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Paleoclimate Data Constraints on Basin Thermal History and Petroleum Generation Modeling: Piceance Basin, Colorado

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ABSTRACT

Basin thermal history is critical to reconstructing subsidence/uplift history and modeling petroleum generation in sedimentary basins. For a hydrocarbon rich province, modeling the hydrocarbon generation process involves solving heat flow equations, given initial and boundary conditions, across geological time. This could be very challenging given the complex evolution history of many basins, especially basins that have undergone substantial subaerial elevation change over time.

In most basin modeling approaches the upper basin thermal boundary condition is assumed to be the sediment-water-interface temperature (Hantschel & Kauerauf, 2009). To estimate this time-varying sediment-water-interface temperature, an average paleo-air-surface temperature (T_S) is first estimated from paleo-latitude of the study area (Wygrala, 1989). Then, T_S is corrected to the actual sediment-water-interface temperature (T_{SWI}) accounting for the paleo-water depth. This T_{SWI} is used as the time-varying sediment-water-interface temperature and serves as the upper thermal boundary condition for the basin models. Similarly, modern sediment-water-interface temperature is obtained by the modern annual mean ground surface temperature and corrected by modern water depth following the equations from Beardsmore and Cull (2001) and Hantschel and Kauerauf (2009). These methods are suitable for marine basins with known paleo-water depths, but provide poor estimates of surface temperatures in terrestrial basins. We propose a novel approach for better constraining the basin upper thermal boundary condition, the time-varying sediment-surface-temperature (SST), by using the extensive data and studies conducted by the terrestrial paleoclimate community.

Our study area, the Piceance Basin transited from shallow marine waters during the Upper Cretaceous (Johnson and Nuccio, 1986) to discrete intermontane sedimentary basin during the Laramide Orogeny (Chase et al., 1998; DeCelles and Graham, 2015), and, by the late Eocene, was uplifted several kilometers (Chamberlain et al., 2012). The basin thermal history and the sediment-surface-temperature would have been impacted by both the tectonically driven elevation changes and global cooling over the Cenozoic (Zachos et al., 2001; Beerling and Royer, 2011). As such, we reconstruct the sediment-surface-temperature using paleobotanical data of Mean Annual Temperature in the study region. Two primary approaches have been used to estimate paleotemperatures using macroflora: Leaf Margin Analysis (LMA) (Wilf, 1997) and Climate-Leaf Analysis Multivariate Program (CLAMP) (Wolfe, 1995). We compiled all available temperature estimates from Colorado, Utah, Nevada and Wyoming. The resulting temperature compilation suggests temperatures of 17 to 25 °C during the Eocene, which drop through the Cenozoic to modern temperatures of 5 to 12 °C.

Two one-dimensional (1-D) basin models were constructed for the Exxon Love Ranch #1 well using two different upper thermal boundary condition scenarios and additional geological and geochemistry input data (Yurewicz et al., 2003, 2008; Zhang et al., 2008). One model scenario uses the upper thermal boundary condition (SST) estimated from paleoclimate macro floral assemblage data. In the other scenario, SST is estimated from standard method where paleo-latitude information were considered and corrected by paleobathymetric changes without considering the impact of elevation change (Wygrala, 1989). The basin model predictions indicate that source rock maturation is very sensitive to the upper thermal boundary condition for terrestrial basins with variable elevation histories. The models show substantial differences in source rock maturation and kerogen transformation ratio processes. Cumulatively, there is a 0.21 %Ro vitrinite reflectance decrease, 10.5 % source rock transformation ratio decrease and 16 % hydrocarbon mass generation decrease using the paleoclimate macro floral assemblage temperature data compared to the standard case.

These differences demonstrate the importance of constraining thermal boundary conditions for terrestrial basins. For many Cenozoic terrestrial basins, paleoclimate data can provide reliable paleo-temperature reconstructions and could be used as constraints for basin thermal history modeling. Although the paleo-temperature reconstruction compiled for this study is region specific, the approach presented here is generally applicable for other terrestrial basin settings, particularly basins which have undergone substantial subaerial elevation change over time. Presumably, the effects demonstrated here would be much more pronounced in basins where surface elevation changes are even more substantial than the North American cordillera, such as similar aged basins found on the Tibetan Plateau, where elevation changed from sea level to ~5-6 km from the Cretaceous to the late Cenozoic (Ritts et al., 2008; Wang et al., 2008)