GEOCHEMISTRY OF INTER- AND INTRA-SALT SHALES AND IMPLICATIONS FOR HYPERSALINE LACUSTRINE SHALE OIL PRODUCTION

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Shale oils currently produced from the Neogene hypersaline lacustrine shales in the Qianjiang Formation, Jianghan Basin, central China, bear thermally immature to mature hopane and sterane signatures. Initial daily oil production rate without stimulation ranges from 20-30 barrels to over 7000 bbl/well. Strangely, oils with the highest API gravity and highest initial daily output show the lowest maturity level judging from the saturate biomarker ratios. Petrographic and geochemical parameters suggest that Qianjiang shale oil reservoirs within the Eq3 section from the pilot production blocks have undergone some uplift as a result of salt tectonics, but their maximum burial depths and temperatures correspond mostly to early oil window. Although both oil generation from low-maturity hypersaline lacustrine shales and oil migration from downdip mature kitchens are possible, this degree of burial diagenesis and thermal maturation raises several critical questions regarding the oil and reservoir quality of the rocks. Shallow burial diagenesis of variable clastic-carbonate lithologies implicates compaction, cementation, redox reactions involving sulphate and hydrocarbons, hydrocarbon expulsion and in-migration, and water chemistry, water loss and dissolution/re-precipitation processes. All of these processes may enhance or diminish reservoir potential by retaining or releasing oil from the system at low thermal maturities and by diagenetically altering shale rock properties.

To help understand such early-mature shale oil reservoirs, we studied seven production test oil samples, as well as 137 selected core samples of Qianjiang Formation organic rich shales from the QYP-2, WY-11 and W4X-7-7 wells in Qianjiang Municipality, Hubei. We employed an integrated suite of high-resolution analytical techniques to determine quantitative mineralogy, measure quantity, quality and thermal maturity of organic matter, acquire detailed molecular marker data from saturate and aromatic hydrocarbon fractions of solvent extracts, describe and classify porosity, and develop a diagenetic and oil accumulation history of the Qianjiang Formation in the region.

The organic-rich intervals of the Qianjiang Formation are minerologically complex, consisting of laminated to thinly bedded, fossiliferous, calcareous, dolomitic, anhydritic, glauberitic shales. The inter-salt rocks are dominated by calcite or dolomite, whereas the intra-salt shales are often associated with sporadic glauberite. All of the inter-salt organic-rich intervals meet the requirements for commercial shale oil reservoirs, with most of the cored intervals having 2-17% TOC, and dominated by Type I-II organic matter. The intra-salt rocks show generally low TOC values (most below 2%), with Type I, II and III organic matter. The generally high porosity (7-20%) and Hydrogen Index (300-950 mgHC/gTOC) indicate the rocks are currently at low thermal maturity. The Qianjiang rocks are highly oil stained from visual core description. Microscopic and SEM examination along with thermal and solvent extraction show that bitumen comprises a significant volume of the rocks. Meanwhile, high temperature pyrolysis of whole rock samples also indicates significant remaining oil

generative potential. Based on the large difference in the measured rock porosity before and after sequential solvent extraction, most of the porosity in the Qianjiang shales appears to be associated with conventional rock matrix. Early diagenesis of the Qianjiang sediments mostly involved mechanic compaction and dewatering of the muds during initial burial. Chemical compaction as greater burial depths was likely dominated by salt and calcite dissolution/re-precipitation, dolomitization, clay mineral transformations, which may effectively destroy most original porosity. However, the relatively low maturity level and high oil content of the organic rich shales dictates that chemical compaction in these rocks has not proceeded to a great extent.

Within 193 identified evaporatic rhythms in the Qianjiang Formation, most data come from the shallow buried Eq2-Eq3 sections, with limited data from the deeper Eq4 section in the basin. Rock-Eval analysis of three cores reveals a clear increase in TOC, S1 and S1/TOC values from intra- to inter-salt shales, suggesting that high oil content is mainly in the inter-salt shales and associated with organic-rich laminates. Many previous studies indicate that shale oil occurs in a variety of modes, either in free or adsorbed–kerogen miscible phase. Free oil exists mainly in fractures and pores, whereas adsorbed–miscible oil associates dominantly with organic matrix and to a lesser extent on mineral surface. As free oil is the major contributor for shale oil production, quantitative characterization of shale oil occurring in different phases is of considerable significance for the estimation of producible shale oil resources. A combination of sequential solvent extraction and an improved Rock-Eval method in this study has enabled us to achieve reasonable quantitative resolution of free versus immobile oils in the studied shales.

Detailed correlation between bulk oil yields and molecular geochemistry of solvent extracts for the studied cores leads to several significant observations. Firstly, hopane and sterane biomarker signatures of the intra- and inter-salt shales in the Eq3 cores show clear differences reflecting their difference in the environment of deposition (e.g. paleosalinity and water column stratification). Secondly, the thermal maturity levels of the intra-salt shales as reflected by C_{29} sterane isomer ratios approximate their maximum burial depth, whereas the adjacent inter-salt shales show much higher levels of thermal maturity indicating significant contribution of in-migrated, high maturity oils. Thirdly, comparison of sterane and hopane distributions as well as maturity parameters suggests that the oils in the inter-salt shales are geochemically similar to conventionally reservoired oils that have a proven hypersaline lacustrine source in the deeper Eq4 section of the Qianjiang Formation. Quantification of absolute concentrations of a number of saturated and aromatic hydrocarbon biomarkers using isotopically-labeled standard compounds reveals that mixing of low maturity biomarker signature in indigenous bitumen with more mature oils could potentially produce lighter oils with lower apparent maturity.

Integration of the results of this geochemical investigation with regional tectono-stratigraphic framework provides useful constraints for the likely models of inter-salt shale oil accumulation in the Jianghan Basin. In regions where structural traps were formed as a result of salt tectonic development, up-dip lateral oil migration along variably deformed shallow shale laminates may be conducive for hybrid shale oil/conventional oil systems. In thermally mature source kitchens and the deeper Eq4 section, in contrast, continuous oil accumulation in structurally undisturbed areas may produce even more attractive unconventional drilling targets. In both cases, the presence of halite, organic rich and relatively brittle laminated shale, suitable maturity and early oil emplacement are among the key elements for the self-contained, inter-salt, petroleum system.