Goldschmidt 2026 Abstract
https://doi.org/10.46427/gold2026.34681

Multistage tungsten mineralization from skarn- to vein-type systems constrained by U–Pb geochronology and geochemistry of titanite and apatite

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Large tungsten deposits commonly record multiple overprinting hydrothermal episodes, yet distinguishing these events and their fluid sources remains challenging. The Nanwenhe deposit, the largest W resource in southeastern Yunnan, is a representative example: it hosts both stratabound skarn-type scheelite and later quartz-vein-type W mineralization, giving rise to long-standing debate over its metallogenic history and fluid origins. In this study, skarn-stage titanite and apatite yield consistent Indosinian ages of ~205 Ma, whereas three successive generations of vein-type mineralization record distinct Yanshanian ages of ~160 Ma, ~140 Ma, and ~92 Ma. Trace-element systematics and principal component analysis (PCA) show that skarn titanite forms a coherent geochemical population characterized by high Th/U, low Y/Ho Sn and Lu/Hf, consistent with crystallization from a metamorphic-hydrothermal fluid during regional amphibolite-facies metamorphism and extensional unroofing of the Laojunshan dome. In contrast, titanite from all vein stages defines a separate, internally evolving population with systematically lower Th/U, and higher Y/Ho, Sn, and Lu/Hf, reflecting involvement of evolved magmatic-hydrothermal fluids. Apatite compositions display an analogous dichotomy: skarn apatite (Ap-SK) is strongly Sr-rich and Mn–Y–REE-poor, whereas vein apatite (Ap-V1–V3) shows the inverse pattern. PCA separates these two groups along the Sr versus Fe–Mn–Y–REE loading vectors, reinforcing their contrasting fluid signatures. Integrating geochronological and mineral-chemical constraints, the Nanwenhe system preserves two fundamentally different hydrothermal regimes: (1) an Indosinian (~205 Ma) metamorphic-hydrothermal event responsible for skarn-hosted scheelite, and (2) three Yanshanian (~160 Ma, ~140 Ma, ~92 Ma) magmatic-hydrothermal events corresponding to successive vein-type mineralization. Among them, the ~140 Ma episode represents the dominant W mineralization stage, whereas the ~92 Ma event reveals previously unrecognized late Cretaceous magmatic-hydrothermal activity and highlights additional exploration potential at depth.