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# Ore textures and remobilization mechanisms of the Hongtoushan copper–zinc deposit, Liaoning, China

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A B S T R A C T

The Hongtoushan copper–zinc deposit is a volcanic-associated massive sulfide deposit in the Archean greenstone belt in Liaoning, China. Polymetamorphism has resulted in changes to the composition and textures of minerals in the deposit, along with remobilization. During metamorphism, the original alteration minerals that formed with the ore minerals, such as chlorite and sericite, were transformed into cordierite, anthophyllite, and phlogopite. After further remobilization, new minerals, such as gahnite and actinolite, were formed. In this process, the original textures were destroyed and new textures were formed, including recrystallization and growth textures, brittle and ductile deformation textures, durchbewegung textures, replacement textures, chalcopyrite disease, and retrograde textures. The ore-forming components underwent two periods of remobilization. In the first (early) stage, mechanical remobilization was important, and formed a high grade Cu–Zn–Au–Ag "ore pillar" along the vertical hinge of a synformal fold. In the second (late) stage, the mixed hydrothermal–mechanical remobilization affected the ores, and was typically characterized by matrix sulfides, together with silicate minerals, moving from the matrix into individual fractured pyrite metablasts and replacing them to varying degrees.


## 1. Introduction

The final textures and structures of sulfide deposits affected by metamorphism depend on both the physical conditions of metamorphism, such as temperature and pressure, and the initial properties of the materials (Vokes, 1969). The Hongtoushan copper–zinc deposit is an example of a sulfide deposit affected by multi-phase metamorphism and deformation. Located in an Archean greenstone belt in Liaoning, China, the deposit is a volcanic-associated massive sulfide deposit (Sun, 1992; Zhang, 2010; Zhang et al., 1984) of importance both in geological and economic terms. Various processes related to the multi-phase deformation and metamorphism have influenced the geometry of the ore bodies and their textures and structures, including the process of remobilization (Liu and Chen, 1982).

Although the Hongtoushan deposit has been reasonably well studied (Gu et al., 2004a,b; Liu and Chen, 1982; Zhang et al., 1984), several issues are yet to be resolved. These include: (1) the origin of phlogopite gneiss that is located near the ore bodies; (2) the nature of changes in ore composition, texture, and structure during metamorphism and deformation; and (3) the mobilization mechanism(s) of minerals. This paper combines field geological data, microscope observations, scanning electron microscopy data, and electron probe test data in an effort to provide a clearer understanding of these issues.

## 2. Geological setting

The Hongtoushan copper–zinc deposit is located in the Archean granite–greenstone terrane of the northeastern section of the North China Craton, in Qingyuan County, Liaoning Province (Fig. 1). The greenstones in the area of the deposit comprise the Hongtoushan Formation of the Qingyuan Group. The formation comprises mainly hornblende gneiss interbedded with biotite gneiss, and these rocks contain garnet, sillimanite, and anthophyllite. Petrological and geochemical investigations by previous authors indicate that the parent volcanic rocks of Qingyuan Group are continuously differentiated volcanic rocks varying in composition from mafic through intermediate to felsic of both the tholeiitic and calc-alkaline affinities, and are thus the protoliths of lithologies that typically form in an island-arc environment (Li et al., 1995; Zhai et al., 1984; Zhang, 2010; Zhang et al., 1984).

In the early Precambrian, the Hongtoushan deposit was affected by the Anshan and Lvliang movements (Gu et al., 2004b) resulting in the Anshan and Lvliang deformation cycles. The Anshan deformation cycle occurred during amphibolite facies regional metamorphism, with medium pressure and temperatures of 500–700 °C, and was characterized by plastic flow deformation. The Lvliang deformation cycle was characterized by brittle deformation of greenstone belts and late injection of mafic dikes.

The thinly layered, interbedded Hongtoushan Formation experienced upper amphibolite facies metamorphism, with temperatures of 600–650 °C and pressures of 0.8–1.6 GPa (Yang and Yu, 1984). The gneissic fabric therein is essentially parallel to lithological boundaries, and dips toward the southeast at 70–80°, defining an isoclinal fold

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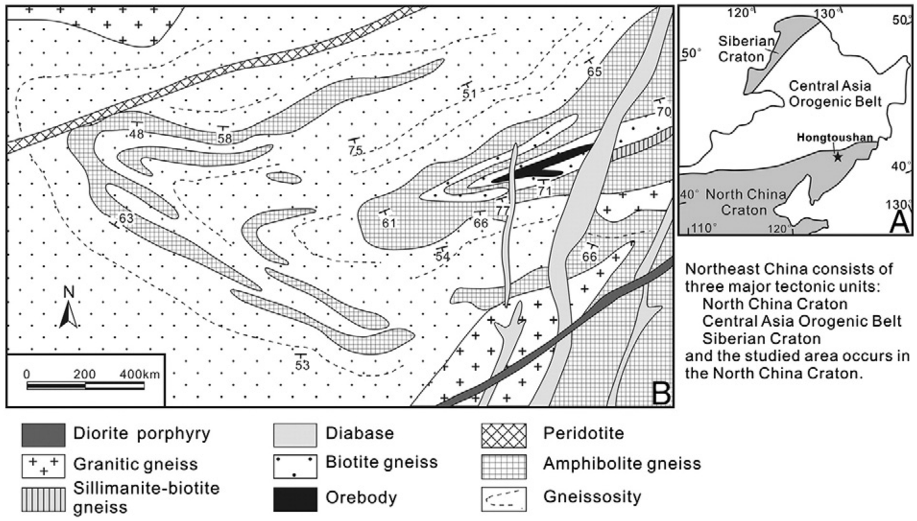


**Fig. 1.** Simplified geological map of the Hongtoushan copper–zinc deposit (B) (modified after Yang and Yu, 1984) and sketch of regional geology and distribution of the Hongtoushan deposits (A).

(Fig. 1) that plunges at 80° towards the southeast. The shapes of the ore bodies are controlled by this fold with the ore bodies occurring mainly in the hinge. The overall configuration of the ore bodies is in the shape of a horizontal "Y", with the two arms of the "Y" opening towards the east (Fig. 1). The ore bodies at the junction of the Y-shape attain the maximum thickness and the highest grade in Cu, Au and Ag, and thus form a substantial, vertical "ore pillar". The axis of the ore pillar points progressively counterclockwise with increasing depth. Below a depth of −467 m (all depths are relative to sea level), the dip angle of the fold axis decreases to less than 30° and in this zone the ore bodies occur mainly in the limbs of the fold.

The ore bodies are mainly stratiform or stratiform-like in shape, and have a massive structure. The stratiform ore bodies dip toward the southeast in general, sub-parallel to the gneissosity of the wall rocks. In contrast, the stratiform-like ore bodies, which were affected by deformation and metamorphism, occur mainly as veins and lenticular bodies, and, at small scales, cut across the stratigraphy. Quartz–sulfide veins, composed predominantly of quartz, muscovite, chlorite, carbonate, and sulfides, cut across the wall rocks and ore bodies.

In volcanic-associated massive sulfide deposits, alteration pipes initially have a chlorite core that grades laterally and vertically into a sericite-rich outer zone and finally into unaltered rocks (Barrett et al., 2005; Large et al., 2001; Theart et al., 2010; Yao and Sun, 2006). In such deposits, the most characteristic features of the altered rocks, relative to fresh rocks, are increased contents of Mg and Fe, and decreased Ca and Na, giving rise to the formation of chlorite and sericite. Cordierite–anthophyllite gneiss, which is distributed near the Hongtoushan ore bodies, is considered to represent metamorphosed seafloor hydrothermal alteration zone (Zhang et al., 1984; Zheng et al., 2008). Relative to the unaltered protolith, the gneiss is geochemically characterized by strong enrichment in Fe, Mg, and Si, and a corresponding depletion in K, i.e., the same characteristics as chloritic and silicified rocks near unmetamorphosed VMS systems.

## 3. Samples and analytical methods

For this study we collected 550 samples, including ore and wall rocks, from 32 tunnels at seven underground mining levels between depths of −467 and −827 m in the Hongtoushan copper–zinc deposit. Ninety-one rock and ore samples were selected from which thin sections and polished sections were made to examine the minerals, textures, and structures of the ore rocks and wall rocks. Microprobe analyses were performed using a JEOL JXA-8100 Electron Probe housed at the Analytical Laboratory of the Beijing Research Institute of Uranium Geology, Beijing, China, operated at an accelerating voltage of 30 kv and a beam current of 10 nA, using a focused beam.

## 4. Minerals of ore-bearing rocks

The predominant ore minerals of the Hongtoushan ores are pyrite and pyrrhotite, with less chalcopyrite and sphalerite, and minor cubanite, magnetite, galena, rutile, and electrum. Gangue minerals are dominated by quartz, plagioclase, and biotite, with less biotite, gahnite, cordierite, anthophyllite, muscovite, actinolite, andradite, clinozoisite, chlorite, carbonate, sillimanite, and anhydrite. Pyrite grains and included silicate minerals have been replaced by chalcopyrite and sphalerite. Quartz–sulfide veinlets, if present, fill cracks in the sulfides and contain sulfide, quartz, chlorite, carbonate, and muscovite.

### *4.1. Ore minerals*

Here we describe the dominant ore minerals in turn, based on observations of the thin sections and polished sections. Previous studies have also characterized the ore minerals in some detail (Gu et al., 2004a; Yu, 2006).

#### *4.1.1. Pyrite*

Pyrite crystals in the massive sulfide ores are generally coarse porphyroblasts in a matrix of pyrrhotite, chalcopyrite, and sphalerite. Pyrite porphyroblasts contain inclusions of spherical plagioclase and quartz. Pyrite porphyroblasts are fragmented, and fissures are commonly filled with remobilized chalcopyrite, pyrrhotite, sphalerite, and quartz. In the disseminated ores, pyrite is usually subhedral or anhedral, and is locally elongate within the plane of the gneissosity, and is even boudinaged into multiple sections. In the disseminated ores, chalcopyrite occurs in pressure shadows, and pyrite occurs as a retrograde mineral that replaces pyrrhotite.

#### *4.1.2. Pyrrhotite*

Two generations of pyrrhotite occur in the massive ores: one occurs mainly among the matrix sulfides, and has straight grain boundaries and no replacement relationship with pyrite; the other generation, together with chalcopyrite and sphalerite, fills fissures in cataclastic pyrite and replaces pyrite porphyroblasts. The appearance of pyrrhotite, chalcopyrite, and sphalerite therefore represents a new phase of