

The role of bedding-parallel fractures in fluid activity within relatively closed lacustrine shale systems: Petrographic and geochemical evidence from calcite veins

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Fluid activity plays a critical role in the redistribution of materials and elements within rocks, hydrocarbon transport, lithosphere rheology, and greenhouse gas sequestration. However, in relatively closed lacustrine shale systems that have undergone intense physical and chemical compaction, the mechanisms and pathways of fluid activity remain poorly understood due to limited records of fluid-rock interactions. To investigate these processes, we present the petrography, isotope geochemistry, cathodoluminescence, fluid inclusions, electron probe microanalysis, and rare earth elements of bedding-parallel calcite veins (BPCVs) found in the lacustrine organic-rich shales of the Chang 7₃ sub-member of the Yanchang Formation in Ordos Basin.

The calcite growth temperature recovered by clumped isotope ($\Delta 47$) indicated that BPCVs were mainly formed during the oil generation window period. Based on petrological and geochemical characteristics, BPCVs can be divided into three distinct stages: Cal-1, Cal-2 and Cal-3. Cal-1 formed through active fracturing of host rocks driven by crystallization forces during in-situ recrystallization following pressure dissolution of inorganic micrite carbonate minerals. The diagenetic fluid of Cal-2 mainly come from the dissolution of micrite carbonate minerals in host rocks by organic fluid, and BPFs accommodating Cal-2 may be opened under the oil generation overpressure to promote oil expulsion. Cal-3 is associated with micro-thrust fault structures and displays positive δEu anomalies, distinct from the host rocks, indicating that BPFs opened under horizontal tectonic compression and subsequently served as flow channels for organic fluids and deep hydrothermal fluids.

This study highlights the multi-stage and episodic opening of BPFs in relatively closed lacustrine shale systems was caused by crystallization force, periodic overpressure during oil generation, and discrete tectonic compression events. In addition, these BPCVs enhance the brittleness of rocks, which is conducive to subsequent sustained hydraulic fracturing. These processes significantly enhance fluid flow, material exchange, and diagenetic evolution, representing a critical response to multi-