

Petroleum Geochemistry and Mudstone Diagenesis of the Woodford Shale, Anadarko Basin, USA - An Integrated Approach

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ABSTRACT

We undertook an integrated organic geochemical and petrologic study of the Upper Devonian- Lower Mississippian Woodford Shale on cores recovered from thermally mature and liquids-rich mudstone reservoirs in the Anadarko basin of south-central Oklahoma, USA. The purpose of the work was to identify the critical mechanisms that control oil and natural gas generation, expulsion, migration, and retention in an active petroleum source rock that is also a producing unconventional reservoir.

We identified five microfacies in the Woodford Shale; 1) siliceous mudstone; 2) silicified mudstone; 3) chert and argillaceous chert; 4) argillaceous, siliceous dolostone; and 5) phosphatic mudstone. All of these microfacies exceed the minimum TOC and S₂ threshold values for effective petroleum source rocks. The original hydrogen index (iH) values, calculated from visual kerogen data, indicate oil-prone organic matter in the rocks. Thermal maturity approximates the boundary between low-volatile and high-volatile liquid generation. Sixty to 75% of the petroleum generation process is complete with a 61 to 83% expulsion efficiency. Plots of oil crossover effect and oil saturation indices denote

Woodford Shale intervals that retained adequate volumes of hydrocarbons for potential economic production.

Reservoir quality in the productive intervals is controlled by the diagenetic fabric of the mudstones. Phosphate mineralization, pyrite framboids, and calcite, dolomite, magnesite, and barite mineralization/dissolution all occurred concomitant with deposition and shallow burial diagenesis. Mechanical compaction was the most important diagenetic process down to a burial depth of about 1 km (3,280 ft.) during which approximately 70% of the original pore water was probably expelled from the sediments. The transformation of Opal-A to Opal-CT to quartz occurred from just after deposition to burial temperatures of approximately $\pm 80^{\circ}\text{C}$. Silica dissolution and reprecipitation accompanying the phase changes associated with the opal to quartz transition led to early quartz cementation and hardening of the mudstone prior to bitumen expulsion into the mineral matrix pore system. Smectite dehydration was probably iterative between burial temperatures of about $\pm 80^{\circ}\text{C}$ to 125°C . The low salinity of aqueous inclusions in epigenetic quartz cement support our interpretation of smectite dehydration occurring in the Woodford Shale. The measured homogenization temperatures of aqueous and petroleum inclusions indicate that quartz cementation continued beyond opal to quartz dissolution and reprecipitation well into the oil generation window, and was concomitant with bitumen and oil expulsion and migration. The estimated API gravity of light oil inclusions in quartz cement ($46 - 48^{\circ}$) trapped at burial temperatures of $80 - 105^{\circ}\text{C}$ indicates petroleum migration from deeper Woodford Shale prior to the principal phase of oil generation in the Woodford at the Williams well location. Migration of hydrocarbons generated deeper in the basin was controlled by the relative porosity and permeability of the mineral matrix pore system prior to significant loss of mineral matrix porosity with increasing burial. The pre-oil bitumen network, a precursor to oil, was an early generation product of amorphous kerogen breakdown in the rocks. Significant oil and gas generation from the pre-oil bitumen

started approximately 300 m.y. before present at burial temperatures of 100 - 110°C and continued through maximum thermal stress equivalent to a mean VR, of 0.9 % about 58 m.y. before present. Solid bitumen reflectance and carbon isotope compositions of methane through propane support our interpretation of maximum thermal stress in the reservoir. Maximum burial temperature, based on aqueous inclusion data and the 2, 4DMP/2, 3DMP ratio of extracted bitumen was approximately 124-134°C. Framboidal pyrite altered to massive euhedral pyrite with increasing thermal maturity in the rocks. Oil generation in the Woodford Shale continued during uplift and is ongoing today, but the main phase of petroleum generation occurred during maximum burial. Pervasive post-oil solid bitumen in the Woodford Shale is the residue of primary hydrocarbon migration in the reservoir. An effective organic pore system developed within the post-oil solid bitumen network and serves as the principal storage for the hydrocarbons produced from the Williams well.