Incursion of evaporites in the Zhangjiawa iron skarn deposit of Laiwu district, North China Craton: Mineralogical, sulfur and strontium isotopic study

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The Zhangjiawa iron skarn deposit in the Laiwu district, North China Craton contains 283 Mt of ores at an average grade of 46 wt%. The mineralization is dominated by massive magnetite ores, most of which occurs along the contact zone between the early Cretaceous (132 Ma), Na-rich Kuangshan dioritic intrusion and middle Ordovician dolomitic limestones that contain numerous evaporitic intercalations. Hydrothermal alteration is characterized by extensive albitization in the dioritic stock and minor magnesian skarn assemblages within the contact zone, consisting of diopside, forsterite, spinel, serpentine and phlogopite. Magnetite from the iron ores commonly has high contents of MgO (3.03-5.36 wt%) and is characterized by abundant fine-grained spinel exsolutions. Minor magnesioferrite (12.39-13.77 wt% MgO) is associated with the Mg-rich magnetite. The ore-related dioritic rocks have $\delta^{34}S$ values (13.0-21.3‰) that are unusually high relative to magmatic-derived sulfur, indicating introduction of external sulfur into the magam during its ascent and/or emplacement, most likely from the evaporites-bearing Ordovician carbonate rocks. Pyrite from the magnetite ores has $\delta^{34}S$ values of 8.6-18.1‰, further confirming a major sulfur source from the Ordovician marine sulfate sequences. Hydrothermal apatite associated with magnetite has Sr isotopic compositions ($^{87}Sr/^{86}Sr$ = 0.70765-0.70903) intermediate between the the dioritic intrusions (0.70594-0.70750) and Ordovician sedimentary rocks (0.70806-0.70899) in Laiwu district. The S and Sr isotope data demonstrate that the Ordovician evaporites have been significantly assimilated by the ore-related magmas and were continuously introduced into the ore-forming fluids. The sodic nature of the ore magmas and extensive sodic alteraiton in the intrusion, as well as the high-Mg signature of magnetite, provide additional evidence for important roles of the evaporite in iron skarn mineralization at Zhangjiawa.