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Metamorphic evolution and boron enrichment mechanisms in the Houxianyu borate deposit in eastern Liaoning, China: Insights from mineral geochemistry and oxygen isotopes

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The Houxianyu borate deposit in eastern Liaoning represents one of the most economically significant borate resources in China, yet its genesis remains highly debated. It is uniquely characterized by its mineral assemblages and is hosted within Paleoproterozoic metamorphic strata. This study integrates petrographic analysis, major and trace element geochemistry, and oxygen isotope data from key minerals including olivine, apatite, and magnetite to unravel the metamorphic evolution and boron enrichment mechanisms.

Our results demonstrate that the forsterite-rich rocks at Houxianyu are not exclusively magmatic or mantle-derived; instead, metamorphic processes, particularly the metamorphism of Mg-rich carbonate rocks, plays a significant role in their formation. This conclusion is supported by the low concentrations (<50 ppm) of Cr, Co, and Ni in both olivine and phlogopite, as well as significantly elevated and highly variable $\delta^{18}O$ values in olivine (ranging from +6.19‰ to +19.03‰). We identify a clear paragenetic sequence associated with two main metamorphic stages: (1) a prograde metamorphic stage reaching peak temperatures of 600–700°C, during which primary hydrous borates were transformed into anhydrous phases such as suanite and ludwigite, releasing boron-rich fluids into the system; and (2) a subsequent retrograde stage, characterized by pervasive serpentinization, phlogopitization, and the secondary precipitation of szaibelyite.

The wide range of oxygen isotope compositions in olivine suggests mixing between high-$\delta^{18}O$ fluids derived from sedimentary dehydration and low-$\delta^{18}O$ formation water (interpreted as trapped paleo-seawater) within the stratigraphic sequence. Additional evidence comes from geochemical signatures in apatite (distinct REE patterns and Sr/Th ratios) and magnetite (V-Ti variations). Together, these data document the fluid-rock interaction history and the evolution of the hydrothermal system. Based on these findings, we propose a two-stage genetic model for the Houxianyu borate deposit: (1) an early evaporitic pre-enrichment stage (~2.2 Ga) and (2) a late regional metamorphic mineralization stage (~1.9 Ga). This work underscores the critical role of metamorphic processes in both concentrating and preserving boron in high-grade metamorphic terranes and provides a conceptual framework for understanding similar borate deposits in ancient orogenic belts.