Brunson Abstract

Past researchers have suggested that elevated heat flow once existed in the Williston Basin during the Eocene Epoch or younger time frame, based on petroleum maturity indices data. Further, they have argued that those attempting to computationally model the region have incorrectly assumed constant heat flow through time. The present work attempts to address the different positions taken by updating geophysical modeling evidence concerning heat flow in the Williston Basin in which paleogeothermal conditions are variable over geologic time. After conducting the investigation, present research demonstrates that elevated heat flow may have existed in the Williston Basin in the geologic past but did not necessarily have to occur during or after the time period suggested. Furthermore, variable radioactivity in the crystalline basement rock demonstrated by the present models can explain the enhanced thermal maturity described by past researchers. Only more detailed study will eventually lead the scientific community to a more precise explanation of the cause and time constraints of such paleogeothermal conditions.

GEOPHYSICAL ANALYSIS OF THE PALEOGEOTHERMAL GRADIENT AND HEAT FLOW IN THE WILLISTON BASIN, ND

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Abstract

Past researchers have suggested that elevated heat flow once existed in the Williston Basin during the Eocene Epoch or younger time frame, based on petroleum maturity indices data. Further, they have argued that those attempting to computationally model the region have incorrectly assumed constant heat flow through time. The present work attempts to address the different positions taken by updating geophysical modeling evidence concerning heat flow in the Williston Basin in which paleogeothermal conditions are variable over geologic time. After conducting the investigation, present research demonstrates that elevated heat flow may have existed in the Williston Basin in the geologic past but did not necessarily have to occur during or after the time period suggested. Furthermore, variable radioactivity in the crystalline basement rock demonstrated by the present models can explain the enhanced thermal maturity described by past researchers. Only more detailed study will eventually lead the scientific community to a more precise explanation of the cause and time constraints of such paleogeothermal conditions.

Statement of Hypothesis

It has been argued that previously attempted 1-D temperature models based on present day heat flow values do not explain the thermal maturity conditions experienced by the Williston Basin because those models have assumed constant heat flow through time. The argument made also contends that a thermal event must have taken place in the Eocene Epoch or younger time period. The present study will perform those suggested updates to computational models and combine those data with thermostratigraphy data. We hypothesize that our thermostratigraphy analysis and updated models and data will indicate that elevated heat flow could have existed in the Williston Basin at some time in the geologic past. However, we further hypothesize that the time frame suggested is incorrect and anticipate that our models will show the time frame necessary for a successful model could be much older than the Eocene. If the models are successful, they will indicate two things: 1) variable heat flow resulting from a thermal pulse event and allowed to equilibrate over time could have resulted in present day heat flow, and 2) the variable heat flow could be modeled to begin before the Eocene Epoch, such as the Cretaceous, and still result in present day heat flow.

Background and Introduction

Vitrinite reflectance (R_o) and ROCK-EVAL (T_{max}) hydrocarbon (HC) maturity indices (MI), developed in petroleum geochemistry studies, can be used to estimate the maximum temperatures to which a rock has been buried, referred to as a hydrocarbon's "rank." Prior scientific study of the Williston Basin (Scattolini, 1977; Majorowicz et al., 1986, 1988; Price et al., 1984; Price 1996) all inferred or directly measured high paleogeothermal conditions. The Scattolini and Majorowicz work used thermal conductivity estimates of 4 cal cm^{-1} deg^{-1} sec^{-1}, or about 2.4 W m^{-1} K^{-1}, for the Pierre Formation Shale (Combs and Simmons, 1973). However, the value that should have been used was closer to 1.0 to 1.2 W m^{-1} K^{-1} (Gosnold, 1990). Price et al. (1984) produced R_o profiles versus depth and Total Organic Carbon (TOC) data suggesting high to extreme temperatures once existed in the Williston Basin. In addition to the argument that higher temperatures once existed in the basin, it has also been suggested by Price, based upon the same lines evidence, that the higher temperatures must have occurred in the Eocene or younger time frame. It is also acknowledged that the present-day burial temperatures are lower than those that are postulated to have once existed. As a result of these observations, some scientists have concluded that the previously existing conditions of the Williston Basin, i.e. the elevated temperature and heat flow conditions, are responsible for the volume of oil and gas resources existing, when compared to reasonably similar basins with hydrocarbon source systems that have not experienced those same conditions.

However, as evidenced by the work available to date by those attempting to computationally model the Williston Basin, assumptions have been made that are not in congruence with the findings of other researchers. Specifically, those modelers have assumed that heat flow in the Williston Basin was constant over other geologic time (Gosnold and Huang, 1987; Gosnold, 1990; Burrus et al., 1995, 1996). The findings of Burrus et al. (1995; 1996), particularly, led to the development of two potential heat flow conditions experienced by the Williston Basin in the past, both of which were much lower than the expectations of other investigators. As such, objections have been raised about the work of the geophysicists attempting to create these previously simulated models. Concession was made for the fact that, to date, the computational processing capability could not match the needed complexity for a model of the system of interest.

Study Location

The Williston Basin is an intracratonic basin that extends into parts of southwestern Saskatchewan, southeastern Manitoba, and eastern Montana. Structurally, the Williston Basin is considered the simplest sedimentary basin the world, with little to no major and only minor faulting and mostly flat-lying sediments. Present day conditions in the North Dakota portion show evidence for sedimentation occurring in the region from Cambrian to the Early Tertiary. Evidence also shows, in the form of unconformities, the occurrence of nondeposition and/or erosion throughout the region. As such, it can be problematic to determine exactly what extent of sedimentation took place above the Cretaceous Pierre Fm. Shale. Generally, the Williston Basin contains 1 to 2 km of clastic rocks Cenozoic to Mesozoic in age overlying approximately 2 to 3 km of carbonate rocks Paleozoic in age. Sloss (1963) developed a set of sequence subdivisions that are still mostly used to this day when describing the sequence stratigraphy of the area.

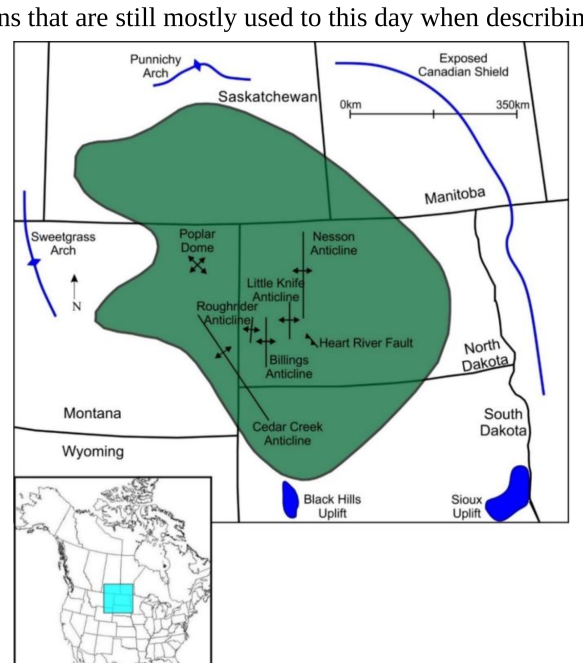

Fig. 1 The Williston Basin (Permission of Faye Ricker, 2017; modified from Gerhard et al., 1982)

Methodology

Two methodologies were employed in this study. First, measurement of temperature at depth via thermostratigraphy data generation was conducted. Next, heat flow simulation models under steady-state conditions were carried out.

Thermostratigraphy

Scientists have previously used thermostratigraphy in order to model geothermal conditions present in sedimentary basins. If the expression for Fourier's Law of Heat Conduction is rewritten as $dT/dz = q/\lambda$ and solved for temperature, T, this simple rearrangement leads to the basic expression of thermostratigraphy

The temperature at any depth, T(z), can be calculated by:

$$T(z) = T_o + \sum_{i=1}^{n} \frac{q z_i}{\lambda_i}$$

Where:
T_o is surface temperature
q is surface heat flow
z_i and λ_i are the thicknesses and thermal conductivities, respectively, of the *ith* stratum

9 NDGS wells (#25, #527, #607, #2010, #2615, #6464, #6616, #7020, and #7783) were chosen for the present study, as these are the same wells used in previous study of the topics central to this issue (Price, 1996). For this study, the q-values were obtained from the recent results of Mark McDonald for the North Dakota Geological Survey (2015).

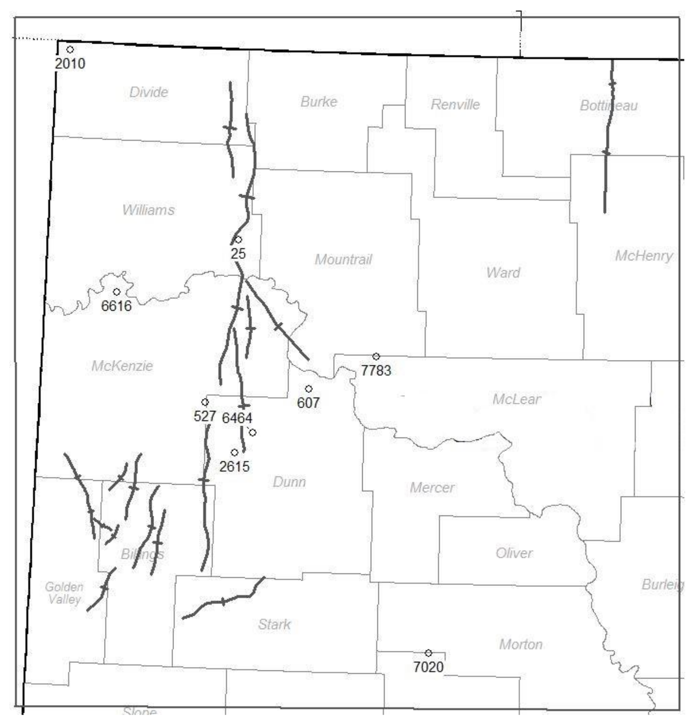

Fig. 2 Map of the wells used for thermostratigraphy measurements (generated in PETRA).

Heat Flow Simulation Models

Despite the fact that a number of other software solutions exist to accomplish steady-state heat flow modeling, Dr. William Gosnold's Finite Difference Heat Flow Simulation (v. 2.5.4), or "ARC," software offers the advantages of being developed by the researchers performing the present study and is, thus, highly modifiable for the user's needs. ARC was developed in order to perform finite difference determination of steady-state heat flow by calculating temperature and heat generation for a given system subdivided into cells and heat transfer to and from surrounding cells (Crowell, J, 2015). A system is modeled using ASCII format input codes and desired values of system parameters in a Microsoft Excel file: thermal conductivity, radiogenic heat production, basal heat flow, heat capacity of rock and fluid density, advection constraints, starting temperatures, fluid velocity, and direction and cell size and model dimensions. Two models were run for this study consisting of 35 my and 65 my durations to test the results of Price (2006).

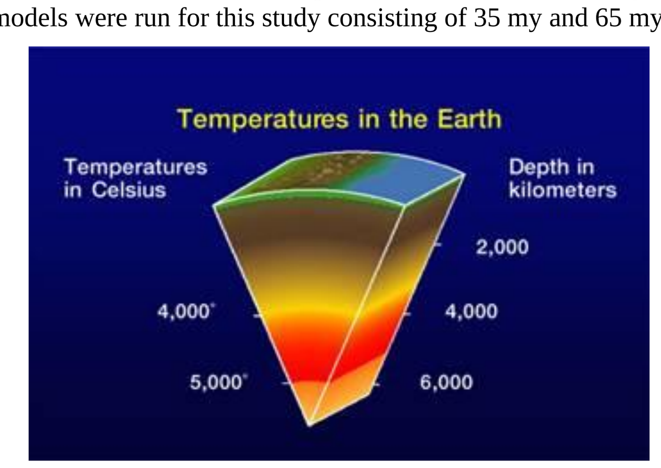

Fig. 3 Temperature regime in the Earth (Geothermal Energy Association, 2014).

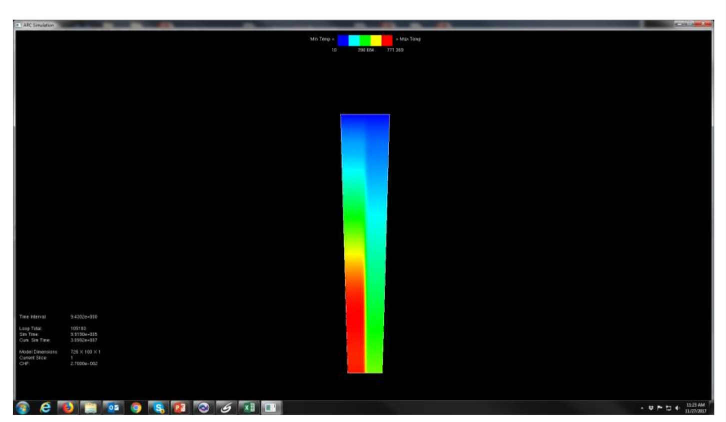

Fig. 4 Demonstration of the ARC simulation software performing a model of a transect of the Williston Basin developed for this study, which includes the thermal pulse event of a magma lens intrusion resulting from a rifting event (similar to conditions that might be seen in the Rio Grande Rift).

Thermostratigraphy Results

The Williston Basin, generally, has a bimodal composition, with a 1 to 2 km thick layer of clastic rocks Cenozoic and Mesozoic in age overlying 2 to 3 km of carbonates Paleozoic in age (Gosnold, 2012). That feature is observable in the present datasets when, in each dataset at approximately 2km in depth, the gradient shown changes from a steep gradient to a shallow gradient.

If heat flow in the past were constant, all curves generated by thermostratigraphy would be laying on top of one another. Clearly, these curves do not do that. This would indicate that the heat flow coming out of the basement of the crust must be different across the basin or that the heat flow within the basin itself must be variable. While this dataset does not conclusively tell us that heat flow throughout the basin has been variable in the past, the data does mirror the findings of other researchers, such as Scattolini, Majorowicz, and Price, that concluded elevated heat flow conditions from other lines of evidence.

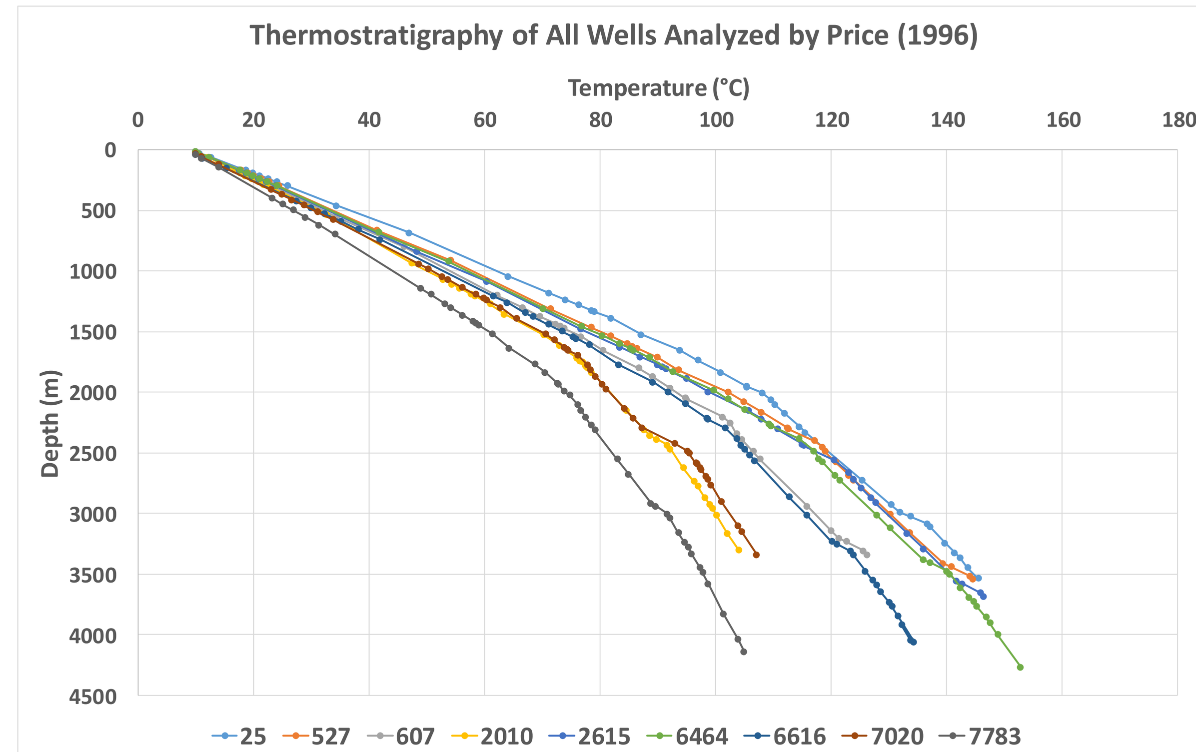

Fig. 5 Combined thermostratigraphy results for all wells analyzed by Price (2006)

Heat Flow Simulation Results

The thermal event demonstrated here would have caused significant uplift accompanied by faulting and erosion, and it would still exhibit high heat flow. The Rio Grande, which did experience a thermal event beginning in the late Eocene, presents all of those characteristics today in addition to standing an average of 2 km above sea level. In contrast, the Williston Basin, the surface of which lies within 500 m of sea level, was rapidly subsiding from the Early Cretaceous through the Tertiary times and accumulated approximately 700 m of sediments from the Eocene through the Tertiary. There was no uplift, faulting, or erosion, and there is no remnant thermal signal that would exist from whole crustal heating. As such, other geologic processes may account for the variable heat flow throughout the Basin. After updating steady state heat flow conduction computational models to account for the variability of the thermal regime and heat flow conditions previously unaccounted for, it is clear that the thermal pulse event could have occurred before the Eocene Epoch and still resulted in present day thermal conditions within the basin.

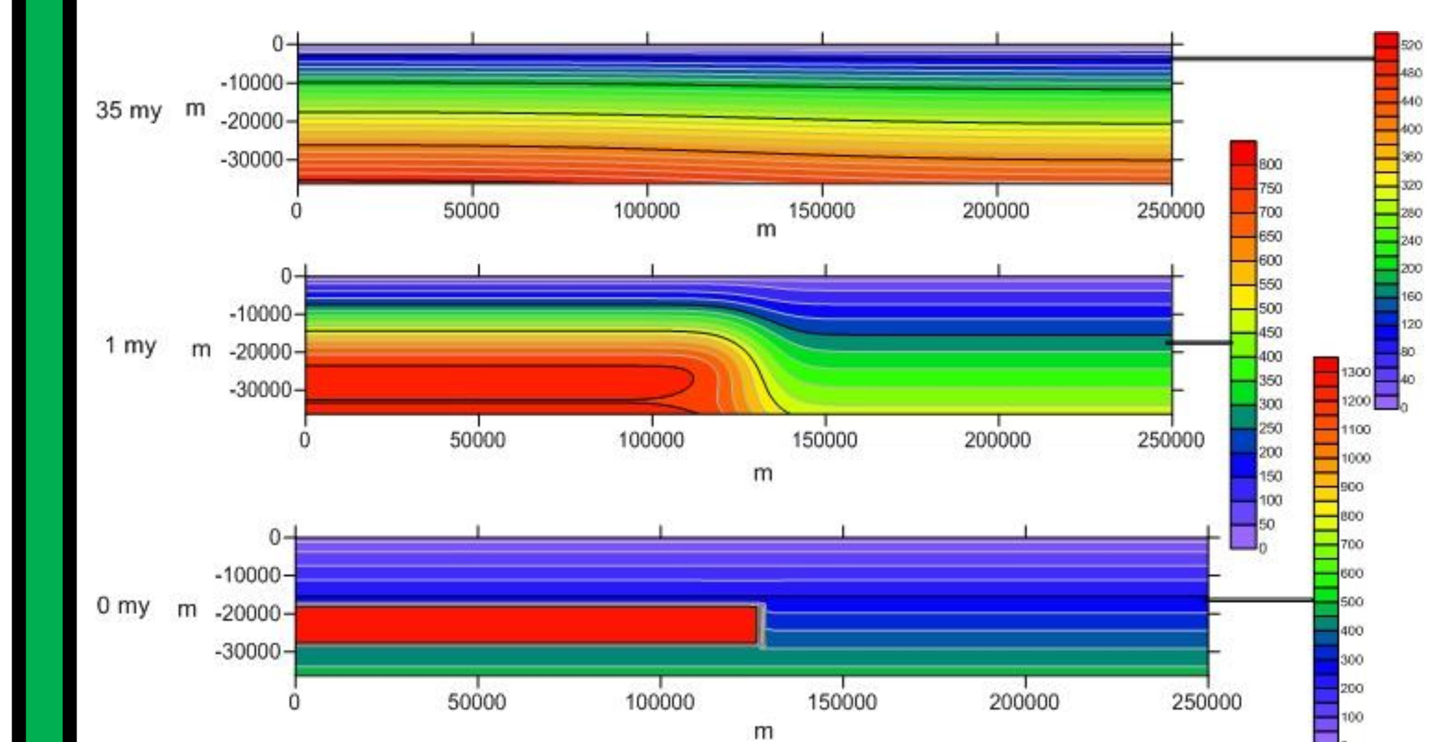

Fig. 6 Results of heat flow simulation model run for 35 my duration. A 3650 km deep x 400 km wide section representing a slice through the Williston Basin was modeled. Vertical exaggeration was minimized to help display the results.

Heat Flow Simulation Results

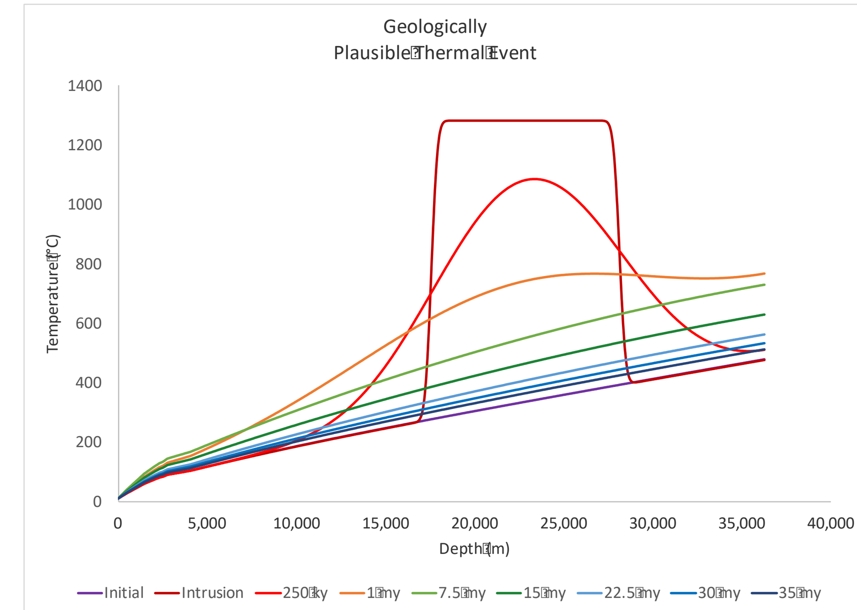

Fig. 7 Plot of simulated thermal event evolution taking place in heat flow models.

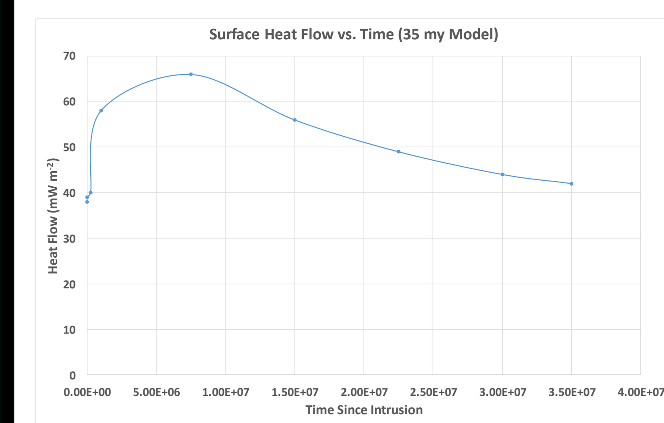

Fig. 8 Plot of surface heat flow change over geologic time in the 35 my heat flow model.

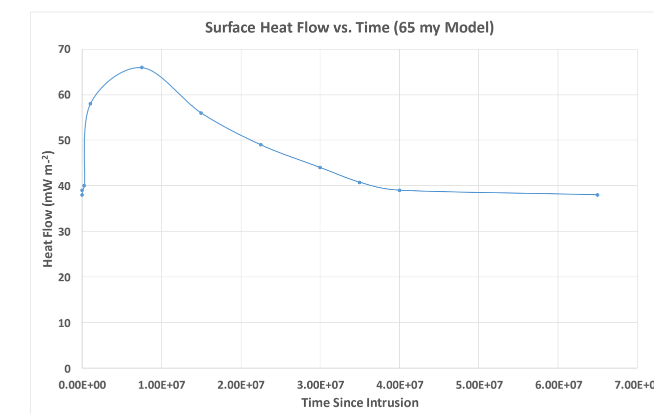

Fig. 9 Plot of surface heat flow change over geologic time in the 65 my heat flow model.

Conclusions

Thermostratigraphy and updated model data indicates that elevated heat flow conditions did exist in the Williston Basin at some time in the geologic past. The data generated also indicates that the time frame necessary for an event that could have elevated the thermal regime of the Williston Basin and subsequently dissipated to allow for basin cooling could be much older than the Eocene Epoch. Only more dedicated and detailed study of numerous lines of geologic and geophysical evidence will allow for a rigorous explanation of the processes involved in these elevated heat flow conditions once existing throughout the Basin. As the Williston Basin is one of the simpler sedimentary basin systems found anywhere in the world, the ramifications of having extensive temperature, heat flow, kinetics, and thermal maturation datasets on such an area, and the resulting insights that might be made from such study, would surely be of value to the global research community and a major step forward for North Dakota

References

Blodgett, L. (2014), Basics. GEA, Washington, DC, http://geo-energy.org/Basics.aspx.
Burrus, J., K. Osadetz, S. Wolf, B. Doligez, and K. Visser (1995), Resolution of Williston Basin Oil System Paradoxes Through Basin Modelling, pp. 235–251.
Burrus, J., K. Osadetz, S. Wolf, B. Doligez, K. Visser, and D. Dearborn (1996), A Two-Dimensional Regional Basin Model of Williston Basin Hydrocarbon Systems, Am Assoc Pet Geol Bull, 80(2), 265–290, doi:10.1306/64ED87AA-1724-11D7-8645000102C1865D.
Cengel, Y., and A. Ghajar (2015), Heat and Mass Transfer: Fundamentals and Applications, 5 ed., McGraw-Hill.
Clauser, C. (2009), Heat Transport Processes in the Earth's Crust, Surv Geophys, 30(3), 163–191, doi:10.1007/s10712-009-9058-2.
Crowell, A. M. (2011), Identifying Potential Geothermal Resources From Co-Produced Fluids Using Existing Data From Drilling Logs: Williston Basin, North Dakota, 1–51 pp. Grand Forks, ND, April.
Crowell, J. (2015), Improving the Availability of Thermal Conductivity Data and Modeling How Inaccurate Thermal Conductivity Data Affect Geothermal Power Production Models, 1–80 pp. University of North Dakota, Grand Forks, ND.
Gosnold, W. D., Jr (1984), Geothermal Resources in the Williston Basin: North Dakota, vol. 8, pp. 431–436, Davis, CA.
Gosnold, W. D., Jr, and Y. C. Huang (1987), Factors Determining the Thermal History of a Continental Basin, pp. 17–21, Fifth International Williston Basin Symposium, Saskatchewan.
Gosnold, W. D. (1990), Heat Flow in the Great Plains of the United States, J Geophys Res, 95(B1), 353, doi:10.1029/jb095ib01p00353.
Gosnold, W. D., Jr (1991), Subsurface Temperatures in the Northern Great Plains, in Neotectonics of North America, edited by D. B. Slemmons, pp. 467–472, Geological Society of America, Denver, CO.
Gosnold, W. D., Jr (1999), Stratabound Geothermal Resources in North Dakota and South Dakota, Nat Resour Res, 8(3), 177–192, doi:10.1023/A:1021689813375.
Gosnold, W. D., J. A. Majorowicz, R. Klenner, and S. A. Hauck (2010), Implications of Post-Glacial Warming for Northern Hemisphere Heat Flow, vol. 35.
Gosnold, W. D., M. R. McDonald, R. Klenner, and D. Merriam (2012), Thermostratigraphy of the Williston Basin, vol. 36, pp. 663–670.
Lachenbruch, A. H. (1970), Crustal Temperature and Heat Production: Implications of the Linear Heat-Flow Relation, J Geophys Res, 75(17), 3291–3300, doi:10.1029/JB075i017p03291.
Majorowicz, J. A., F. W. Jones, and A. M. Jessop (1986), Geothermics of the Williston Basin in Canada in Relation to Hydrodynamics and Hydrocarbon Occurrences, Geophysics, 51(3), 767–779, doi:10.1190/1.1442129.
Majorowicz, J. A., F. W. Jones, and K. G. Osadetz (1988), Heat Flow Environment of the Electrical Conductivity Anomalies in the Williston Basin, and Occurrence of Hydrocarbons, Bull Can Pet Geol, 36(1), 86–90.
McDonald, M. R. (2015), Preliminary Results of Temperature Logging in the Williston Basin to Determine Heat Flow, edited by E. C. Murphy and L. D. Helms, North Dakota Geological Survey, Grand Forks, ND.
Murphy, E. C., S. H. Nordeng, B. J. Juenker, and J. W. Hoganson (2009), North Dakota Stratigraphic Column, edited by E. C. Murphy and L. D. Helms, North Dakota Geological Survey, Grand Forks, ND
Price, L. C. (1996), Origins and Characteristics of the Basin-Centered Continuous-Reservoir Unconventional Oil-Resource Base of the Bakken Source System, Williston Basin,, 1–281.
Price, L. C., T. Ging, T. Daws, A. Love, M. Pawlewicz, and D. Anders (2011), Organic Metamorphism in the Mississippian-Devonian Bakken Shale North Dakota Portion of the Williston Basin, in The Bakken—Three Forks Petroleum System in the Williston Basin, edited by J. W. Robinson, J. A. LeFever, and S. B. Gaswirth, pp. 438–489, The Rocky Mountain Association of Geologists.
Ricker, F. N. (2015), Geothermal Regime of the Williston Basin in North Dakota, The University of North Dakota, Grand Forks, ND.
Scatollini, R. (1978), Heat-Flow and Heat-Production Studies in North Dakota, 1–264 pp. The University of North Dakota, Grand Forks, ND.
Sloss L.L. (1963), Sequences in the Cratonic Interior of North America, Geological Society of America Bulletin, vol. 74, p. 93 - 114.