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Genesis of the Stratiform Hydrothermal Manganese Mineralization of the Tizi-n'Isdid District (Western High Atlas, Morocco): Ore Mineralogy, Paragenesis, and Geochemical Evolution

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The Tizi-n-Isdid manganese deposit, located along the western margin of the Ouzellarh Precambrian promontory in the western High Atlas, represents a key example of hydrothermally stratiform-type manganese ore deposit formed during the late Ediacaran to early Cambrian transition. This study integrates field observations, petrography, SEM-EDS analyses, automated mineralogical mapping and whole-rock geochemistry to reconstruct the mineralogical evolution and origin of the deposit. Macroscopic observations reveal massive, banded and brecciated Mn-rich bands hosted within lower Cambrian claystones (Adoudou Formation), with MnO contents ranging from 21 wt.% to 49 wt.%. The ore is dominated by braunite, piemontite, hollandite- group minerals, cryptomelane, pyrolusite, and subordinate amounts of barite and carbonate minerals. Textural relationships identify four successive stages: a detrital pre-ore stage; an early hydrothermal silicification stage; a carbonatation stage marked by brecciation and barite–carbonate veining; and a final near-surface oxidation stage. Major and trace elements (Mn/Fe, Co/Ni, Co/Zn) consistently indicate a hydrothermal origin, while REE patterns, characterized by low ΣREE, strong negative Ce anomalies, positive Eu anomalies, HREE enrichment and high Y/Ho ratios, reflect the mixing of Mn-rich hydrothermal fluids with oxic seawater on a shallow platform. Structural and tectonic evidence links ore formation to late Ediacaran N–S extension, fault-controlled hydrothermal circulation and early Cambrian marine transgression. These combined mineralogical, geochemical and geological data support a genetic model in which Mn was leached from volcanic and basement rocks, transported upward along normal faults and precipitated syngenetically with clay-rich sediments in an oxygenated marine environment.