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Skarn mineral signatures and their geological significance in the Nuocang Cu-Pb-Zn deposit, Tibet

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The Nuocang deposit, located in the western part of the Nyainqentanglha Pb-Zn-Cu-Fe-Ag metalogenic belt, mainly occurs in the Permian Angjie Formation. Ore minerals primarily are sphalerite and galena, followed by chalcopyrite, pyrite, magnetite, and pyrrhotite. Non-metallic minerals are predominantly pyroxene, garnet, and epidote, with minor ilvaite, phengite, chlorite, and fluorite. Pyroxene is dominated by hedenbergite, with the end-member composition being $Di_{0.14-25}Hd_{57-92}Jo_{6-20}$. The ranges for Mn/Fe and Mg/Fe ratios are 0.07-0.34 and 0.1-0.45, respectively, which are similar to other Pb-Zn skarn deposits worldwide. Garnet ($And_{23-100}Gro_{0-74}$) is rich in Mn (MnO = 0.5 wt.%, average) and contains minor F (0-0.92 wt.%). Epidote is characterized by enrichments of Al and Ca, and a lack of Fe and Mg. Magnetite is rare, whereas the ilvaite is well-developed, which is rich in Mn (MnO = 3.1-6.5 wt.%), but is relatively depleted in Fe (FeO = 45.3-48.9 wt.%). Chlorite is mainly leptochlorite and chamosite, with a high content of Fe (FeO = 22.4-44.3 wt.%). Sphalerite is generally rich in Fe (1.7-12.2 wt.%, average 8.3 wt.%), which can be defined as iron-rich sphalerite.

The metallogenic evolution of the Nuocang deposit began with a prograde stage of pyroxene and garnet formation. The enrichment of early andradite with a small amount of F (0.54 wt.%) reflects a fast growth, high temperature, and oxidizing environment. The subsequent substitution of Fe^{3+} for Al^{3+} in the andradite indicates the variation of fluid fugacity, which results in a distinct oscillatory zoning. The later grossular-dominant garnet with a low component of F (0.27 wt.%) and lesser zoning developed as a vein or/and coexisted with hedenbergite, which suggests a reducing environment. In the retrograde stage, the temperature and oxygen fugacity continue to be reduced, but the hydrolysis enhanced, and epidote±magnetite formed. Although the fluid has a high iron content, the lower oxygen fugacity hinders the formation of magnetite. The late retrograde stage mainly formed ilvaite and chlorite. The presence of ilvaite indicates the declining iron in the ore. It is favorable for the formation of the Pb-Zn skarn deposit. The presence of the ilvaite. which is Mn-rich and has a relatively high Fe^{2+}, shows a reducing environment to be present. The continuing decreasing temperature and oxygen fugacity lead to the addition of the metallic elements (Cu, Pb, Zn) from the hydrothermal fluid into the skarn system, and the various sulfides precipitated when reacting with the S^{2-}. The molecular values of FeS (>10%) and the Zn/Cd range (170-490) in sphalerite indicates a medium temperature for ore deposition.