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Modeling the Maturation History of the Stacked Petroleum Systems of the Williston Basin, USA

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Abstract

A three-dimensional petroleum systems model was built to support the 2020 and 2021 U.S. Geological Survey assessments of undiscovered oil and gas resources in the Williston Basin of North Dakota, Montana, and South Dakota. Numerous Paleozoic source rocks have been proven or postulated in the basin, of which five were the focus of maturation and migration modeling: the Ordovician Icebox Shale, the kukersite beds of the Ordovician Red River Formation, the shales of the Devonian-Mississippian Bakken Formation, the Mississippian Madison Group, and the Pennsylvanian Tyler Formation. Results from the calibration of the 3D model to present-day temperature data indicate a north-south trend of high heat flow in western North Dakota, along with a region of high heat flow in eastern Montana. These high heat flow trends strongly control the maturity of all studied source intervals. A Bakken-specific hydrocarbon generation kinetic model was developed to match the calibrated time-temperature history of the basin to spatial trends in Hydrogen Index from programmed pyrolysis data. Generation of hydrocarbons occurred in the Cretaceous through Paleogene due to increased burial. Subsequent uplift and erosion in the Neogene cooled the basin, ending hydrocarbon generation for all source rocks. The cumulative volume of hydrocarbons generated by each of the source rocks was calculated and used to compare their relative robustness. The shales of the Bakken Formation are estimated to have generated approximately 460 billion barrels of oil equivalent (BBOE), while the Red River Formation generated approximately 130 BBOE, the Tyler Formation, 94 BBOE, the Madison Group, 44 BBOE, and the Icebox Formation, 28 BBOE. Gross migration trends were analyzed with respect to historical oil and gas production in the basin and generally indicate segregation of petroleum systems throughout the stratigraphic column. However, most modeled scenarios indicate significant loss of Bakken oil to the overlying Madison Group, suggesting that mixing of Madison and Bakken oils may be more prevalent than has recently been recognized in the U.S. portion of the Williston Basin, and is particularly likely in fractured regions of the basin. In addition to petroleum systems applications, this modeling study may also provide useful inputs for other future energy-related resource studies. For example, fully calibrated heat flow and temperature grids for all major stratigraphic surfaces from the Cretaceous Inyan Kara Formation and deeper may provide useful constraints for geothermal exploration and regional carbon sequestration studies.