.

Calculating the TTI of any unit requires summing the calculated TTI$_n$ for each time interval that makes up the burial history of the unit in question. In practice, this is done by calculating the incremental TTI$_n$ of the source rock over the time interval specified by the addition of each stratigraphic unit that makes up the overlying section. With the addition of each stratigraphic interval (n), the temperature at the top ($T_{n+1}$) and the base ($T_n$) of the unit is estimated from the following expression (Gosnold, 1985):

Eq. 1

$$T_n = T_o + Q \sum_{i=1}^{i=n} L_i / K_i$$

Where:

$T_o$ = Average surface temperature (°C)
$T_n$ = Temperature at the base of the nth layer (°C).
Q = Conductive heat flow (mW/m$^2$).
$L_i$ = Thickness of the ith layer (m)
$K_i$ = Thermal conductivity of the ith layer (W m$^{-1}$ °K$^{-1}$).
n = Number of layers

**Table 1**

TTI Model Constants:

| Stratigraphic Interval | Age of the Bottom (Ma) | Age of the Top (Ma) | Thermal Conductivity (w/M?K) |
|---|---|---|---|
| Surface to Pierre | 72 | 0 | 1.7[2] |
| Pierre to Mowry | 100 | 72 | 1.2[1,2] |
| Mowry to Inyan Kara | 126 | 100 | 1.2[1,2] |
| Inyan Kara to Swift | 140 | 126 | 1.6[1,2] |
| Swift to Spearfish | 200 | 140 | 2.8[1,2] |
| Spearfish to Madison | 335 | 200 | 3.1[1,2] |
| Madison to Base of the Last Salt | 343 | 335 | 3.0[1] |
| Base of the Last Salt to Bakken | 363 | 343 | 3.5[1] |
| Bakken to Three Forks | 366 | 363 | 1.5[1] |

[1] Haung, 1988

[2] Gosnold, 1984

To illustrate this, consider the situation immediately following the deposition of the Bakken Formation. At this point in time, the top of the Bakken is at the surface and is presumably subjected to the same mean surface temperature ($T_o$) present today. Assuming that subsidence and sedimentation occurred at a more or less constant rate during deposition, the temperature at the base of the Bakken could be estimated using Eq. 1 with i equal to 1, $L_{i=1}$, $K_i$, and Q being equal to the present day thickness, thermal conductivity and conductive heat flow of the Bakken respectively. Maturation of organic matter during deposition of the Bakken would then be given by the TTI$_n$ from Eq. 4. The next step is to calculate the TTI$_n$ for the Bakken following the deposition of the Madison. In this case the surface temperature is applied to the top of the Madison and the temperature at the base of the Madison is found from Eq. 1 with i =2 (the second unit), $L_{i-2}$ being equal to the thickness of the Madison and $K_{i-2}$ being equal to the thermal conductivity of the Madison (Table 1). The conductive heat flow (Q) is assumed to be constant. Using the temperature at the base of the Madison (top of Bakken we can find the temperature at the base of the Bakken, again with Eq. 1. The new upper and lower temperatures for the Bakken together with the interval of time represented by the Madison Group are used in Eq. 4 to find the additional amount of maturation that occurred during Madison time. The total amount of maturation in the Bakken is found by adding the maturation that occurred during Madison time (TTI $_{n=2}$) to the maturation that occurred during Bakken time (TTI $_{n=1}$). Repeating this process for the n intervals in the section produces a set of incremental TTI$_n$ for the Bakken that covers its burial history. Once a TTI$_n$ is found for each interval, the total TTI of the Bakken is found by summing all of the TTI$_n$'s in the section (Eq. 5).

## Calculation of the Time Temperature Index

Lopatin's method for determining the maturation index of source rocks is a simplified version of the Arrhenius equation that states that chemical reaction rates increase exponentially with increasing temperatures. Lopatin simplified the Arrhenius equation by replacing the thermodynamic variables within the Arrhenius equation with a simple constant ( r ) that reflects the increase in reaction rate that results from increasing temperature. In general, chemical reaction rates tend to double with every 10º C rise in temperature. Therefore, in order to estimate the difference in reaction rate between two temperatures one could set r equal to two and raise r to a power that describes the number (i) of 10ºC increments between the two temperatures. Algebraically this relationship may be expressed as follows:

Eq. 2

$$\gamma = r^{i}$$

Where

i = Temperature (ºC)/10
γ = Maturation rate factor or relative reaction rate.

Lopatin modified Eq. 2 so that γ would equal 1 in the temperature interval that spans 100º to 110º C. Incorporating this into Eq. 2 yields (Wood, 1988):

Eq. 3

$$\gamma = r^{(T/10)-10.5}$$

It should be obvious that for a reaction that doubles with every 10º C increase in temperature (r=2) that after the temperature rises 30º C one could expect an eightfold ($2^3$) increase in maturation rate. Lopatin indexed the temperature variable n so that n=0 over the temperature interval 100-110ºC. These considerations are summarized in the following table (Modified from Waples, 1980).

**Table 2**

| Temperature Interval (°C) | Temperature Index (n) | Maturation Rate Factor (γ) |
|---|---|---|
| 90 - 100 | -1 | $r^{-1}$ |
| 100 - 110 | 0 | 1 |
| 110 - 120 | 1 | $r^{1}$ |
| [100 + (m * 10)] to [110 + (m * 10)] | m | $r^{m}$ |

The maturation rate factor (γ) describes the instantaneous rate at which oil is generated. In order to evaluate the relative oil generation potential of a source rock, the maturation rate factor must be integrated over the time during which maturation occurs at the rate indexed by γ. Under the assumption of a constant rate of temperature change, Eq. 3 is integrated over time $t_{n1}$ to $t_{n2}$ to yield the corresponding incremental Time-Temperature Index (TTI$_n$). The TTI$_n$ in this situation expresses the potential oil generation capacity of a source rock for the interval n under the given time-temperature limits. Recast as an integral that, when solved for constantly changing temperature from $T_{n1}$ to $T_{n2}$ over the time interval $t_{n1}$ to $t_{n2}$, yields (Wood, 1988):

Eq. 4

$$TTI_n(t_{n1} \text{ to } t_{n2}) = 10/q_n\{1/\ln(r)\,(r^{[(T_{n2}/10)-10.5]} - r^{[(T_{n1}/10)-10.5]}\}$$

Where :

n = Number of stratigraphic intervals
TTI$_n$ = Time-Temperature Index for the interval defined by $t_{n1}$, $t_{n2}$ and $T_{n1}$, $T_{n2}$.
$q_n = (T_{n2}-T_{n1})/(t_{n2}-t_{n1})$
$t_{n1}$ = Starting age of interval n
$t_{n2}$ = Ending age of interval n
$T_{n1}$ = Starting temperature (ºC) of interval n
$T_{n2}$ = Ending temperature (ºC) of interval n

Because maturation is a cumulative process, the time temperature index (TTI) is found by summing the TTI$_n$ calculated for each time interval as follows (Waples, 1980):

Eq. 5

$$TTI = \sum_{n=1}^{n=max} TTI_n$$

**Table 3**

Waples (1980) suggests that oil generation from organic rich shales is limited to TTI values between 15 and 160. This interval is frequently referred to as the "oil window".

| Oil generation potential | TTI |
|---|---|
| Immature | <15 |
| Onset of oil generation | 15 |
| Peak oil generation | 75 |
| End oil generation | 160 |
| Upper limit for wet gas | 1,500 |

## Map Construction

The Time-Temperature Index map of the Bakken Formation is generated from a burial history defined by isopach maps that use the tops listed in Table 1. The advantage of using maps is that they: 1) allow for the inclusion of wells that do not penetrate the entire section through the Bakken or have an incomplete list of tops 2) allow for reducing the amount of data that needs manipulation and 3) allow for clustered data or spurious data points to be averaged. The maps used to build the TTI map in this study use North Dakota Industrial Commission's database that provides measured depths to several key horizons for over 14,000 wells in North Dakota. The process of producing the TTI map also involves the construction of a conductive heat flow map. Together, these maps, along with the ages of the various horizons used to define the isopach maps, reconstruct the temperature history of the Bakken Formation in North Dakota.

## Conductive Heat Flow Map

The conductive heat flow (used to find Q in Eq. 1) within the Williston Basin was built from data reported by the Southern Methodist University Geothermal Lab (2008), Gosnold (1984) and Scattolini (1978). This map is assumed to represent the local variation in heat flow within the Williston Basin. However, use of this map in calculating the TTI of the Bakken Formation also implies that there has been no variation in heat flow through time. Temperature estimates of the Bakken are based on a constant 5ºC (41ºF) average surface temperature (Manz, 2007).

## Isopach Maps

All of the maps are generated with the Petra ® program. Petra ® like most computer mapping routines, generates maps of well data by first setting up a regular grid of nodes. The value for each node is found from data found surrounding each node. In order to calculate the TTI for any given horizon, the various grids must be resampled so that the locations of the nodes for each isopach match.

## TTI Map Calculation

A map of the TTI for the Bakken Formation was calculated for each node in the final grid using the isopach grids of the various stratigraphic intervals and the grid of heat flow values. The map assumes the present day thickness of each stratigraphic interval to be equivalent to the original thickness of the interval. Furthermore, the map assumes that the modern thermal conductivities of the units have remained constant through time and that average surface temperatures have been a constant a 5ºC (41ºF) (Manz, 2007).

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