Goldschmidt 2025 Abstract
https://doi.org/10.7185/gold2025.27387

Granular calcites originated from hydrothermal fluids in lacustrine fine-grained sedimentary rocks

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Granular calcite, as a significant authigenic mineral in fine-grained sedimentary rocks, provides critical insights into deep interfacial geochemical processes under high-temperature conditions. This study integrates core observation, cathodoluminescence analysis, fluid inclusion microthermometry, SEM-EDS, and isotopic composition analysis to investigate the genesis of granular calcite in the Permian Lucaogou Formation, Junggar Basin. The results show that the granular calcite is distributed with laminated characteristics in fine-grained sedimentary rocks in tuffite zones (or the transitional zone between tuffite and micritic dolomite). Granular calcite has an obvious cathodoluminesence band, and it can be divided into three stages. Stage-I calcite, characterized by non-luminescence, high Sr content, carbonyl Sulfide (COS)-bearing inclusions, and homogenization temperatures >170°C, formed through direct volcanic-hydrothermal deposition at reactive mineral-fluid interfaces. Stage-II calcite, showing bright yellow luminescence, enrichment in Fe, Mn, Mg, and LREEs, and high homogenization temperatures, originated from recrystallization of calcareous edges through exhalative hydrothermal deposition. Stage-III calcite, with dark orange luminescence band, high contents of Mg, P, V and other elements, no obvious fractionation among LREEs, and low homogenization temperature, formed via diagenetic transformation during burial, demonstrating the evolution of interfacial geochemistry over time. The vertical distribution and temperature gradient from calcite particle centers to margins provide direct evidence for volcanic-hydrothermal events during Lucaogou Formation deposition. These events significantly influenced organic matter enrichment and the development of high-quality source rocks through interfacial reactions at elevated temperatures. Furthermore, the volcanic-hydrothermal events created intergranular pores and fractures during evolution, establishing favorable conditions for shale oil self-generation and storage. This study highlights the crucial role of interfacial geochemical processes in deep sedimentary systems, particularly in mediating material and energy exchange between volcanic-hydrothermal fluids and sedimentary rocks. The findings contribute to our understanding of deep carbon cycling and hydrocarbon generation in high-temperature environments, bridging the gap between deep geochemical processes and surface hydrocarbon accumulation.