

Post-Orogenic Copper Mineralization in the Tiddiline Formation (Anti-Atlas, Morocco): Insights into Critical Metal Systems for the Energy Transition

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Copper is a cornerstone metal for the global energy transition, playing a critical role in renewable energy systems, electrification, and infrastructure development. In this context, understanding the formation and distribution of copper deposits is essential for sustainable resource exploration. The Bou Azzer–El Graara inlier (Central Anti-Atlas, Morocco), located along the northwestern margin of the West African Craton, hosts significant Neoproterozoic copper mineralization within the Tiddiline Formation. This study focuses on the Aït Abdellah deposit and aims to constrain the origin and controlling factors of this mineralization within a post-orogenic framework.

The Tiddiline Formation consists of immature arkosic sandstones deposited during the late Neoproterozoic, with U–Pb zircon ages constraining a maximum depositional age of 611 ± 11.5 Ma. Structural analysis indicates that copper mineralization is strongly controlled by NE–SW-oriented shear zones developed during the late stages of the Pan-African orogeny. Petrographic and SEM-microprobe investigations reveal a multiphase paragenesis, including early diagenetic pyrite and quartz, followed by syn-tectonic copper sulfides (chalcopyrite and bornite), and late carbonate veining.

Sulfur isotope compositions ($\delta^{34}\text{S} = +5.9\text{‰}$ to $+22.8\text{‰}$) indicate a mixed sulfur source, involving both ophiolitic and sedimentary contributions. Carbon and oxygen isotopic data suggest interaction between hydrothermal fluids, marine carbonates, and meteoric waters, possibly linked to post-glacial conditions. Fluid inclusion microthermometry (195–310 °C; 5.7–23.2 wt.% NaCl eq.) supports a model involving the mixing of basinal and magmatic-hydrothermal fluids.

These results highlight a structurally controlled, post-orogenic hydrothermal system, where fluid circulation along shear zones played a key role in copper concentration. This study provides new insights into critical metal systems in Precambrian terranes and underscores the exploration potential of shear zone-hosted copper mineralization in the Anti-Atlas.