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Thermal Maturation Modeling of the Michigan Basin

Hybza

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THERMAL MATURATION MODELING OF THE MICHIGAN BASIN

by

Jack H. Hybza

A thesis submitted to the Graduate College
in partial fulfillment of the requirements
for the degree of Master of Science
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Jack H. Hybza
THERMAL MATURATION MODELING OF THE MICHIGAN BASIN

Jack H. Hybza, M.S.
Western Michigan University, 2019

Given present day heat flow and burial depths in the Michigan Basin, hydrocarbons should be immature. However, oil and gas are abundant within the basin. Our hypothesis is that thermal maturation distributions in the Michigan Basin can be explained by variations in proximity to the Midcontinent Rift (MCR) system, thermal cooling, crustal convection, high temperature fluid advection, and eroded overburden.

For each of the seven wells in this study, a geohistory plot is coupled with a range of geodynamic models to calculate the thermal and maturation histories of each sediment unit within the well. Backstripping was used to generate basement heat flow estimates. Time temperature index values are calculated based on the thermal models. Comparison of calculated time temperature index values and recorded thermal maturation data from surrounding wells are used to test the hypothesis.

Calculations show that well locations above the MCR (Grand Traverse, Missaukee, Gratiot, and Livingston) require 1000 m of eroded overburden, thermal cooling, crustal convection, and high temperature fluid advection to match surrounding thermal maturation data in the Michigan Basin. Well locations away from the MCR (Ogemaw and Lenawee) require 1000 m of eroded overburden, thermal cooling, and high temperature fluid advection to match surrounding thermal maturation data in the Michigan Basin.
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INTRODUCTION

Given present day heat flow and burial depths in the Michigan Basin, hydrocarbons should be immature. However, oil and gas are abundant within the basin. Several explanations have been proposed in order to understand how thermal maturation within the Michigan Basin reached present day values. Explanations include an elevated geothermal gradient based on the assumption of 1000 m of missing (eroded) overburden prior to the Late Jurassic to elevate the geothermal gradient (Cercone, 1984); adding heat through an anomalous event with subsequent thermal subsidence (Nunn et al., 1984); increasing heat flow as a result of periods of free crustal convection (Nunn, 1994; Schoofs & Trombert, 2000); and adding heat through hydrothermal fluid advection derived from deep seated fault and fracture systems (Luczaj et al., 2006).

Wagenvelt (2015) used inverse modeling and incorporated the above models to estimate the thermal maturation of hydrocarbons in the Doornbos 5-30 well. He then compared the results with thermal maturation data from wells within a 25 km radius. His thermal maturation model results matched observed thermal maturation data from the surrounding wells. Most of the data can be explained by a combination of thermal cooling, crustal convection, high temperature fluid advection, and 1000 m of eroded overburden.

In this work, geodynamic models similar to that of Wagenvelt (2015) will be applied to multiple wells across the Michigan Basin at a range of burial depths and distances from the Midcontinent Rift (MCR) system. My goal is to test the hypothesis that thermal maturation distributions in the Michigan Basin are related to proximity to the MCR, thermal cooling, crustal convection, high temperature fluid advection, and eroded overburden.

Seven wells were selected across the Michigan Basin for this study (see fig. 1). These wells bottom near or in basement rock and have been selected for their spatial distribution
relative to the MCR and their proximity to thermal maturation data available from the Michigan Basin (Wagenvelt, 2015).

Figure 1 – Map of Michigan showing wells with thermal maturation data available for this study. Green squares indicate wells chosen for this study. Blue dots indicate wells with thermal maturation data. Red dots indicate thermal maturation data from (Wagenvelt Pyrolysis Data_2014). The black dashed line represents the Midcontinent Rift. C = Well 30682 (Cheboygan); GT = Well 34292 (Grand Traverse); O = Well 25099 (Ogemaw); M = Well 34376 (Missaukee); G = Well 29739 (Gratiot); L = Well 43727 (Livingston); and LEN = Well 10448 (Lenawee). This map was modified from Wagenvelt (2015).

For each well a geohistory plot was coupled with heat flow models to calculate the thermal and maturation histories of each sediment unit within the well. Backstripping was performed in order to generate basement heat flow estimates. Lopatin’s (1971) method for calculating thermal maturation of hydrocarbons through time was utilized by applying the
calibration of Waples (1980). This method produces time temperature index (TTI) values. The comparison of calculated TTI and recorded thermal maturation data from surrounding wells (Wagenvelt, 2015) were used to test the hypothesis that proximity to the MCR, thermal cooling, crustal convection, high temperature fluid advection, and eroded overburden can explain thermal maturities observed in the Michigan Basin as suggested by Wagenvelt (2015).

Geologic Context

The Michigan Basin is a cratonic basin. The basin covers the entire Lower Peninsula of Michigan and extends to parts of Michigan’s Upper Peninsula, Wisconsin, Indiana, Illinois, Ohio, and Ontario. The basin covers an area of approximately 260,000 km² and reaches depths of 4800 m (see Fig. 2). Sedimentation within the basin ranges in age from Cambrian to Pennsylvanian (Barnes et al., 2009; Cohee, 1965). The oldest strata within the Michigan Basin are Cambrian to Early Ordovician in age. These strata include: mature sandstones that were derived from a cratonic source. Above these units Middle Ordovician to Middle Devonian carbonate and evaporite cycles were deposited. The youngest deposits range in age from Late Devonian to Jurassic and consist of carbonates, evaporites, and Appalachian sourced siliciclastics (Nunn, 1994; see Fig. 3). The basement consists of crystalline Precambrian rock, including the northwest to southeast oriented Midcontinent Rift (Fig. 1; Wagenvelt, 2015; Hinze, 1992).

The MCR is Mid-Proterozoic in age. This approximately 1.1 Ga rift extends 2,000 km across the North America craton. The rift is approximately 70 km wide near the middle of Michigan’s Lower Peninsula (Fig. 1). The rift represents a major tectonic disruption to the lithosphere and produced large volumes of mantle derived volcanic flows (Hinze, 1997; Nunn, 1994).
Various subsidence mechanisms for the Michigan Basin have been proposed including; subsidence after an anomalous thermal event (Sleep, 1971; Nunn et al., 1984); cooling through stagnant lid convection (Sleep, 2009); periodic heat loss from episodes of free convection (Nunn 1994); as well as, stretching and cooling of the lithosphere (McKenzie, 1978).

Figure 2 – Geologic cross section of the Michigan Basin (North-South).
Figure 3 – Chronostratigraphic chart showing the ages of formations for the wells in this study. Swezey (2008) and the Stratigraphic Nomenclature for Michigan Chart (2000) were used to determine ages and stages. All ages were adjusted to The Geologic Time Scale of Gradstein et al., (2012).
METHODS

Geohistory Plot

A geohistory plot was generated in order to calculate the thermal and maturation histories of the sediments (Waples, 1994). A geohistory plot was created for each stratigraphic unit in the seven selected wells by utilizing Van Hinte’s (1978) equation:

\[ TD = Wd + S^* \]

Where: \( TD \) = total subsidence of the basement with decompacted sediment and water above it; \( Wd \) = the paleo-water depth at which each sediment unit was deposited; \( S^* \) = decompacted sediment thickness.

The sediments must be decompacted in order to obtain their original depositional thicknesses. Lithology dependent porosity versus depth curves were used to obtain the decompacted sediment thickness \( (S^*) \) of a sediment unit. In the Michigan Basin, sediment units are lithified as a result of compaction from the overlying sediment load and cementation. Because the sediments are lithified modern porosity values cannot be used to determine compaction. Following the approach of Bond & Kominz (1984), Wagenvelt (2015) used published porosity versus depth curves to establish a maximum and minimum limit of compaction due to burial. In this work, I will assume that compaction follows the exponential decay equation (Athy, 1930):

\[ \varphi = \varphi_0 e^{-\frac{Z}{C}} \]

Where, \( \varphi \) = porosity at burial depth \( Z \), \( \varphi_0 \) = surface porosity, and \( C \) = decay constant.

To determine the decompacted sediment thickness \( (S^*) \), average initial porosity and the change in average porosity during burial was calculated for each sediment unit. This is done by
applying porosity vs. depth curves for common lithologies present in the section (e.g., Fig. 4; Bond & Kominz, 1984).

![Porosity vs. depth curves](image)

**Figure 4**- Porosity vs. depth curves used in this study. Curves show common lithologies found in the Michigan Basin.

**Backstripping**

Backstripping of the seven wells provided heat flow estimates. The equation used for backstripping is from Bond & Kominz, (1984):

\[
T.S = \Phi \left( S^* \left( \frac{\rho_m - \rho_s}{\rho_m - \rho_w} \right) - \Delta SL \left( \frac{\rho_w}{\rho_m - \rho_w} \right) \right) + Wd - \Delta SL
\]

Where: \( T.S \) = tectonic subsidence or uplift; \( \Phi \) = the basement response function; \( \rho_m \) = the mean density of the mantle (3.18 g/cm\(^3\)); \( \rho_s \) = the mean bulk density of the sediments; \( \rho_w \) = the density of sea water (1.03 g/cm\(^3\)); \( \Delta SL \) = the change in eustatic sea level; \( Wd \) and \( S^* \) (see above, same as geohistory). Both sediment density and compaction are lithology-dependent. Additional age input, including ages of unconformities, are required to interpret the backstripping result.
In this study, a variety of thermal models are applied in order to reconstruct the temperature history of the sediments. The present-day model simulates present-day heat flow, burial depths, and assumed eroded overburden. In this model, heat flow remains constant through time and overburden is added from 305 Ma to 265 Ma. The overburden is then eroded/subtracted from 265 Ma to 157.3 Ma (Wagenvelt, 2015).

The thermal cooling model simulates the effects of thermal cooling following an anomalous heating event, whereby, heat flow is based on a simple thermal stretching assumption. Tectonic subsidence is fit to McKenzie’s (1978) thermal model to estimate basement heat flow through time.

The crustal convection upwelling and downwelling models simulate rapid subsidence effects due to intermittent periods of free convection. The free convection periods are cyclic as they intermittently open and close upper-crustal fracture networks (Nunn, 1994; Schoofs & Trumbert, 2000). Periods of crustal convection are assumed to correlate with Appalachian orogenies. In this model heat flow increases for the first 2 Ma. Heat flow then decreases to background thermal cooling levels after 17 Ma (Nunn, 1994; Wagenvelt, 2015).

The advection from the crustal convection model simulates the heating effects of hot upward migrating fluids along fault networks (Wagenvelt, 2015). In all thermal models we assume thermal equilibrium within the sediment column. Thus, temperatures of the sediment units are calculated by the following equation:

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

Where: \( T_n \) = temperature at the base of the nth interval (rock unit from the top); \( T_0 \) = temperature at the surface; \( q \) = heat flow (W/m\(^2\)); \( \Delta Z_i \) = thickness of the ith interval from the top, \( K_i \) = average thermal conductivity of the ith interval. To determine surface temperature (\( T_0 \)),
information on paleoclimate, paleogeography, and time must be gathered (see next section). Thermal conductivity ($K_i$) of a sediment unit is dependent on both lithology and porosity assuming that porosity is fully saturated with seawater. Therefore, thermal conductivity depends on the compaction history of that unit (see conductivities section) (Wagenvelt, 2015).

**Paleo-Surface Temperatures**

Phanerozoic surface temperatures for the Michigan Basin were calculated by utilizing the PALEOMAP project by Scotese (2015). The project contains global temperature averages from 540 Ma to modern day. Scotese (2015) developed seven tropic to pole temperature gradients that apply to different paleoclimatic conditions through time. The hottest gradient symbolizes extreme hothouse conditions and has a global mean and pole temperature of 23°C and 13°C, respectively. In contrast, the coldest gradient simulates severe icehouse conditions and has a global mean and pole temperature of 12.5°C and -50°C, respectively (Scotese, 2015). The tropic to pole temperature gradients are different depending on continent configurations in the northern and southern hemispheres.

Paleo-latitude of the Michigan Basin was determined by utilizing the PALEOMAP model on the GPlates Portal Paleomap Maker website. Paleo-latitude vs. time was calculated in order to determine the appropriate tropic to pole temperature gradient. As noted above, the chosen gradient depends on paleo-climate, which is a function of paleo-latitude and time (Scotese, 2015).

Temperature changes at the equator shift tropic to pole temperature gradients. This is taken into account by utilizing the tropical temperature curve of Royer et al., (2004) with ages modified by Scotese, (2015), whereby temperature variations are added to the tropic to pole
temperature gradients, thus allowing paleo-surface temperatures to be calculated for the Michigan Basin (Fig. 5).

![Graph showing temperature over age](image)

**Figure 5**- Calculated Paleo-Surface Temperatures used for each well and model in this study.

**Thermal Conductivities**

Lithology and porosity are used to determine thermal conductivities. Lithology dependent conductivities are constrained by trying to reproduce the modern-day geothermal gradient. Lithology dependent conductivities in this study were calculated to obtain a geothermal gradient between 19 and 22 °C/Km (Wagenvelt, 2015), which matches the present-day geothermal gradient (Pollack & Watts, 1976; Vugrinovich, 1988).

Porosities obtained from decompacting sediments from the geohistory analysis were input into Beck’s (1976) two-phase conductivity formula. This formula is used to calculate total unit thermal conductivities. That is, $K_d$ is the dispersive conductivity of the mixed medium. The formula to calculate $K_d$ is:
\[
K_d = K_s \left\{ \frac{(2r + 1) - 2\phi(r - 1)}{(2r + 1) + \phi(r - 1)} \right\}
\]

Where: \( r = K_s/K_f \), \( K \) is thermal conductivity; \( \phi \) = porosity; \( K_s \) = the conductivity of the continuous phase; \( K_f \) = conductivity of dispersed phase; and \( K_d \) = dispersive conductivity of the mixed medium. The thermal conductivity of saltwater is assumed to be 0.61 W/mK (Horai, 1971). The continuous phase is assumed to be water until a porosity of 60% or less is reached in the sediment unit, at which point, the solid is assumed to be the continuous phase.

**Table 1** - Table showing lithology dependent properties used in this study. \(^1\) = Carmichael (1984); \(^2\) = Cermak & Rybach (1982); \(^3\) = Horai (1971); and *** = model assumption. Modified from Wagenvelt (2015).

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Density (^1) (g/cm(^3))</th>
<th>Thermal Conductivity (^2) (W/mK)</th>
<th>Surface Porosity (\phi_0) (%)</th>
<th>Porosity Curve</th>
<th>Depth Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siltstone</td>
<td>2.66</td>
<td>1.83</td>
<td>62</td>
<td>( \phi = 62 e^{-z/1258} )</td>
<td>( 0 &lt; z &lt; 1000 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \phi = 44 e^{-z/2234} )</td>
<td>( z &gt; 1000 )</td>
</tr>
<tr>
<td>Shale</td>
<td>2.67</td>
<td>1.84</td>
<td>70</td>
<td>( \phi = 70 e^{-z/715} )</td>
<td>( 0 &lt; z &lt; 400 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \phi = 52 e^{-z/1514} )</td>
<td>( z &gt; 400 )</td>
</tr>
<tr>
<td>Limestone</td>
<td>2.71</td>
<td>2.04</td>
<td>62</td>
<td>( \phi = 62 e^{-z/1102} )</td>
<td>( 0 &lt; z &lt; 800 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \phi = 39 e^{-z/2913} )</td>
<td>( z &gt; 800 )</td>
</tr>
<tr>
<td>Micrite</td>
<td>2.71</td>
<td>2.04</td>
<td>62</td>
<td>( \phi = 62 e^{-z/1102} )</td>
<td>( 0 &lt; z &lt; 800 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \phi = 39 e^{-z/2913} )</td>
<td>( z &gt; 800 )</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2.65</td>
<td>2.11</td>
<td>40</td>
<td>( \phi = 40 e^{-z/2128} )</td>
<td>( 0 &lt; z &lt; 1000 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \phi = 32 e^{-z/2923} )</td>
<td>( z &gt; 1000 )</td>
</tr>
<tr>
<td>Dirty Sandstone</td>
<td>2.65</td>
<td>2.11</td>
<td>54.5</td>
<td>( \phi = 54.5 e^{-z/1636} )</td>
<td>( 0 &lt; z &lt; 1173.7 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \phi = 44 e^{-z/2378} )</td>
<td>( z &gt; 1173.7 )</td>
</tr>
<tr>
<td>Dolostone</td>
<td>2.87</td>
<td>3.3</td>
<td>62</td>
<td>( \phi = 62 e^{-z/1102} )</td>
<td>( 0 &lt; z &lt; 800 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>( \phi = 39 e^{-z/2913} )</td>
<td>( z &gt; 800 )</td>
</tr>
<tr>
<td>Chert</td>
<td>2.65</td>
<td>1.76</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Anhydrite</td>
<td>2.96</td>
<td>3.57</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Salt</td>
<td>2.16</td>
<td>3.58</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water</td>
<td>1.03***</td>
<td>0.61(^3)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Time Temperature Index**

The above data are used to calculate the temperature of the sediment units through time. Lopatin’s (1971) method was used to calculate the thermal maturation (TTI) for each stratigraphic unit. Constants come from Waples (1980).

\[ TTI = \sum_{n_{\text{min}}}^{n_{\text{max}}} (\Delta t_n)2^{(T_n-105)/10} \]

The equation shows that the reaction rate doubles for every 10°C increase. The variable \((n)\) represents the number of time steps through which each unit is buried. Waples (1980) established a quantitative relationship between TTI and vitrinite reflectance. Calculated TTI values will be compared to thermal maturation data of the surrounding wells in order to test our models. The thermal maturation dataset was compiled by Wagenvelt (2015).

Rock-Eval pyrolysis involves slowly heating a sample in a vessel under a chemically inactive atmosphere. The hydrocarbons are then volatized due to the increasing heat in the vessel and multiple measurements are taken generating \(S_1\), \(S_2\), \(S_3\), and \(S_4\) peaks. The \(S_1\) peak reflects the amount of hydrocarbons that were initially present in the sample. The \(S_2\) peak reflects the amount of hydrocarbons produced from the kerogen that was present in the sample. The \(S_3\) peak reflects the amount of \(\text{CO}_2\) that was generated. The \(S_4\) peak represents the amount of residual carbon in the sample (Law, 2000).

Vitrinite reflectance (Ro) is a measurement of incident light that is reflected off of vitrinite particles within a sample. Tmax is defined as the temperature in which the maximum amounts of hydrocarbons are generated from a kerogen source (\(S_2\) peak) (Law, 2000). Tmax values associated with small \(S_2\) peaks (<0.2 mgHC/g) are considered to be inaccurate (Peters, 1986). Tmax values with \(S_2\) peaks greater than 0.5 mgHC/g are assumed to be a reliable estimate of maturation (Wagenvelt, 2015). In this study, vitrinite reflectance and Tmax data with \(S_2\) peaks
greater than 0.5 mgHC/g are assumed to be good quality data and are indicated in the maturation plots.

Different kerogen types affect the onset of oil generation (Peters, 1986). A transition window was defined in order to account for the variable onset of oil production due to variability in kerogens (Wagenvelt, 2015). We also recognize that observations could be impacted by vertical and lateral migration of hydrocarbons. This is most likely to occur in heavily fractured or coarse-grained rocks (Peters, 1986). For example, it is suggested that the composition of Silurian oils in the Southern reef trend of Michigan exhibit mixing of Silurian-type and Ordovician-type oils. These Ordovician-type oils appear to have migrated into the Silurian petroleum system from the stratigraphically lower Trenton Formation (Swezey et al., 2005). In contrast, the Antrim Shale acts as both a petroleum source rock and a reservoir rock (Swezey et al., 2005). Because of this the Antrim was determined to be a quality baseline for the beginning of the transition window. It is assumed that all thermal maturation data represents the thermal maturation of the formations.

Table 2 – Table comparing immature, transition, oil, and gas windows to associated Tmax, R₀, and TTI values. Table taken from Wagenvelt (2015).

<table>
<thead>
<tr>
<th>Level of Maturation</th>
<th>Tmax (⁰C)</th>
<th>R₀ (%)</th>
<th>TTI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Immature</td>
<td>&lt; 435</td>
<td>&lt; 0.60</td>
<td>&lt; 10</td>
</tr>
<tr>
<td>Transition Window</td>
<td>435 - 444</td>
<td>0.6 - 0.64</td>
<td>10 - 14</td>
</tr>
<tr>
<td>Oil Window</td>
<td>445 - 470</td>
<td>0.65 - 1.35</td>
<td>15 - 160</td>
</tr>
<tr>
<td>Gas</td>
<td>&gt; 470</td>
<td>&gt; 1.35</td>
<td>&gt; 160</td>
</tr>
</tbody>
</table>
RESULTS

Seven wells were modeled in this study with different spatial relationships to the MCR. Geodynamic models used to estimate thermal maturation were selected based on the location of the well in respect to the MCR. In this section, wells 43727 (Livingston) and 25099 (Ogemaw) will be discussed in greater detail with respect to the geodynamic models than the other five wells in the study. (Well names will be referred to as the county in which they are located for the remainder of the manuscript). Detailed thermal maturation results for each well are presented in Appendix (E).

![Figure 6](image)

**Figure 6**- Tectonic subsidence results from backstripping well 43727 (Livingston). Black line represents calculated tectonic subsidence and the red line represents best-fit thermal subsidence curve with a corresponding stretching factor ($\beta$) of 1.6.

**Backstripping Results**

The tectonic subsidence results from the Livingston well are presented in Figure 6. The overall shape of the modeled subsidence curve is consistent with that of a thermally cooling plate
This observation suggests that it is appropriate to use McKenzie’s (1978) lithospheric stretching model to quantify heat flow in the basin during subsequent models, which are discussed below.

Also observed in the tectonic subsidence curve are short phases (<10 Ma) of rapid subsidence, that are generally followed by periods of uplift or very slow subsidence (Fig. 6). Nunn, (1994) attributed this type of subsidence to free thermal convection. For example, the fractures in an igneous body located in the upper crust are periodically opened due to changing stress regimes. This allows for the convection of hot hydrothermal fluids. In our model the igneous body is assumed to consist of the basalts formed at the MCR. During periods of inferred free crustal convection a massive amount of heat would be lost to the overlying sediments (Nunn, 1994). As a result of free crustal convection, periods of a rapid subsidence take place within the basin and overlying sediments are significantly heated. We quantify free crustal convection (Nunn, 1994) as a means to increase the temperature of the sediments in the Michigan Basin in several of the following models (next section).

**Thermal Model Results**

Heat flow values utilized in the following models are based on published geodynamic models or from published modern day heat flow values. Calculated formation temperatures in the following models depend on multiple factors which include: porosity; grain conductivity, paleo surface temperature, and basement heat flow. A table describes parameters used in each well for easy reference (e.g. Table 3 and 4).

We try to limit the change in variables, such as porosity vs. depth relationships, paleo surface temperatures and thickness and composition of eroded overburden (EO). Each model in this study utilizes the same EO composition and thickness, porosity vs. depth curves, and the
same paleo surface temperatures. Heat flow values are dependent on the geodynamic model used and are thus relatively free variables that change as we compare calculated TTI values with the surrounding observed thermal maturation data.

**Livingston: Present-Day Model**

The Present-Day model simulates modern heat flow within the Michigan Basin and the effect that present-day conditions have on thermal maturation if heat flow remained constant through time. The present-day heat flow value for the Michigan Basin was assumed to be 48 mW/m² based on Vugrinovich, (1988). Isotherms in this model remain relatively stable through time (Fig. 7). The change in depth of the isotherms in Figure 7 reflects variability in thermal conductivity between rock units and changes in the surface temperature. An EO of 1000 m was assumed to accumulate from 305 Ma (post-Desmoinesian) to 265 Ma and then erode from 265 Ma to 157.3 Ma (pre-Kimmeridgian) (Vuginovich, 1988). EO was assumed to have a rock composition of 50% sandstone and 50% shale. This composition results in a thermal conductivity of 1.97 W/mK. The same deposition and erosion scenario is applied to all wells.
Figure 7 – Geohistory plot of Livingston well. Black dashed lines represent isotherms produced from the Present-Day model. The green overlay represents the oil window generated by the model.

The Present-Day model accurately predicts 6 observed oil window data points and 3 immature data points, but only 1 transition window data point. The Antrim is the shallowest formation with good quality observed maturation data. This data suggests that the Antrim is at the top of the transition window while the model suggests that the transition window begins 360 m deeper in the Bois Blanc (Fig. 8). The following models are used to attempt to raise the depth of the modeled transition window to the Antrim Shale. We focus on the Antrim because it is likely that the hydrocarbons in the Antrim were generated and matured in place rather than migrating from depth. Expanding the analysis to all formations, 19 observations of maturation were obtained from within a 30 km radius of the site. These maturation estimates are based on quality data ($S_2 > 0.5$ mgHC/g or Ro). The average Tmax/Ro and standard deviation of each
formation are plotted. Note that poor maturation data (Tmax S₂ < 0.5 mgHC/g) are also shown (e.g. Fig. 8). The Present-Day model correctly predicts a total of 10 out of 19 of the good Tmax and Ro averaged values (Fig. 8 and Appendix E). Within this model, the geothermal gradient at the time of Antrim deposition was 21.4 °C/km.

![Figure 8: Thermal maturation plot of the Present-Day model for well 43727 (Livingston). Circles represent the best quality observed Tmax and Ro data. Ro values have been transposed into the T-max scale for plotting as have the TTI model results (grey rectangles). Triangles represent poor quality Tmax data. Colors correspond to specified surrounding wells with observed thermal maturation data as indicated in the key.](image-url)
**Livingston: Thermal Cooling Model**

In the Thermal Cooling model (TC), McKenzie’s (1978) lithospheric stretching model is used to quantify heat flow resulting from a thermally subsiding basin. Thermal anomalies have been proposed as the reason for tectonic subsidence of the Michigan Basin (McKenzie, 1978; Nunn et al., 1984). Heat flow values used in this model result from a stretching factor ($\beta$) of 1.6 (Fig. 6). The TC model has the greatest effect on thermal maturation during the beginning of basin formation when heat flows are relatively high. Over time the basin cools resulting in a limited effect on thermal maturation of the younger strata in the Michigan Basin. The increase in heat flow to the sediments resulting from the TC model did not significantly affect thermal maturation. The same results were predicted as the Present-Day model with a total of 10 out of 19 averaged Tmax and Ro values, which are correctly modeled. No change in the depth of the transition window was observed in the TC model. The TC model produced a geothermal gradient for Antrim deposition of 23.5 °C/km, which is, 2.1 °C/km greater than the Present-Day model.

**Livingston: Crustal Convection Model**

Free crustal convection (Nunn, 1994) was proposed to explain periods of rapid subsidence and increased thermal maturation in the Michigan Basin. In the Crustal Convection model (CCD/CCU), the basaltic rocks of the MCR are assumed to be fractured allowing for rapid heat loss, which increases thermal maturation in the sediments in a relatively short amount of time (<10 Ma). This cycle of accelerated heat loss causes short periods of rapid subsidence in the basin. The timing of free crustal convection events is constrained by far-field Appalachian orogenies (Fig. 3). We model the timing of free crustal convection in our models to begin at 460, 439, 372, and 320 Ma (Fig. 9). These ages correlate to periods of rapid subsidence in the Michigan Basin (Fig. 6) and to the timing of the Taconic, Acadian, and Alleghanian orogenies.
Although rapid subsidence in the Michigan Basin during the Alleghanian orogeny is not observed, a free crustal convection event at this time is still modeled. This is necessary to increase the thermal maturation of the youngest sediments in the Michigan Basin.

Heat flow values in Crustal Convection model depend on well location. A relatively minor increase in heat flow occurs if the well is above a crustal convection downwelling (CCD). In contrast, a maximum heat flow elevation occurs above a crustal convection upwelling (CCU) zone. In the crustal convection models, during the first 2 Ma heat flows values are increased by 30% and 125% above background Thermal Cooling model values. After 10 Ma those percentages decrease to 10% and 75%, respectively. After 17 Ma, heat flow values return to background thermal cooling levels. The timing and magnitude is based on the models of Nunn (1994).
Figure 9 – Geohistory plot of the Livingston well. Black dashed lines represent isotherms produced by the CCU model. The green overlay represents the oil window generated by the model. In this model there are four upwelling crustal convection events at 460, 439, 372, and 320 Ma. During these periods of crustal convection temperatures to the sediments are significantly increased over a time span of 17 m.y. (Nunn, 1994).

The results of the CCD model show a slight shallowing of the oil window, from the A2 Carbonate to the Salina B Unit. As a result, an additional data point accurately matches the model prediction of the oil window (Fig. 8). However, the model still does not increase thermal maturation sufficiently to raise the transition window to the Antrim Shale (Fig. 8 and 10). The CCD model correctly predicts 11 out of 19 observed thermal maturation values. The CCD model produces a geothermal gradient at the time of deposition of the Antrim Shale of 29 °C/Km.

The CCU model predicts an increase in thermal maturation compared to those predicted by the lower heat flows of the CCD model. The CCU model raises the top transition window into the Lucas Formation and the oil window into the Salina F Unit. The transition window still does not reach into the Antrim Shale, however (Fig. 10). A total of 10 of 19 observed Tmax and Ro
values are accurately predicted. A geothermal gradient of 49.6 °C/km was calculated at the time of deposition of the Antrim Shale.

Table 3- Summary of models performed on well 43727. The same EO lithologies were used for each model. The previously discussed porosity vs. depth curve was used to decompact each lithology quantified in the well. Heat flow information with regard to each model is shown. Model abbreviations: PD = Present-Day; TC = Thermal Cooling; CCD = Crustal Convection Downwelling; CCU = Crustal Convection Upwelling; ACCD = Advection Crustal Convection Downwelling; ACCU = Advection Crustal Convection Upwelling; and APD = Advection Present-Day.

<table>
<thead>
<tr>
<th>Model</th>
<th>Heat Flow</th>
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<tr>
<td>CCD</td>
<td>Lithospheric Stretching &amp; Downwelling Free Convection</td>
</tr>
<tr>
<td>CCU</td>
<td>Lithospheric Stretching &amp; Upwelling Free Convection</td>
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<tr>
<td>ACCD</td>
<td>Lithospheric Stretching, Downwelling Free Convection, &amp; Fluid Event at 320-319.98 Ma</td>
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<td>ACCU</td>
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</tr>
<tr>
<td>APD</td>
<td>48 mW/m² &amp; Fluid Event at 335-310 Ma</td>
</tr>
</tbody>
</table>

Livingston: Advection Crustal Convection Downwelling/Upwelling Model

Within the Michigan Basin there is evidence of localized hydrothermal activity. Studies suggest that advecting fluids have reached temperatures of at least 145°C and possibly up to 260°C (Luczaj et al., 2006; Ma et al., 2009). The Advection Crustal Convection Downwelling / Upwelling model (ACCD/ACCU) simulates background heat flows identical to the CCD and CCU models but accounts for a short burst of hot hydrothermal fluids that migrate to the surface at a specified time and for a specified duration. The temperature of the advecting fluid is assumed to equal that of the sediments in contact with the igneous basement. In the ACCD model, 130°C fluids were assumed to migrate to the surface over a 20 ka time span from 320 Ma
to 319.98 Ma. The results show only a slight shallowing in the transition window so that the model did not predict that the Antrim shale reached the transition window (Fig. 10). A total of 10 of 19 averaged Tmax and Ro values were accurately matched. It is possible that the Antrim shale would fall in the transition window if advection was modeled for a longer duration. This was not performed because 20 ka was considered to be the maximum duration for fluid advection.

The ACCU model, which utilizes the background heat flow values of the CCU model simulated migration of 210°C hydrothermal fluid to the surface. Compared to the ACCD model, hotter fluids in the ACCU model pushed the Antrim shale into the transition window. Only 2 ka (320.0 to 319.998 Ma) of fluid movement in the ACCU model was required to bring the Antrim shale into the transition window and accurately predict 12 out of 19 average Tmax and Ro values (Fig. 10).

Livingston: Advection Present-Day

The Advection Present-Day model (APD) simulates a scenario where the Michigan Basin had a constant heat flow through time. The heat flow is assumed to be equal to the modern value of 48 mW/m². In APD model, basement fluids are transported to the surface through advection processes. The timing of the fluids is adjusted so that the model output best matches observed maturations for each well. For the Livingston well, for example, advection of hydrothermal fluids is modeled during the Alleghanian orogeny for 25 Ma (335-310 Ma). This model was used to test the hypothesis that present-day heat flow coupled with fluid advection cannot explain observed maturations found in the Michigan Basin. The results of this model match 15 out of 19 observed Tmax and Ro values (Fig. 10).
Figure 10- Thermal maturation plot of well 43727 (Livingston) that shows each models’ maturation windows. The top number in each group represents the number of incorrectly predicted observed data (high quality) points that are shallower than the calculated maturation window. The middle number in each group corresponds to the number of correctly predicted observed data points (high quality). The bottom number in each group represents the number of incorrectly predicted observed data points (high quality) that are deeper than the calculated maturation window. PD = Present-Day; TC = Thermal Cooling; CCD = Crustal Convection Downwelling; CCU = Crustal Convection Upwelling; ACCD = Advection Crustal Convection Downwelling; ACCU = Advection Crustal Convection Upwelling; and APD = Advection Present-Day.
Ogemaw

Because Well 25099 in Ogemaw County is located away from the MCR, the CCD, CCU, ACCD, and ACCU models cannot be used to model the observed maturation. These models require heat from free crustal convection, which is only applicable in a location above the MCR. The geodynamic models used in locations away from the MCR, which will be discussed below, include the, Present-Day, Thermal Cooling (TC), and Advection Upwelling (AU).

Ogemaw: Present-Day Model

The present-day model utilizes the same parameters as previously discussed. The resulting geothermal gradient was 20.5°C/km, which is in range of the present-day geothermal gradient of 19-22°C/Km (Pollack & Watts, 1976; Vurginovich, 1988). In general, this model under-predicts the maturation levels in Ogemaw and surrounding wells. The Present-Day model calculated the gas window at the top of the Black River Formation. In reality, gas is observed 1276 m shallower in the Salina Group. The model also predicts that the top of the transition window occurs at the top of the Detroit River Group with a mix of transition and immature samples observed in the Antrim, Coldwater, Sunbury, and Berea formations. In total, the model matched 9 of 23 average Tmax and Ro values from surrounding wells (Fig. 12).
Figure 11 - Thermal maturation plot of AU model for well 25099 (Ogemaw). Circles represent the best quality observed Tmax and Ro data. Triangles represent poor quality Tmax data. Different colors correspond to different surrounding wells with observed thermal maturation data.

Ogemaw: Thermal Cooling Model

The Thermal Cooling (TC) model utilizes the same parameters as previously discussed. Heat flow values in this model are based on a stretching factor ($\beta$) of 4.3. The added heat from lithospheric stretching brought the gas window in the model up to the Trenton, which matched one more gas window data observation than did the Present-Day model. The TC model could not accurately predict any observed maturation points in the Antrim and shallower formations. The TC model matched 10 of 23 average Tmax and Ro data points (Fig. 12).
Table 4- Summary of models performed on well 25099. The same EO lithologies were used for each model. The previously discussed porosity vs. depth curve was used to decompact each lithology quantified in the well. Heat flow information with regard to each model is shown. Model abbreviations: PD = Present-Day; TC = Thermal Cooling; and AU = Advection Upwelling.

<table>
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<tr>
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<tr>
<td>TC</td>
<td>Lithospheric Stretching</td>
</tr>
<tr>
<td>AU</td>
<td>Lithospheric Stretching, Fluid Events at 372-371.98 Ma &amp; 312-311.999 Ma</td>
</tr>
</tbody>
</table>

Ogemaw: Advection Upwelling Model

The Advection Upwelling (AU) model is designed to simulate the effects of a fault dilating from the MCR that reaches the well location. Heat flow values consistent with the CCU model are imposed for a very short time span. The timing of these modeled hydrothermal fluid events is constrained by the Acadian and Alleghanian orogenies at 372 Ma and 312 Ma, respectively. Fluid temperatures are uncertain. A temperature of the bottommost sediments in this well was used in the CCU model to produce 225°C fluids coming to the surface for 20 ka and 1 ka, respectively (Table 4). This value is within 25°C of the fluids used for the MCR wells (e.g., 230°C at Missaukee). This dramatically elevates the gas, oil, and transition windows. The calculated gas window matches the observed maturation of the Salina Group. The calculated oil window correctly matches the observed data of the Bass Islands, Bois Blanc, and Traverse Group. The calculated transition window also matches the more mature samples observed in the shallowest formations (e.g. Antrim and Coldwater) (Fig. 11 and 12). The AU model accurately matches 18 of 23 high quality observed Tmax and Ro averages.
**Figure 12** - Thermal maturation plot of well 25099 (Ogemaw) that shows each models’ maturation windows. The top number in each group represents the number of incorrectly predicted observed data (high quality) points that are shallower than the calculated maturation window. The middle number in each group corresponds to the number of correctly predicted observed data points (high quality). The bottom number in each group represents the number of incorrectly predicted observed data points (high quality) that are deeper than the calculated maturation window. PD = Present-Day; TC = Thermal Cooling; and AU = Advection Upwelling.

**Cheboygan**

Well 30682 in Cheboygan County is also located away from the MCR zone and thus crustal convection geodynamic models are not used to calculate thermal maturation. Thermal
maturation data in this location is limited in quality and quantity. The area has only three observed low quality ($S_2 < 0.5\text{mgHC/g}$) Tmax data points sampled from the Cabot Head and Utica formations which suggest immature hydrocarbon maturation. The Present-Day model performed on the Cheboygan well used a modern heat flow of 48 mW/m$^2$ (same values as in all Present-Day models). The results of the Present-Day model over predicted all 3 maturation values in the Utica and Cabot Head Fms. In an attempt to achieve maturation window predictions that matched observations, a heat flow value of 30 mW/m$^2$ (Vurginovich, 1988) was substituted into the Present-Day and TC models (Table 5 and Appendix E). As a result, both the Present-Day and TC model matched 3 of 3 observed Tmax values.

Table 5- Summary of models performed on well 30682. The same EO lithologies were used for each model. The previously discussed porosity vs. depth curve was used to decompact each lithology quantified in the well. Heat flow information with regard to each model is shown. Model abbreviations: PD = Present-Day and TC = Thermal Cooling.

<table>
<thead>
<tr>
<th>Model</th>
<th>Heat Flow</th>
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<tbody>
<tr>
<td>PD</td>
<td>30 mW/m$^2$</td>
</tr>
<tr>
<td>TC</td>
<td>Lithospheric Stretching</td>
</tr>
</tbody>
</table>

**Grand Traverse**

The Present-Day, TC, CCD, CCU, ACCD, ACCU, and APD models were all performed on well 34292 in Grand Traverse County. All models matched 5 of 9 observed Tmax and Ro averages. Observed maturation data from the Antrim is variable in this well, placing it either in the immature or transition window. Because the models are deterministic, a single model could not predict both observations. The Present-Day, TC, CCD, CCU, and ACCD models matched the immature data point for the Antrim. The ACCU and APD models, in contrast, matched the transition window data point for the Antrim. The Glenwood Formation is also observed to have
variable maturation including both oil and gas (Appendix H). The CCU and ACCU models were able to match the observed gas window data point in the Glenwood, but not the oil window observation due to increased calculated maturation.

Table 6 - Summary of models performed on well 34292. The same EO lithologies were used for each model. The previously discussed porosity vs. depth curve was used to decompact each lithology quantified in the well. Heat flow information with regard to each model is shown. Model abbreviations: PD = Present-Day; TC = Thermal Cooling; CCD = Crustal Convection Downwelling; CCU = Crustal Convection Upwelling; ACCD = Advection Crustal Convection Downwelling; ACCU = Advection Crustal Convection Upwelling; and APD = Advection Present-Day.

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</tr>
<tr>
<td>ACCD</td>
<td>Lithospheric Stretching, Downwelling Free Convection, &amp; Fluid Events at 372-371.98, 364-363.98, 320-319.98, &amp; 312-311.98 Ma</td>
</tr>
<tr>
<td>ACCU</td>
<td>Lithospheric Stretching, Upwelling Free Convection, &amp; Fluid Event at 320-319.99 Ma</td>
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<tr>
<td>APD</td>
<td>48 mW/m² &amp; Fluid Events at 497.5-373.2 Ma &amp; 323.2-312.2 Ma</td>
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</table>

Gratiot

The Present-Day model for well 29739 in Gratiot matched 0 of 11 observations. The TC and CCD model raised the gas window from the Trempealeau to the Prairie Du Chien but could not match Tmax values. The most successful model matches came from the ACCU. Maturation data place the Berea, Antrim, and Squaw Bay in the transition window. The ACCU model raised the level of the transition window to the Sunbury and was able to match 3 observed data points (Appendix E). The same model also predicted an elevated gas window, which accurately
matched an observed data point in the Utica. The ACCU model was able to match 4 of 11 observed Tmax values.

Table 7- Summary of models performed on well 29739. The same EO lithologies were used for each model. The previously discussed porosity vs. depth curve was used to decompact each lithology quantified in the well. Heat flow information with regard to each model is shown. Model abbreviations: PD = Present-Day; TC = Thermal Cooling; CCD = Crustal Convection Downwelling; CCU = Crustal Convection Upwelling; ACCD = Advection Crustal Convection Downwelling; ACCU = Advection Crustal Convection Upwelling; and APD = Advection Present-Day.

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<tr>
<td>APD</td>
<td>48 mW/m² &amp; Fluid Event at 323.2-321.2 Ma</td>
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</table>

Lenawee

Well 10448 in Lenawee County is located away from the MCR, because of this only the Present-Day, TC, and AU model can be used to calculate thermal maturation. The Present-Day and TC model both predicted the transition window at the top of the Glenwood, resulting in 0 of 9 Tmax and Ro matches. The higher temperatures in the AU model raised the transition window to the Cincinnatian, correctly matching 8 out of 9 observed Tmax and Ro data points.
Table 8- Summary of models performed on well 10448. The same EO lithologies were used for each model. The previously discussed porosity vs. depth curve was used to decompact each lithology quantified in the well. Heat flow information with regard to each model is shown. Model abbreviations: PD = Present-Day; TC = Thermal Cooling; and AU = Advection Upwelling.

<table>
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<td>PD</td>
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<tr>
<td>TC</td>
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<td>AU</td>
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Missaukee

The Present-Day and TC models for well 34376 in Missaukee County matched 6 of 25 Tmax and Ro observations. There is high quality observed maturation data to suggest the base of the transition window is at the top of the Antrim shale (Appendix E). The CCD model showed no increase in the transition window but did raise the gas window to the top of the Trenton, matching 6 of 12 gas window observations. That is 4 more than the Present-Day and TC models. The CCU model did not raise the transition window enough to include the Antrim but did raise the gas window even higher than the CCD to match 12 of 12 observed gas window data points. The ACCD and ACCU models calculated the transition window to be at the top of the Antrim and matched a total of 13 and 17 out of 25 observed Tmax and Ro values, respectively.
Table 9- Summary of models. The same EO lithologies were used for each model. The previously discussed porosity vs. depth curve was used to decompact each lithology quantified in the well. Heat flow information with regard to each model is shown. Model abbreviations: PD = Present-Day; TC = Thermal Cooling; CCD = Crustal Convection Downwelling; CCU = Crustal Convection Upwelling; ACCD = Advection Crustal Convection Downwelling; ACCU = Advection Crustal Convection Upwelling; and APD = Advection Present-Day.

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DISCUSSION

The results of the Present-Day model in the Michigan Basin wells clearly demonstrate that the modern day heat flow in the Michigan Basin alone cannot explain the observed thermal maturation data. In the case of well locations above the MCR, and for those distant from it, heat flow into the sediments had to be increased through both geodynamic models and fluid advection to match local thermal maturation observations. The following discussion will first focus on wells above the MCR, and then on wells that are at a distance from the MCR, and lastly a comparison of both.

Wells above the MCR

Wells 43727 (Livingston), 34376 (Missaukee), 34292 (Grand Traverse), and 29739 (Gratiot) are located above the MCR (Fig. 1). The same geodynamic models were performed on
each well utilizing the same parameters of EO thickness and composition, as well as, the same porosity vs. depth curve in order to limit variables and achieve a better understanding of the heat flows and geothermal gradients necessary to match observed thermal maturation data.

The Present-Day model did not correctly predict the observed transition window maturation in any of the four wells. In each of the wells the Antrim was the shallowest formation that shows evidence of hydrocarbons with Tmax or Ro within the transition window. Outputs from the Present-Day model consistently predicted the Antrim to be immature. Also, the Present-Day model consistently could not explain deeper hydrocarbons observed in the gas window. As a result, it is clear that the Present-Day model cannot account for observed maturation in the wells located above the MCR. That is, higher heat flows in the past are required at these locations in order to increase geothermal gradients and thus, account for the overly mature observed maturation data.

The TC model had little to no effect on matching observed maturation data in each of the four wells. The Present-Day and TC model correctly matched the same maturation observations in these wells, which suggests that, geothermal gradients in the basin were elevated by geodynamic processes other than lithospheric stretching.

The CCD model exhibits slightly higher calculated thermal maturation windows in the Missaukee, Grand Traverse, and Livingston wells but no change was predicted in the Gratiot well. It is only in the CCU model where a significant rise in calculated hydrocarbon maturation is predicted. Although the CCU model raised the transition window in each well, it still does not predict the transition window maturation in the Antrim. The main impact of the CCU model was to reduce the depth of the gas window, increasing maturations in the deeper units. In fact, 3 of the 4 wells matched the observed maturations in the gas window. Maturation values from the
CCU model matched significantly more maturation data points compared to the Present-Day, TC, and CCD models in these four wells. This result provides evidence that Nunn’s (1994) model of free crustal convection can be used to match gas window observed maturation data in the Michigan Basin. That being said, the CCU models for the four wells was unable to account for the observed transition window maturation of the Antrim.

The ACCU model for each well was able to match the transition window maturation of the Antrim while correctly matching observed gas window data. The results of this model provide evidence that higher heat flows associated with upwelling zones of crustal convection can explain gas and oil window maturations within the Michigan Basin. Hot upward migrating fluids simulated in the ACCU model are required to increase the maturation of the shallowest strata in the Michigan Basin.

Crustal Convection coupled with advecting fluids can explain the variability in thermal maturation data observed within the Michigan Basin. The observed maturation data in each of the four wells show variable maturation for a given formation (Fig. 15). It is plausible that the observed variability is related to local variations in fluid advection such that even a single formation does not experience the same amount of heat through time. The ACCD and ACCU models simulate fluids of different temperatures reaching the surface from the basement through dilating faults. These models are able to account for the variability of maturation within the same formations. It is possible that formations in each well were exposed to different temperature fluids or no fluids at all. This would account for the same formation in different wells having disparate observed maturations (Appendix E).

The APD model was used to test the hypothesis that present-day heat flows coupled with fluid flow control thermal maturation in the Michigan Basin. The results show that the APD
The model can match observations in each well. This is only true, however, if fluid flow persisted for 2 to 125 Ma depending on well location (Table. 3, 6, 7, and 9). This range is considered unrealistic due to the extensive length of time in which fluids must have been flowing. The APD model, therefore, is not considered to be an acceptable explanation for hydrocarbons maturation in the Michigan Basin.

Wells at a distance from the MCR

Wells 25099 (Ogemaw), 30682 (Cheboygan), and 10448 (Lenawee) are located off of the MCR. As previously discussed, only the Present-Day, TC, and AU models were performed at these locations because the CCD, CCU, ACCD, and ACCU models require crustal convection. In our conceptual framework, the crustal convection models can only be applied to locations above the MCR.

The Cheboygan well is an outlier compared to the Ogemaw and Lenawee wells. The Present-Day and TC model, which used a heat flow of 48 mW/m², over-calculated thermal maturation compared to the data (Fig. 13). There are only 3 observations of maturation near this well, and none are well constrained. However, if these values are accurate, the Present-Day model yields over-mature results for this well.
Figure 13 – Thermal maturation plot of well 30682 (Cheboygan). Shaded grey area shows a Present-Day model with a heat flow of 48 mW/m² and predicted overly mature maturation windows. Grey crosshatched area shows a Present-Day model with a heat flow of 30 mW/m² and predicted maturation windows that match observed data.

It is possible to generate the low maturation values by applying a geologically reasonable model. Vugrinovich (1988) developed a heat flow map of the Michigan Basin that suggests 48 mW/m² as a consistent and quality heat flow value to assume for the Michigan Basin as a whole. The map from Vugrinovich (1988) delineates an abnormally low heat flow value of 30 mW/m² in Cheboygan County. When a basement heat flow of 30 mW/m² is used in the Present-Day and TC models, lower heat flow values correctly match the observed immature maturation values of the Cabot Head and Utica formations (Fig. 13). Data that suggests immaturity surrounding the Cheboygan well are not anomalous (Fig. 15). That is, observations from, other study wells, with equivalent ages and depths also include both good quality and poor immature observed maturations. However, in the other wells, there are also good quality observed oil or gas
maturation levels at these depths (ages) or at shallower depths (younger ages; Fig. 15). For this reason, immature maturation observations in the Cheboygan well do not require lower heat flow values in this region.

The results from modeling the Ogemaw and Lenawee wells do an excellent job of demonstrating the fact that higher geothermal gradients are needed in these locations. The Present-Day and TC models in the Ogemaw well predict that the transition window only reaches the bottom of the Dundee Formation and Traverse Group respectively. This does not match the observed maturations in the Coldwater, Sunbury, and Antrim (Fig. 15 & Appendix E). Also, these two models under predict the observed gas window maturation of the Salina Group (Appendix E). Additional heat is needed to match observed maturations in each of these wells despite their distance from the MCR. The added heat from fluid advection simulated in the AU model can explain observed maturation data of the Antrim and Salina Group. Similar results occur in the Lenawee well where observed transition maturations of the Cincinnatian and Trenton Formation are only predicted when heat is added through advecting fluids as is the case in the AU model.
The results from modeling the Ogemaw and Livingston wells reveal that well locations away from the MCR likely experienced elevated thermal conditions in the past compared to present-day heat flow. Observed maturation data match predictions only when advecting hot hydrothermal fluids derived from the MCR reaching these remote locations, presumably through dilating faults and fractures. The Cheboygan well is considered an outlier in the basin based on
the anomalously low heat flows required to match observed maturation data, which is of poor quality.

It is important to note that these results are non-unique, in that, the same results could be attained through different model assumptions. For example, the same results can be computed in the Lenawee well from the AU model by advecting fluids at different times and durations. For example, fluid advection from 320-319.98 Ma (20,000 years) results in the same degree of hydrocarbon maturation as advection of fluids from 372 to 371.995 Ma and 320 to 319.995 Ma (5,000 years each) (Appendix E).

**Comparison: Above and away from the MCR**

Some trends are observed in the comparison of wells located above the MCR with those away from the MCR. To match observed maturation data, increased temperatures to the sediments beyond that generated from the Present-Day and TC models were required in all wells except Cheboygan. For the wells above the MCR, the best model match with observed maturation came from the ACCU. This model simulates 1000 m of eroded overburden coupled with increased heat flow from lithospheric stretching, crustal convection upwelling, and hydrothermal fluid advection. This supports the original hypothesis and validates the conclusions of Wagenvelt (2015).

Wells outside the rift required increased heat flow from advecting fluids of the AU model to match observed variations in maturation data. Proximity to the MCR shows no discernable effect on observed maturation data (Fig. 15). Therefore, from the results of this study, the original hypothesis that proximity to the rift affects thermal maturation is inconclusive or negative. It is possible that off rift basement sourced faults could also open in response to far
field stress changes associated with Appalachian orogenies and bring up hot water from deep in
the crust. This could account for the lack of variability in maturation with proximity to the MCR.

It is plausible that multiple crustal convection events may not be necessary to match
observed maturation data for well locations above the MCR. Future work should look into
utilizing the AU model for well locations above the MCR to examine the need for multiple
crustal convection events to match observed data. Also, information on the faults and fracture
networks near the well locations in this study could provide additional constraints regarding
possible hydrothermal fluid activity at the well locations.
Figure 15 - Observed thermal maturation data with depth or time. Surrounding data was gathered within a 30 Km area of each well location. Different colors represent thermal maturation windows. Different shades of each color represent good ($S_2 > 0.5$ mgHC/g or $R_o$) vs. poor quality data ($S_2 < 0.5$ mgHC/g). Highlighted well name = above the MCR. Ch = Cheboygan, GT = Grand Traverse, Og = Ogemaw, Ma = Missaukee, Gr = Gratiot, Li = Livingston, and Le = Lenawee.
CONCLUSIONS

Thermal maturation data and model predictions were presented for seven wells across the Michigan Basin. These wells represent different proximities to the MCR, which was hypothesized to exert a major control on thermal maturation. Through the use of the modeling this study demonstrates:

1.) Present-day heat flow in the Michigan Basin cannot explain observed thermal maturation data.

2.) Well locations above the MCR (Grand Traverse, Missaukee, Gratiot, and Livingston) require 1000 m of eroded overburden, thermal cooling, crustal convection, and high temperature fluid advection to match surrounding thermal maturation data in these and immediately surrounding wells.

3.) Well locations away from the MCR (Ogemaw and Lenawee) require 1000 m of eroded overburden, thermal cooling, and high temperature fluid advection to match surrounding thermal maturation data in the Michigan Basin
   - Cheboygan required a reduced heat flow value of 30 mW/m² compared to the Michigan Basin average of 48 mW/m² in order to match limited surrounding thermal maturation data.

4.) The effect on thermal maturation from proximity to the MCR is uncertain.

5.) High-temperature fluid advection is necessary to increase the maturation of the shallowest strata and can account for the variable maturations observed in formations across different wells in the Michigan Basin.

6.) Geodynamic models similar to Wagenvelt (2015) can be used to match thermal maturations observed in the Michigan Basin.
REFERENCES


CATACOSINOS, P. & DANIELS, P. JR. (1991) Stratigraphy of Middle Proterozoic to Middle


WAPLES, D (1980) Time and temperature in petroleum formation: application of Lopatin’s


APPENDIX A
Formation Properties, Water Depths, and Drilling Reports

Each wells drilling report is referenced below. These reports were used to determine the stratigraphy of the well. The qualitative descriptions of lithologies in the reports were quantified in this study. Each report was taken from the Michigan Department of Environmental Quality GeoWebFace website. Quantitative interpretations for each of those reports were made. An example of those interpretations is shown below for the Livingston well. Environments of deposition taken from literature sources were used to quantify water depths. An example of the water depths used in the Livingston well is shown in the table below with references used in the following table.

Cheboygan:

http://www.deq.state.mi.us/GeoWebface/GeoWebface/DL/031/30682_DL.pdf

Grand Traverse:

http://www.deq.state.mi.us/GeoWebface/GeoWebface/DL/055/34292_DL.pdf

Gratiot:

http://www.deq.state.mi.us/GeoWebface/GeoWebface/DL/057/29739_DL.pdf

Lenawee:

http://www.deq.state.mi.us/GeoWebface/GeoWebface/DL/091/10448_DL.pdf

Livingston:

http://www.deq.state.mi.us/GeoWebface/GeoWebface/DL/093/43727_DL.pdf

Missaukee:

http://www.deq.state.mi.us/GeoWebface/GeoWebface/DL/113/34376_DL.pdf

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<td>20 to 50</td>
<td>Budai &amp; Wilson, 1991; Dr. Voice Communication</td>
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<td>100 to 500</td>
<td>Harrison, 1985; Droste &amp; Shaver, 1983; Dr. Voice Communication</td>
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<td>Drillers Log (Permit #: 43727)</td>
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APPENDIX B

Porosity vs. Depth Curves

Porosity vs. depth curves are used to delithify sediments to their original depositional thickness. In order to calculate porosity, information on burial depth and lithology must be determined. In this study, for each well and model we utilize only one set of porosity vs. depth curves (below) in order to limit free variables.

Figure B1- Porosity vs. depth curves used in this study. Curves show common lithologies found in the Michigan Basin. Clean sandstone, dirty sandstone, and silt curves are taken from Wagenvelt’s (2015) derived Michigan best porosity vs. depth curves.
APPENDIX C

Paleolatitude and Paleo Surface Temperature

Paleo-surface temperature is a function of paleo-latitude and paleo-climate. Temperatures for the Michigan Basin were calculated by utilizing the PALEOMAP project by Scotese (2015). In his model, Scotese (2015) developed a set of tropic to pole temperature gradients as well as a model of the climatic history of the earth. Temperature change through time at the equator shifts the tropic to pole temperature gradients. The shift is taken into account by utilizing Royer et al., (2004) who produced a tropical temperature curve with ages modified by Scotese, (2015). The paleo-latitude of the Michigan Basin was determined by utilizing PALEOMAP model on the GPlates Portal Paleomap Maker website (Fig. C2). Finally, paleo-surface temperatures can be calculated for the Michigan Basin through time (Fig. C1)

Figure C1- Calculated Paleo-Surface Temperatures used for each well and model in this study.
Figure C2 – Estimated paleo-latitude of the Michigan Basin.
APPENDIX D

Geohistory and Thermal Maturation Diagrams

A geohistory plot for well 43727 (Livingston) is provided for each geodynamic model that was run in this study. Thermal maturation diagrams were created for each of the seven wells in this study. Both Ro and model TTI results have been converted to Tmax units following the convention of Table 2 in the thesis. Large circles represent more confident data points which is a combination of vitrinite reflectance ($R_0$) and Tmax with $S_2$ values greater than 0.5 mgHC/g. Tmax data points with $S_2$ values less than 0.5 mgHC/g are represented by triangles on the diagram. Error bars are presented, including the maximum, minimum and the averaged data. Colors of the data points on the plots represent different wells as indicated in the key. The grey shaded areas represent thermal maturation windows. These windows always start at immature, transition, oil, and finally, gas, when reading left to right or top to bottom on the diagram. A summary thermal maturation diagram was also created for each of the seven wells in this study. These diagrams show which geodynamic models were used on that well and the calculated thermal maturation windows. The numbers located in the middle of the maturation windows represent the number of correctly predicted observed thermal maturation values.
Figure D1 – Geohistory plot of Livingston with Present-Day model. The isotherms are shown at 10° intervals. The burial depth of each formation is shown through time by the colored lines (see key for formation identification). The geologic time scale is indicated at the top: C = Cambrian, O = Ordovician, S = Silurian, C = Carboniferous, P = Permian, TR = Triassic, J = Jurassic, K = Cretaceous, and T = Tertiary.
Figure D2 - Geo history plot of Livingston with TC model. The isotherms are shown at 10° intervals. The burial depth of each formation is shown through time by the colored lines (see key for formation indentification). The geologic time scale is indicated at the top C = Cambrian, O = Ordovician, S = Silurian, C = Carboniferous, P = Permian, TR = Triassic, J = Jurassic, K = Cretaceous, and T = Tertiary.
Figure D3 - Geohistory plot of Livingston with CCD model. The isotherms are shown at 10° intervals. The burial depth of each formation is shown through time by the colored lines (see key for formation identification). The geologic time scale is indicated at the top: C = Cambrian, O = Ordovician, S = Silurian, C = Carboniferous, P = Permian, TR = Triassic, J = Jurassic, K = Cretaceous, and T = Tertiary.
Figure D4- Geohistory plot of Livingston with CCU model. The isotherms are shown at 10° intervals. The burial depth of each formation is shown through time by the colored lines (see key for formation identification). The geologic time scale is indicated at the top: C = Cambrian, O = Ordovician, S = Silurian, C = Carboniferous, P = Permian, TR = Triassic, J = Jurassic, K = Cretaceous, and T = Tertiary.
Figure D5 - Geohistory plot of Livingston with ACCD model. The isotherms are shown at 10° intervals. The burial depth of each formation is shown through time by the colored lines (see key for formation identification). The geologic time scale is indicated at the top C = Cambrian, O = Ordovician, S = Silurian, C = Carboniferous, P = Permian, TR = Triassic, J = Jurassic, K = Cretaceous, and T = Tertiary.
Figure D6 - Geohistory plot of Livingston with ACCU model. The isotherms are shown at 10° intervals. The burial depth of each formation is shown through time by the colored lines (see key for formation identification). The geologic time scale is indicated at the top C = Cambrian, O = Ordovician, S = Silurian, C = Carboniferous, P = Permian, TR = Triassic, J = Jurassic, K = Cretaceous, and T = Tertiary.
Figure D7 - Geohistory plot of Livingston with APD model. The isotherms are shown at 10° intervals. The burial depth of each formation is shown through time by the colored lines (see key for formation identification). The geologic time scale is indicated at the top C = Cambrian, O = Ordovician, S = Silurian, C = Carboniferous, P = Permian, TR = Triassic, J = Jurassic, K = Cretaceous, and T = Tertiary.
Figure D8- Thermal maturation diagram of well 30682 (Cheboygan). Model: Present-Day 30 mW/m².
Figure D9- Thermal maturation diagram of well 30682 (Cheboygan). Model: Thermal Cooling.
**Figure D10** - Summary thermal maturation diagram of well 30682 (Cheboygan). The top number in each group represents the number of incorrectly predicted observed data points that are shallower than the calculated maturation window. The middle number in each group corresponds to the number of correctly predicted observed data points. The bottom number in each group represents the number of incorrectly predicted observed data points that are deeper than the calculated maturation window.
Figure D11- Thermal maturation diagram of well 34292 (Grand Traverse). Model: Present-Day.
Figure D12- Thermal maturation diagram of well 34292 (Grand Traverse). Model: Thermal Cooling.
Figure D13- Thermal maturation diagram of well 34292 (Grand Traverse). Model: Crustal Convection Downwelling.
Figure D14- Thermal maturation diagram of well 34292 (Grand Traverse). Model: Crustal Convection upwelling.
Figure D15- Thermal maturation diagram of well 34292 (Grand Traverse). Model: Advection Crustal Convection Downwelling.
Figure D16- Thermal maturation diagram of well 34292 (Grand Traverse). Model: Advection Crustal Convection Upwelling.
Figure D17- Thermal maturation diagram of well 34292 (Grand Traverse). Model: Advection Present-Day.
Figure D18- Summary thermal maturation diagram of well 34292 (Grand Traverse). The top number in each group represents the number of incorrectly predicted observed data points that are shallower than the calculated maturation window. The middle number in each group corresponds to the number of correctly predicted observed data points. The bottom number in each group represents the number of incorrectly predicted observed data points that are deeper than the calculated maturation window.
Figure D19- Thermal maturation diagram of well 29739 (Gratiot). Model: Present-Day.
Figure D20- Thermal maturation diagram of well 29739 (Gratiot). Model: Thermal Cooling.
Figure D21- Thermal maturation diagram of well 29739 (Gratiot). Model: Crustal Convection Downwelling.
Figure D22- Thermal maturation diagram of well 29739 (Gratiot). Model: Crustal Convection Upwelling.
Figure D23- Thermal maturation diagram of well 29739 (Gratiot). Model: Advection Crustal Convection Downwelling.
Figure D24- Thermal maturation diagram of well 29739 (Gratiot). Model: Advection Crustal Convection Upwelling.
Figure D25- Thermal maturation diagram of well 29739 (Gratiot). Model: Advection Present-Day.
Figure D26: Summary thermal maturation diagram of well 29739 (Gratiot). The top number in each group represents the number of incorrectly predicted observed data points that are shallower than the calculated maturation window. The middle number in each group corresponds to the number of correctly predicted observed data points. The bottom number in each group represents the number of incorrectly predicted observed data points that are deeper than the calculated maturation window.
Figure D27 - Thermal maturation diagram of well 10448 (Lenawee). Model: Present-Day.
Figure D28- Thermal maturation diagram of well 10448 (Lenawee). Model: Thermal Cooling.
Figure D29: Thermal maturation diagram of well 10448 (Lenawee). Model: Thermal Cooling. Fluid from 372-371.98 Ma and 320-319.995 Ma.
Figure D30- Thermal maturation diagram of well 10448 (Lenawee). Model: Thermal Cooling. Fluid from 320-319.98 Ma.
Figure D31- Summary thermal maturation diagram of well 10448 (Lenawee). The top number in each group represents the number of incorrectly predicted observed data points that are shallower than the calculated maturation window. The middle number in each group corresponds to the number of correctly predicted observed data points. The bottom number in each group represents the number of incorrectly predicted observed data points that are deeper than the calculated maturation window.
Figure D32- Thermal maturation diagram of well 43727 (Livingston). Model: Present-Day.
Figure D33- Thermal maturation diagram of well 43727 (Livingston). Model: Thermal Cooling.
Figure D34- Thermal maturation diagram of well 43727 (Livingston). Model: Crustal Convection Downwelling.
Figure D35- Thermal maturation diagram of well 43727 (Livingston). Model: Crustal Convection Upwelling.
Figure D36- Thermal maturation diagram of well 43727 (Livingston). Model: Advection Crustal Convection Downwelling.
Figure D37- Thermal maturation diagram of well 43727 (Livingston). Model: Advection Crustal Convection Upwelling.
Figure D38- Thermal maturation diagram of well 43727 (Livingston). Model: Advection Present-Day.
**Figure D39** - Summary thermal maturation diagram of well 43727 (Livingston). This diagram is unique in that the poor Tmax data are not included in this diagram. This is due to a large number of well constrained maturation estimates in this region. The top number in each group represents the number of incorrectly predicted observed data points that are shallower than the calculated maturation window. The middle number in each group corresponds to the number of correctly predicted observed data points. The bottom number in each group represents the number of incorrectly predicted observed data points that are deeper than the calculated maturation window.
Figure D40- Thermal maturation diagram of well 34376 (Missaukee). Model: Present-Day.
Figure D41 - Thermal maturation diagram of well 34376 (Missaukeee). Model: Thermal Cooling.
Figure D42- Thermal maturation diagram of well 34376 (Missaukee). Model: Crustal Convection Downwelling.
Figure D43- Thermal maturation diagram of well 34376 (Missaukee). Model: Crustal Convection Upwelling.
Figure D44- Thermal maturation diagram of well 34376 (Missaukee). Model: Advection Crustal Convection Downwelling.
Figure D45- Thermal maturation diagram of well 34376 (Missaukee). Model: Advection Crustal Convection Upwelling.
Figure D46- Thermal maturation diagram of well 34376 (Missaukee). Model: Advection Present-Day.
**Summary thermal maturation diagram of well 34376 (Missaukee).**

The top number in each group represents the number of incorrectly predicted observed data points that are shallower than the calculated maturation window. The middle number in each group corresponds to the number of correctly predicted observed data points. The bottom number in each group represents the number of incorrectly predicted observed data points that are deeper than the calculated maturation window.

Figure D47- Summary thermal maturation diagram of well 34376 (Missaukee). The top number in each group represents the number of incorrectly predicted observed data points that are shallower than the calculated maturation window. The middle number in each group corresponds to the number of correctly predicted observed data points. The bottom number in each group represents the number of incorrectly predicted observed data points that are deeper than the calculated maturation window.
Figure D48- Thermal maturation diagram of well 25099 (Ogemaw). Model: Present-Day.
Figure D49- Thermal maturation diagram of well 25099 (Ogemaw). Model: Thermal Cooling.
Figure D50- Thermal maturation diagram of well 25099 (Ogemaw). Model: Advection Upwelling.
Figure D51 - Summary thermal maturation diagram of well 25099 (Ogemaw). As was the case for the Livingston well, the poor Tmax data points are not included in this diagram. Again, this is due to the large number of well-constrained maturation estimates in this region. The top number in each group represents the number of incorrectly predicted observed data points that are shallower than the calculated maturation window. The middle number in each group corresponds to the number of correctly predicted observed data points. The bottom number in each group represents the number of incorrectly predicted observed data points that are deeper than the calculated maturation window.