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Research on Mineralization of the Hongtoushan Massive Sulfide Deposit in the Archean Granite-greenstone Terrane

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1 Geological characteristics

The Qingyuan Archean granite-greenstone terrane, which can be divided into Xiaolaihe granite-greenstone belt, Qingyuan granite-greenstone belt and Jingjiagou granulite-gneiss area, is located in the Tieling-Jingyu paleouplift, anticline of Liaodong Platform, eastern section of the northern margin of North China Platform. Granitic rocks which account for more than 70% mainly include gneissic granitic rocks, belonging to plutons before metamorphism and deformation of greenstone belts, and series of granodiorite, tonalite and potassic granite, products of synorogenic magmatism of metamorphism and deformation. The basement of greenstone belts is high amphibolite/granulite facies metamorphic rocks, which are hosted in granitic rocks in xenoliths with different sizes in the Archean high gradeterrane. The Sm-Nd whole-rock isochron age of supracrustal rocks in Qingyuan high gradeterrane is 3018 ± 20 Ma, belonging to Middle Archean. The Sm-Nd whole-rock isochron age of Qingyuan greenstone belts is 2844 ± 48 Ma. The isotopic ages of symbiotic granitic rocks with greenstone belts are mostly concentrating at 2505Ma~2587 Ma. These data indicate that this area is one of the distribution areas of the oldest rocks in China.

In the north of greenstone belts, the Xianjinchang-Qingyuan dome is located, with ore-bearing rocks of thin interbedded belts, in the upper of Tongshicun formation, Anshan group, forming the northeastern Cu-Zn-FeS₂ metallogenic belt, including Dahuanggou Cu-Zn-bearing FeS₂ deposit, Baizigou Cu (Zn) deposit, etc. The Yangzigou dome with an area of 380km², is located in the northwest, with ore-bearing rocks of thin interbedded belts, in the middle of Tongshicun formation, forming the Hongtoushan-Shujigou ore belt, including Cu (Zn) deposits of Hongtoushan, Shujigou, Xibeishan,

Dongnanshan, Liujiazi, etc.

It is discovered through statistical occurrence locations of ore-bearing strata in every deposit (ore point) that, orebodies are consistent with thin interbedded rocks in occurrence, and they are controlled by lithology along layers, showing stratabound characteristics. The ore-bearing rock series have suffered a strong fold deformation, which not only transformed the occurrence of orebodies, but also played the role of ore-controlling and ore-hosting in transformation, forming ore pillars.

The major ore-forming elements in the Hongtoushan deposit are Cu, Zn and Au, and other elements with industrial value include Ag, Cd and Se. Ore minerals mainly include pyrite, pyrrhotite, sphalerite and chalcopyrite, and minor amounts of cubanite, magnetite, galena, rutile, hematite, electrum and molybdenite. Gangue minerals mainly include quartz, plagioclase, biotite, biotite, muscovite, anthophyllite, gahnite, garnet, sillimanite, kyanite and staurolite. Metamorphic hydrothermal altered minerals include phlogopite (or brown mica), cordierite, tremolite, serpentine, epidote, zoisite, chlorite, calcite and quartz.

2 Cycles of volcanic eruption-deposition

Research on the sequence, assemblages and protolith restoration of ore-bearing rock series shows that, the original rock in this area is constructed by a set of basic-intermediate-acidic lava, pyroclastic rock, tuffaceous sandstone, argillaceous sandstone and clay rocks. The volcanic eruption-deposition has an obvious cyclicity and can be divided into three big cycles and nine subcycles. In the whole volcanic eruption-deposition process, basic volcanic rock accounts for about 50%, acidic volcanic rock about 30%~40% and sedimentary rocks about 10%~20%. This demonstrates that basic volcanic eruptions are quite frequent. Mineralization mainly occurs in three cycles: Cycle I, equivalent to the lower section of

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Tongshicun formation (Shujigou rock section), hosts Cu-Zn deposits of Shujigou, Dongnanshan, Xibeishan and Huajiagou; Cycle II, equivalent to the middle section of Tongshicun formation (Hongtoushan rock section), hosts Cu-Zn deposits of Hongtoushan, Hongqishan, Baizigou and Zhanghuzigou; and Cycle III, equivalent to the upper section of Tongshicun formation (Dahuanggou rock section), hosts Dahuanggou Cu (Zn)-bearing pyrite deposit. Every cycle can be divided into three evolution stages: in the early stage, the outpouring of thick layered mafic lava, containing eruption of basic, intermediate-basic and intermediate-acidic tuff, formed the rock combination dominated by tholeiite, with weakly disseminated pyrite and copper mineralization; in the middle stage, the eruption of thin layered basic, intermediate-basic lavas and tuffs and dacite tuffs, containing deposition of tuffaceous sandstone, argillaceous sandstone and clay rock, formed the special thin interbedded band (also known as ore-bearing sock series) rock combination, which repeatedly emerged with great regularity; in the end stage, volcanic clastic rock and sulfide were erupted, forming the "Hongtoushan-type" massive sulfide Cu-Zn deposits.

Through field survey, relatively complete volcanoclastic rock is found. The volcanoclastic rock with three layers is directionally arrayed in shapes of lens and nodules, and intercalated in thin interbedded band. Clastic materials with a size of $10 \times 5 \times 1.5$ (cm) in general include volcanic bombs, volcanic lapilli and volcanic cake. They are cemented by intermediate-acid dacite, clayey rocks and dacitic tuff (converted to biotite quartz gneiss and biotite plagioclase under metamorphism). The boundary between volcanoclastic rock and wall rock with a basically identical occurrence is quite clear. Main minerals of volcanic clastic materials are quartz, followed by minor amount of sillimanite, sericite and garnet, and accessory minerals include epidote, zircon, apatite and pyrite. The majority of quartz particles are flattened and elongated. Volcanic clastic materials are probably near craters. It can be proposed that the Hongtoushan and Shujigou deposit should be located in the ancient volcanic apparatus.

The interpreting information of airborne and satellite images shows that the Hongtoushan deposit and the Shujigou deposit are both located in annular structures. Deposits are in linear distribution and punctate occurrence in the ore belt. Ore-bearing volcanic-sedimentary rock series are oval in shape, and acidic volcanic rock lies in the central part where deposits occur. Volcanic breccia lava composing wall rock of orebodies is limitedly distributed, and breccia is regularly aligned. These phenomena indicate that the distribution of massive sulfide copper (zinc) deposits is controlled by volcanic

apparatus.

3 Geochemistry characteristics

3.1 Trace elements

In the ore-bearing rock series of Tongshicun formation in the Hongtoushan mine, Cu and Zn are pervasively enriched; Ni, Cr, Co and V are generally enriched in every layer, but Ni content is low in ore-bearing rock series; the content of Ti, Ba and Mn is pervasively lower than the Clark value of each in every layer; the content of Pb with little change is close to the Clark value. Orebodies are always located in the range of 10~150m up the roof interface of the amphibolite layer. The apparent dependency in space indicates that ore-forming materials may come from the submarine volcanic eruption of deep basic magma in the late, and the deposition of sulfide orebodies is mainly accomplished in sedimentary evolution process.

In ore of the Hongtoushan deposit, Cu, Zn, S, Bi, Cd, Ag and Se with hundreds of concentration Clark value are extremely concentrated, especially Bi and Se, with concentration Clark value of 640 and 13111 respectively; Pb, Co, Sn, In and As with concentration Clark value of less than several decades are generally concentrated; Ni, Cr, V and Ti with concentration Clark value of less than one are not concentrated. The features reflected by the trace elements in ore are similar to those in the ore-bearing rock series, showing that strata and ore-forming materials have common sources, namely volcanic eruption. Therefore, it can be concluded that the Hongtoushan deposit is syngenetic of volcanic sediment and it is closely related to ancient volcanic apparatus. Trace elements are in zonation. From the centre of ore pillars and main orebodies to the both sides of the deposit, the content of Cu-Zn turns from high to low and multielement combination turns into single element from multiple elements horizontally. Other elements in apparent zonation include Ag, Cd, Se, Te, Co, etc.

3.2 Halogen elements and mercury

The halogen element analysis of 133 samples acquired at -707 level in Hongtoushan deposit shows that concentration Clark values of F, I and Cl in orebodies are 0.422, 7.18 and 4.138, respectively, while in ore-bearing rock 0.398, 1.82 and 2.492. Further, there is a great disparity between the highest content of halogen elements in orebodies, with F, I and Cl of 2.93, 52.6 and 5.16, respectively, and their background value in wallrock.

Derived from the volcanism, mercury mainly occurs in sulfide. The measurement result of Hg gas in soil in Shujigou area shows that there is an apparent halo

abnormity of Hg gas, with diffusion halo 40~100 m in width, above the known concealed orebody, 30~150 m in depth. This abnormity occurs both in the hanging wall and footwall of orebody in asymmetry distribution, with far greater size than abnormity of Cu-Zn in soil. It can be proposed that Hg is involved in the formation of Hongtoushan-typed deposits, and diffused under later geological processes.

3.3 Sulfur isotope, lead isotope and REE

The sulfur isotope composition in Hongtoushan copper-zinc deposit is stable. The δS^{34} is less than 3‰, in narrow range, generally at 0.3~1.5‰. The vast majority of values are positive, minority negative. The composition is uniform and it mainly enriches heavy sulfur, with light sulfur as auxiliary. The average value of sulfur isotope in this area is 0.81‰ that is close to aerolite sulphur, indicating that ore-forming material comes from the upper mantle. The δS^{34} value of orebodies in the Hongtoushan deposit has obvious vertical zonation, manifested as the fact that the value increases gradually with the increase of depth. The value increases from 0.1 at the 430 level in the shallow to 1.02 at -527 level in the deep. The δS^{34} value also has horizontal zonation from the pillar to the edge in the trend and inclination of orebodies. The pillar enriches δS^{34} while the border orebody enriches δS^{34} . It can be concluded that the zonation of sulfur isotope is caused by the gradual annealing of sulfide from the crater to the edge with the decrease of temperature, which can also prove that mineralization is controlled by volcanic apparatuses.

The Pb isotope research shows the ancient volcanic features of this deposit. Through the evolution curve for the single-stage growth of normal lead, the characteristic of the anomalous lead model in continuous evolution is observed. The ore-bearing rock experienced a great heat event in 2545Ma~2261Ma. In addition, lead isotope of the Hongtoushan deposit and its periphery copper or gold deposits has a large composition range, but in good linear relationship, which may be the result of volcanic rock under homologous evolution. In contrast, the lead isotope composition of VMS deposits within the Abitibi ore belt, Canada, is commonly homogeneous within a single district, but such isotopic compositions are quite different between districts.

The REE pattern of metamorphic rocks in Qingyuan greenstone belt is enriched in LREE, with the mean value of (La/Yb)_N of 4.39, slightly negative Eu anomaly, and the mean value of Eu/Eu* of 0.92, similar to TH₂ basalt. The REE of amphibolite gneiss in the ore-bearing rock series also show the characteristics of volcanic rocks, more similar to alkali basalt. These further show that the ore-bearing rock series consist of volcanic rocks with

cycles, in evolution from basic to acidic volcanic rocks, and mineralized in acidic volcanic rocks.

4 Mineralization

The Hongtoushan massive sulfide deposit, formed in Archean, is closely related to submarine volcanic activity. It may be formed in the extrusion dominated micro expansion environment at weak tectonic belt caused by subduction of oceanic plate. This area has gone through three major cycles and nine sub cycles, of which the larger three ones are related to mineralization. These cycles have a strong similarity, with each end member beginning with basic basalt and ending up with normal sedimentary rocks. Deposits are distributed around ancient volcanic apparatuses, and volcanic rocks have features belonging to calc-alkaline basalt of island arc in the continental margin. Ore-forming materials come from mantle brought by submarine volcanic activity, and the fluid formed by volcanic eruption together with sea water made up of the main fluid in the process of sulfide accumulation. Elements combinations include the most basic combination consisting of ore-forming elements of Cu, Zn, Au and Ag, rare element combination consisting of Cd, In, Bi, As, Te and Se, and remote element combination consisting of F, Cl, I and Hg, which indicates the involvement of seawater in mineralization. Formation of the Hongtoushan deposit consists of three major stages: Stage 1, forming of ore-bearing formation. At Neoproterozoic about 2800Ma-2600Ma, the subduction of oceanic crust induced continental margin rift, where a strong undersea volcanic eruption occurred and a bimodal volcanic rock association mainly composed of mafic-felsic volcanic rock formed; Stage 2, enrichment of ore-forming materials. In volcanic eruption interval, the intrusion of subvolcanic rock drove convective circulation of hydrothermal solution. Mixed hydrothermal fluid reacted with original volcano-sedimentary formation and leached ore-forming materials out. When the ascending flow along fault system mixed with cold sea water, ore-forming material stacked into mineralization; Stage 3, deformation and metamorphism. At the end of Archean (2500 Ma), owing to the intrusion of TTG rock under continental environment, the greenstone and massive sulfide ore bodies were both subjected to metamorphism and deformation at amphibolite facies. The Deformation dominated by plastic deformation led to a great change of orebody, and even to a large-scale physical migration, namely "metamorphic physical replacement", forming ore pillars.

Key words: Hongtoushan, massive sulfide deposit, Archean, granite-greenstone terrane, metallogenesis