PS Thermal Maturation Modeling of the Michigan Basin*

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Abstract

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. My goal is to test the hypothesis that thermal maturation distributions in the Michigan Basin can be explained by proximity from the Midcontinent Rift system, thermal cooling, free crustal convection, high temperature fluid advection, and overburden that has been eroded. In this work, this range of geodynamic models and two different paleo-surface temperature curves will be applied to multiple wells across the Michigan Basin. The wells are located at various distances from the Midcontinent Rift system and include a range of total sediment thickness. For each well a geohistory plot will be coupled with heat flow models to calculate the thermal and maturation histories of each sediment unit within the well. Backstripping will be performed in order to generate basement heat flow estimates. Time temperature index values will be calculated based on the thermal models. Comparison of calculated time temperature index values and available thermal maturation data from surrounding wells will be used to test the hypothesis. This project will reveal significant information on how thermal maturation of hydrocarbons across the Michigan Basin reached their present day values. These results will increase accuracy and precision in the pursuit of petroleum systems within the Michigan Basin.

Thermal Maturation Modeling of the Michigan Basin

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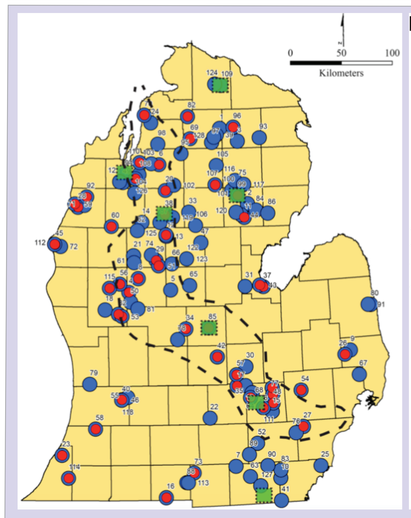
Abstract

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. My goal is to test the hypothesis that thermal maturation distributions in the Michigan Basin can be explained by proximity from the Midcontinent Rift system, thermal cooling, crustal convection, high temperature fluid advection, and eroded overburden. In this work, a range of geodynamic models and two different paleo-surface temperature curves will be applied to multiple wells across the Michigan Basin at various burial depths and distances from the Midcontinent Rift system. Seven wells distributed across the Michigan Basin have been selected for this study. For each well a geohistory plot will be coupled with heat flow models to calculate the thermal and maturation histories of each sediment unit within the well. Backstripping will be performed in order to generate basement heat flow estimates. Time temperature index values will be calculated based on the thermal models. Comparison of calculated time temperature index values and recorded thermal maturation data from surrounding wells will be used to test the hypothesis. This project will reveal significant information on how thermal maturation of hydrocarbons across the Michigan Basin reached their present day values. These results will have a direct impact on increasing accuracy and precision in the pursuit of petroleum systems within the Michigan Basin.



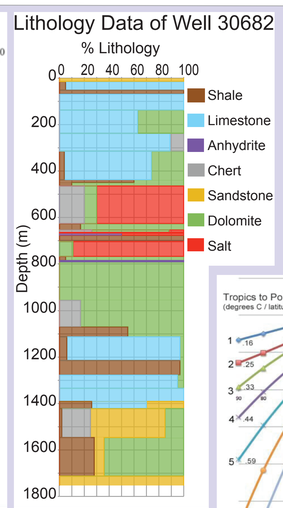
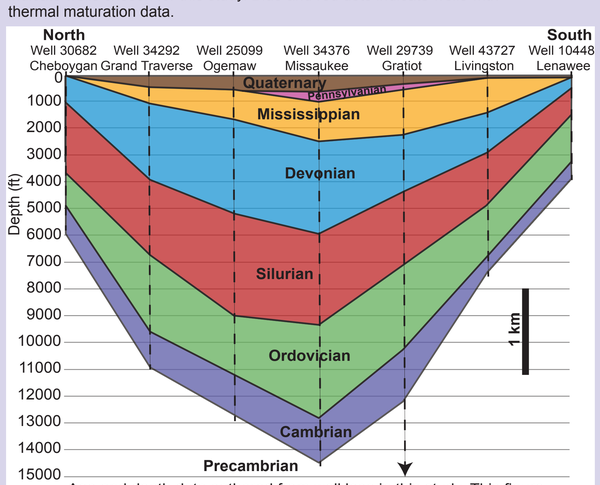
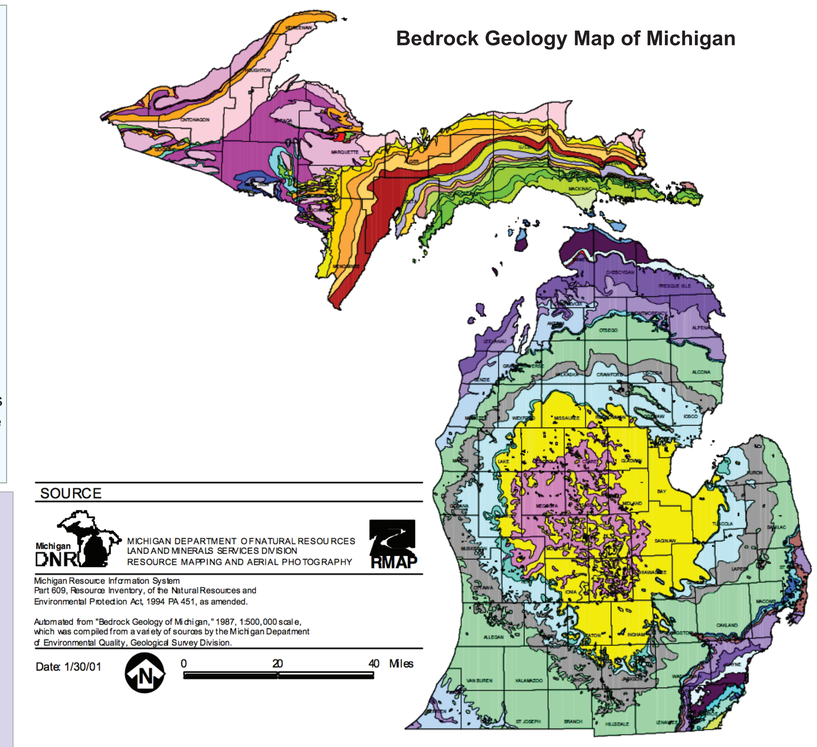


Figure 1 - Map of Michigan showing wells with thermal maturation data. Black dotted line represents the Midcontinent Rift. Green squares indicate wells chosen for this study. Blue and red dots indicate wells with thermal maturation data.



Age and depth data gathered from well logs in this study. This figure represents a North/South transect across the Michigan Basin.



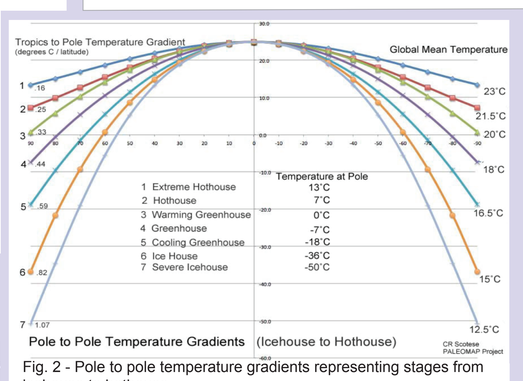
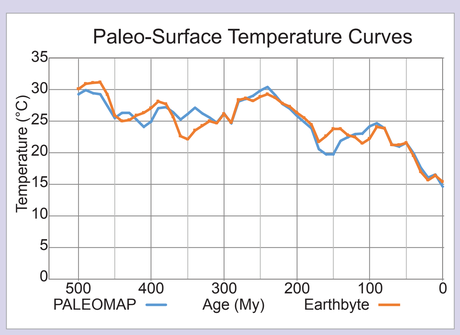
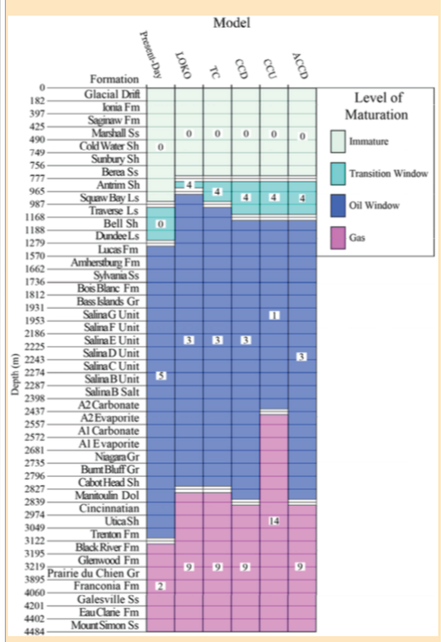


Fig. 2 - Pole to pole temperature gradients representing stages from icehouse to hothouse.

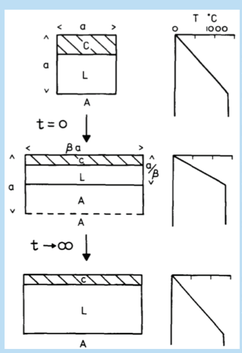


Paleo-Surface Temperatures that will be used in this study. Two different temperature curves were created that utilized different models for calculating the paleo-latitude of the Michigan Basin.

Results

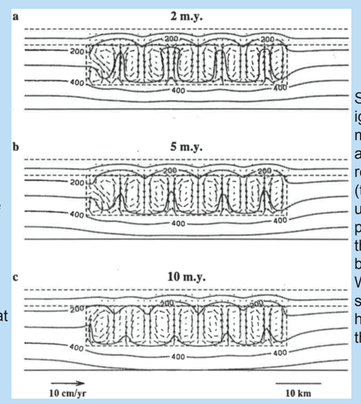


Wagenvelt's (2015) thermal maturation results for each model used in this study. The numbers in the boxes are the total number of observed Ro and Tmax values that fit the modeled thermal maturation. The models include: present-day conditions; low conductivity eroded overburden; thermal cooling, crustal convection, and advection from hot upward migrating hydrothermal fluids.

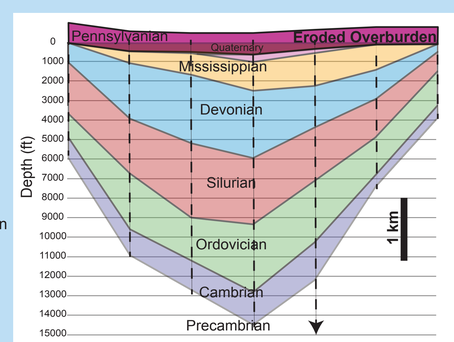


Mckenzie's thermal stretching model shows that at t=0 a piece of the crust is suddenly extended. This causes upwelling of the hot underlying asthenosphere. This increases the temperature in the lithosphere. Eventually the temperature in the lithosphere returns to equilibrium producing subsidence.

In this study, our thermal cooling model uses Mckenzie's stretching model to determine heat flow to the sediments in the Michigan Basin. Taken from Mckenzie, 1978.



Simulated free convection in an igneous body for 2, 5, and 10 million years. The igneous body and sedimentary layers are represented by dashed lines (taken from Nunn, 1994). We use Nunn's model to simulate periods of free crustal convection through the Midcontinent Rift beneath the Michigan Basin. We also use these models to simulate the flow of hot hydrothermal fluids up through the sediment column.



Eroded overburden is important in our models. 1000 meters of eroded overburden is necessary in order to produce porosity vs. depth curves that are observed in the modern day Michigan Basin.

Methods

Geohistory Plot

We will generate a geohistory plot in order to calculate the thermal and maturation histories of the sediments (Waples, 1994). A geohistory plot is 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 thickness; Wd = the paleo-water depth at which each sediment unit was deposited; S* = decompacted sediment thickness.

Backstripping

The six selected wells will be backstripped in order to generate heat flow estimates to the sediments. The equation for backstripping is:

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

Where: T.S = tectonic subsidence or uplift; Φ = the basement response function; ρm = the mean density of the mantle (3.18 g/cm3); ρs = the mean bulk density of the sediments; ρw = the density of sea water (1.03 g/cm3); ΔSL = the change in eustatic sea level; Wd and S* (see above, same as geohistory). Both sediment density and compaction are lithology-dependent. Additional input of ages, including ages of unconformities, are required to interpret the backstripping result.

We assume thermal equilibrium within the sediment column. Thus, temperatures of the sediment units are calculated by the following equation:

$$T_n = T_0 + \Sigma_{i=1}^{n} \frac{q}{K_i} \Delta Z_i$$

Where: Tn = temperature at the base of the nth interval (rock unit from the top); T0 = temperature at the surface; q = heat flow (W/m2); ΔZi = thickness of the ith interval from the top, Ki = average thermal conductivity of the ith interval. In order to determine surface temperature (T0), information on paleoclimate, paleogeography, and time must be gathered (see paleo-surface temperature section). Thermal conductivity (Ki) of a sediment unit is lithology dependent and porosity dependent assuming that porosity is fully saturated. Therefore, it depends on the compaction history of that unit. (see conductivities section) (Wagenvelt, 2015).

Paleo-Surface Temperature

Phanerozoic surface temperatures for the Michigan Basin will be calculated 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. (See fig. 2) The paleo-latitude of the Michigan Basin will be determined by utilizing PALEOMAP and EarthByte Phanerozoic models on the GPlates Portal Paleomap Maker website. The temperature is very much dependent on paleo-latitude.

Temperature change through time at the equator will shift the previously discussed tropic to pole temperature gradients. This is taken into account by utilizing Royer et al., (2004) who produced a tropical temperature curve with ages modified by Scotese, (2015). The change in temperature at the equator is added to or subtracted from the tropic to pole temperature gradients. Finally, paleo-surface temperatures will be calculated for the Michigan Basin through time.

Conductivities

Lithology and porosity are used to determine conductivities. Lithology dependent conductivities in this study have been calculated in order to generate a geothermal gradient between 19 and 22 °C/Km (Wagenvelt, 2015; Pollack & Watts, 1976; Vugrinovich, 1988).

Porosities obtained from decompacting sediments from the geohistory analysis will be input into Beck's (1976) two-phase conductivity formula. This formula will be used to calculate total unit thermal conductivities. In the formula, Kd is the dispersive conductivity of the mixed medium. The formula to calculate Kd is:

$$K_d = K_s\left\{\frac{(2r+1) - 2\varphi(r-1)}{(2r+1) + \varphi(r-1)}\right\}$$

Where: r = Ks/Kf, K is thermal conductivity; φ = porosity; Ks = the continuous phase; Kf = conductivity of dispersed phase; and Kd = 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 50 % or less is reached in the sediment unit. At which point, the solid will be assumed to be the continuous phase.

Time Temperature Index

With all of the above data we can calculate the temperature of the sediment units through time. Lopatin's (1971) method will be used to calculate the thermal maturation (TTI) for each stratigraphic unit. Constants verified by Waples (1980) will be used.

$$TTI = \Sigma_{n_{min}}^{n_{max}} (\Delta t_n) 2^{\left(\frac{T_n - 105}{10}\right)}$$

That is, for every 10°C increase in temperature the reaction rate doubles (r = 2). The variable (n) represents the time steps through which each unit is buried. Waples (1980) established a relation 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 gathered by Wagenvelt (2015) including Rock-Eval and Vitrinite Reflectance data that was released from proprietary hold, as well as, Rock-Eval data produced by Wagenvelt (2015).

Level of Maturation	T_{max} (°C)	R_o (%)	TTI
Immature	< 435	< 0.60	< 10
Transition Window	435 - 444	0.6 - 0.64	10 - 14
Oil Window	445 - 470	0.65 - 1.35	15 - 160
Gas	> 470	> 1.35	> 160

To Do List

1. Gather lithology, age, and water depth data for the rest of the wells.
2. Perform backstripping and induce the different thermal models on each well.
3. Create a geohistory plot for each well.
4. Compare the thermal maturation data to surrounding wells with Rock-Eval and Vitirinite Reflectance data.
5. Produce a comprehensive report for publication in AAPG.

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