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Noble gas tracers reveal episodic openness and selective gas loss during fluid evolution in tight sandstone reservoirs, Sichuan Basin, China

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Tight sandstone reservoirs are commonly treated as closed systems once hydrocarbon charge is established. However, noble gas systematics provide a sensitive means of testing this assumption and quantifying fluid openness during migration and storage. We present new noble gas elemental and isotopic data (He, Ne, Ar, Kr and Xe) from 12 production wells in the Xinchang gas field, Sichuan Basin, China, hosted in the Triassic Xujiahe (T_3x), and the Jurassic Shaximiao (J_2s) and Qianfoya (J_2q) tight sandstone reservoirs (<5% porosity; $<10^{-4}$ mD matrix permeability).

Measured $^{3}He/^{4}He$ ratios (0.0037–0.025 R_a) demonstrate dominantly crustal radiogenic He, while strongly fractionated $^{20}Ne/^{36}Ar$ ratios relative to air-saturated water and elevated $^{4}He/^{20}Ne$ ratios indicate substantial radiogenic He accumulation coupled with multistage Ne loss. Moderate enrichment in $^{40}Ar/^{36}Ar$ (≤858) and relative retention of Kr and Xe require repeated gas-water interaction and selective degassing rather than simple closed-system radiogenic ingrowth. Overlapping noble gas signatures between Triassic and Jurassic reservoirs further imply limited but significant vertical connectivity.

These results demonstrate that even ultra-low permeability sandstones can experience episodic openness, enabling selective gas loss and partial re-equilibration with groundwater. Noble gas tracers therefore provide a quantitative tool to assess charge history, permeability evolution and seal integrity in unconventional reservoirs. More broadly, this study highlights the value of noble gas systematics for de-risking hydrocarbon systems where conventional geochemical indicators alone cannot resolve migration pathways or openness.