AAPG HEDBERG CONFERENCE
"NATURAL GAS GEOCHEMISTRY: RECENT DEVELOPMENT, APPLICATIONS AND TECHNOLOGIES"
MAY 9-12-BEIJING, CHINA

Natural Gases in Puguang and Maoba Gas Fields: Gas Geochemistry and Implications for Effective Gas Source Rocks in Northeastern Sichuan Basin

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Northeastern Sichuan Basin is one of the most significant areas for petroleum exploration in China, with numerous H_2S bearing gas fields being discovered in the past few years, including Puguang, Maoba, Dukouhe, and Leikoupo gas fields. Natural gas in the Puguang gas field, with proved reserves of 356 billion cubic meters, is found in a large composite structural-lithological trap. In this contribution, we document the detailed molecular and isotopic geochemistry of natural gases produced from carbonate reservoirs in the Lower Triassic Feixianguan Formation and Upper Permian Changxing Formation of the Puguang and Maoba gas fields, and discuss possible implications for effective gas source rocks in northeastern Sichuan Basin.

The common characteristics of the natural gases in the Puguang and Maoba gas fields include extremely high dryness (with C_1/C_{1+} greater than 0.996), moderate to high H_2S (5.1-58.3%) and CO_2 contents (7.9-18.0%), high $\delta^{13}C_1$ values (-33.66 to -29.71‰, and a wide range of $\delta^{13}C_2$ values. As indicated by a$\delta^{13}C_1$-$\delta^{13}C_2$ plot, however, at least three types of natural gases can be readily recognized in the study area. These include (1) type III gases in the Maoba 1 well (T_1f reservoir), Pugang 2 well (T_1f reservoir) and Puguang 2 well (P_2l reservoir), with characteristically high $\delta^{13}C_2$ values (~-25‰); (2) type II gases in the Maoba 1 (P_2ch reservoir), Puguang 2 (T_1f and P_2ch reservoirs) with $\delta^{13}C_2$ values varying between -26.67 to -29.07‰; and (3) gases with complex origin, indicated by extremely low $\delta^{13}C_2$ values accompanied by stable carbon isotopic reversal for methane and ethane.

Stable carbon isotope fractionation under subsurface thermal regime in typical sedimentary basins generally follows the order of $\delta^{13}C_{kerogen} > \delta^{13}C_{bitumen} \sim \delta^{13}C_{oil} > \delta^{13}C_{alkane}$ (or $\delta^{13}C_1$). The stable carbon isotope values of kerogens isolated from the Upper Permian and Lower Permian source rocks are slightly higher than or close to those of bitumens in the Feixianguan and

Changxing formations. In contrast to the low TOC contents of the Lower Permian rocks, the Upper Permian Longtan Formation generally shows high TOC contents and excellent source rock quality, and is thus considered to be the main source rocks for the bitumens in the Feixianguan~Changxing reservoirs of the Puguang and Maoba gas fields. The Upper Triassic Xujiahe Formation as the potential source rocks for these bitumens can be readily excluded based on both stable carbon values and stratigraphic association. A Cambrian source can be also ruled out, as the $\delta^{13}C_{kerogen}$ values of the Cambrian source rocks are lower than those of methane in the discovered Puguang and Maoba fields. The $\delta^{13}C_{kerogen}$ values of the Lower Silurian Longmaxi formation source rocks are close to those of methane in the discovered Puguang and Maoba fields, and their possible genetic relationship cannot excluded based on available data.

Although it is generally accepted that natural gases in the Puguang and Maoba fields were the result of in-reservoir thermal cracking and thermochemical sulfate reduction (TSR) of an Upper Permian derived paleo-oil accumulation, the actual mechanisms for the origin of these gas fields remain elusive. Hao et al. (2008) proposed a successive, three-stage TSR series, namely, liquid hydrocarbon involved TSR, heavy hydrocarbon gas dominated TSR, and methane dominated TSR, occurring in reservoirs with sufficient sulfate concentration. This proposal is theoretically quite plausible, but is not supported by geochemical and petrographical data presented by Hu et al. (2010). Methane and other gaseous alkanes can be the dominant organic reactants for TSR at elevated temperature, but only with sufficient sulfate supply and after more reactive liquid hydrocarbons being exhausted. As TSR in the study area appears to have been limited by sulfate concentrations in the reservoirs, TSR reactions cannot be invoked as a significant factor that controls the stable carbon isotope values of the natural gases in the Puguang and Maoba fields. Therefore, the most likely source rocks for type II and type III gases indicated by gas isotopes can be conventionally explained by oil-prone and gas-prone source rocks in the Upper Permian Longtan Formation or off-reef lagoonal facies in the Lower Triassic Feixianguan Formation. Contrary to previous studies, we consider the methane-ethane stable carbon isotope reversal in many of the gas samples in the study area as an indicator for mixing of relatively low maturity ethane inherited from earlier oil accumulation and high maturity methane generated later from in-reservoir oil cracking and thermochemical sulfate reduction.