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Mineralogy and mineral chemistry characteristics of garnet for prospecting and water-soluble mining of skarn polymetallic deposits

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ABSTRACT

The aim is to find skarn polymetallic deposits more accurately. Firstly, the mineralogical and mineral chemical characteristics of garnet are analyzed and studied. Then, the typical skarn deposit is analyzed by means of electron probe, laser inductively coupled plasma mass spectrometry and the mathematical model of rock salt water solution mining. The results show that garnet is one of the main minerals in the skarn polymetallic deposit, and its shape is beneficial to the stability of the roof of the solution cavity. The dissolution rate around the injection well is about 2~3 times that around the outlet well. With the extension of the dissolution and production time, the dissolution rate of the rock salt layer in the whole dissolution chamber decreases. After nearly 100 h of dissolution and production, the dissolution rate around the outlet well is almost zero. The dissolution rate around the injection well decreased to less than 0.1 cm/h. SiO_2 content is generally around 35%, and gradually increases during the formation of the deposit. According to the characteristics of garnet, the polymetallic content and deposit type of skarn deposit are analyzed and calculated, so as to determine the value of skarn deposit. This exploration is of great significance to the prospecting behavior of skarn polymetallic deposit.

Keywords: Garnet; Mineralogy; Skarn; Polymetallic deposits; Mineral chemistry; Prospecting indication

1. Introduction

Skarn polymetallic deposit is one of the crucial sources of W, Sn, Cu, Fe, Zn and other metal minerals in the world, and one of the most widely distributed deposits with high economic value in the world. To find this kind of skarn polymetallic deposit, scholars in China and foreign countries have been deeply studying its characteristics [1].

Group of crack control of the well water soluble extraction method by using hydraulic fracturing cracks along the fracture surface area expanded, and the migration of underground water solution can in the group of inter-well implementation of the regulation, the characteristics of layout at the same time in the salt deposit in many Wells (at least four), choose a well near the middle as fracturing Wells, all the rest as the goal, implementation of hydraulic fracturing well connected; After the group of Wells are connected to form a well pattern, brine production begins. Fresh water is injected in the central original fractured well, and all the surrounding original target Wells produce brine. In the process of production, the water injection well and production well are constantly regulated according to the parameters such as the dissolution thickness of rock salt seam, the brine concentration of the water injection well, the pressure of the water injection well and the dissolution time between Wells, so as to implement the controlled dissolution mining of rock salt seam. The advantages of the method are as follows: according to the information characteristic parameters of surface production, by regulating the water injection pressure and the migration route of solution in the cavity, the controlled water solution mining of rock salt deposit can be realized. Compared with other mining methods, the production cost can be greatly reduced and the recovery rate can be improved. At the same time, because it can control the development of rock salt cavity, it is of great significance to prevent the surface subsidence and to build underground oil and gas storage in rock salt seam.

Garnet minerals in skarn deposits are selected as the research object based on the existing data. The mineralogical and mineral chemical characteristics of garnet are analyzed and studied. The main trace elements in the in situ micro areas are analyzed to reveal chemical characteristics inside garnet, and clarify the physical and chemical conditions and ore body characteristics. The formation reason and origin are discussed [2,3]. The significance of garnet to skarn polymetallic ore field and its directivity to the exploration of polymetallic deposits are evaluated.

2. Mineralogical and mineral chemical characteristics of garnet

2.1. Skarn polymetallic deposit

Skarn polymetallic deposit is a deposit formed by hydrothermal metasomatism of ore-bearing gas on or near the contact zone between intermediate acid - intermediate basic intrusive rocks and carbonate rocks. It is one of the deposit types with crucial industrial significance, and is widely distributed in the world.

In skarn polymetallic deposits, garnet (grossular-andradite), pyroxene (diopside and hedenbergite) and silicate minerals of Ca, Mg, Al and Fe are the constituent minerals. The shape and occurrence of skarn polymetallic deposits in China are also relatively complex. The common forms include layered, nested, lenticular and veined, and their scale is also very inconsistent. The huge ore body covering 1,000 m usually contains various gold materials [4].

According to the formation mechanism of the deposit, skarn can be divided into metasomatic skarn and metamorphic skarn. Metamorphic skarn can be further divided into calcic skarn, magnesium skarn, manganese skarn and alkali skarn [5]. Table 1 presents the information data of these types of skarn deposits.

In Table 1 different types of metamorphic skarns have different shapes, mineral compositions and related metal mineralization. The specific types of skarns can be determined according to these differences.

The mineral composition of the deposit reflects the type and genesis of the deposit. The minerals formed in skarn polymetallic deposits are different in different periods and under different conditions, making each deposit form a unique mineral assemblage. The study of these minerals will be conducive to analyzing the rich materials of the deposit, so as to judge the value of the deposit. Garnet is one of the minerals with obvious characteristics, and its analytical research has been continuing. It is also the mineral with the highest mineral content, and its element content is one of the crucial indicators to judge the type of deposit [6].

2.2. Mineralogy of garnet

Garnet is the general name of a group of inverted silicate minerals in the isometric system, most of which are rhombic dodecahedron, tetragonal trioctahedron or a

Fig. 1. A garnet specimen.

Table 1
Classification of metamorphic skarn

Metamorphic skarn	Morphology and mineralization
Calcic skarn	It can be layered, layered-like, lenticular, saccular and irregular in shape. The common mineral composition is garnet of Ca-Fe or Ca-Al series, which is closely related to the mineralization of W, Sn, Cu, Fe and other metals.
Magnesium skarn	It is composed of aluminum diopside, spinel, forsterite, phlogopite and other magnesium-rich and aluminum-rich silicate minerals. The mineralization is often accompanied by the mineralization of Fe, Cu, Pb, Zn, Be, W and other metals.
Manganese skarn	There are manganese calcium pyroxene, ferromanganese pyroxene, manganese aluminum pyroxene and manganese andalusite, and other silicate minerals containing calcium and manganese, which are usually related to the mineralization of Pb-Zn (Cu-Ag) and other metals.
Alkali skarn	It is mainly composed of aegirine, aegirine pyroxene, arfvedsonite, potassium feldspar and other minerals rich in sodium and potassium, which are closely related to the mineralization of Th, U, Nb and REE.

combination of the two. Fig. 1 shows the mineral morphology of garnet.

The mineral form shown in Fig. 1 is one of the garnet forms. There are several kinds of minerals in garnet under different conditions, and the grain size of each kind of garnet varies greatly. The coarse-grained garnet is more euhedral, while the fine-grained garnet is xenomorphic-granular or hypidiomorphic-granular. The results of the grain size analysis of garnet show that the roundness of minerals gradually decreases from pyrope to almandine, to grossular, and then to spessartine-garnet. The difference is mainly caused by the rocks in the source area of the deposit [7,8].

It is influenced by the paragenetic association of protolith minerals, mineral particles and their chemical composition, which is reflected in the types, chemical composition and morphology. All these can be used as one of the bases for the study of skarn polymetallic deposits.

2.3. Chemical characteristics of garnet minerals

The chemical formula of garnet is generally $A_3B_2[SiO_4]_3$, where A represents divalent cations such as magnesium, iron, calcium and manganese; B stands for trivalent cations, such as aluminum, iron and titanium. The chemical composition of garnet can reflect its color and chemical properties, and Table 2 displays the specific corresponding color.

Table 2 shows that different types of garnets have different chemical compositions, which can be directly reflected from the color level. Some garnets can be directly judged from the color.

The color of garnet varies greatly, and other characteristics are also quite obvious. The fracture is uneven when there is no cleavage. When there is glass luster or diamond luster, the fracture is oil luster and translucent. As a chemically stable mineral, garnet is brittle but not easy to be weathered. Its Mohr hardness is between 6.5 and 7.5 and specific gravity is between 3.32–4.19. These characteristics are the basis for distinguishing garnet [9].

2.4. Mathematical model of water soluble mining

At the same time, the rock salt cavity is constantly deformed and destroyed, and even the ore layer is sinking. Therefore, this is a typical solid-fluid coupling problem, its mathematical models include: salt solution migration equation, concentration diffusion equation, rock mass and fracture deformation equation [10].

2.4.1. Migration equation of salt solution

The migration of water in the cavity can be expressed by the continuity equation

$$\mathrm{div}(\ell q)=\frac{\partial(n\ell)}{\partial t} \tag{1}$$

In the three-dimensional state, taking natural coordinates, the seepage constitutive equation along the boundary surface of the cavity is:

Table 2
Color of different garnets

Garnet type	Garnet color
Pyrope	Purple-red, rose red
Almandine	Reddish brown, orange red
Spessartine	Crimson
Grossular	yellowish brown, yellowish green
Andradite	Brown, yellow green
Uvarovite	Bright green

$$q_1=k_f\frac{\partial p}{\partial s1}\qquad q_2=k_f\frac{\partial p}{\partial s2}\qquad k_f=\frac{w^3}{12\mu} \tag{2}$$

$$\frac{\partial(n\ell)}{\partial t}=\rho\frac{\partial n}{\partial t}+n\frac{\partial \rho}{\partial t}=\rho\frac{\partial w}{\partial t}+n\ell\frac{\partial p}{\partial t} \tag{3}$$

Substituting Eqs. (2) and (3) into equation (1) can be obtained

$$k_f\frac{\partial^2 p}{\partial s1^2}+k_f\frac{\partial^2 p}{\partial s2^2}=\rho\frac{\partial w}{\partial t}+n\ell\frac{\partial p}{\partial t} \tag{4}$$

where p is the water pressure in the cavity; w is the height of the cavity; k_f is permeability coefficient; N is void fraction; S_1 and S_2 are tangential directions of fractures natural coordinates.

3. Analysis and study on prospecting of skarn polymetallic deposit by garnet

3.1. Relationship between skarn deposits and mineralization

The results prove that the types of garnet in skarn polymetallic deposits with different rationality are also different. Fig. 2 can be obtained after the summary of data information.

Fig. 2 reveals that the mineralization of different garnets and metals is also different, and there are corresponding metal types. The general deposit type can be judged based on garnet, and then the deposit type can be further determined by other means.

3.2. Analysis of major and trace elements in garnet

Fig. 3 shows the Sn content of the same garnet.

Fig. 3 shows that the Sn content in different locations is significantly different when the element information of the same garnet is detected. The formation of trace elements in garnet in different regional deposits is different. The growth rate of garnet and formation mode of trace elements can be determined according to the correlation between trace elements and entry mode.

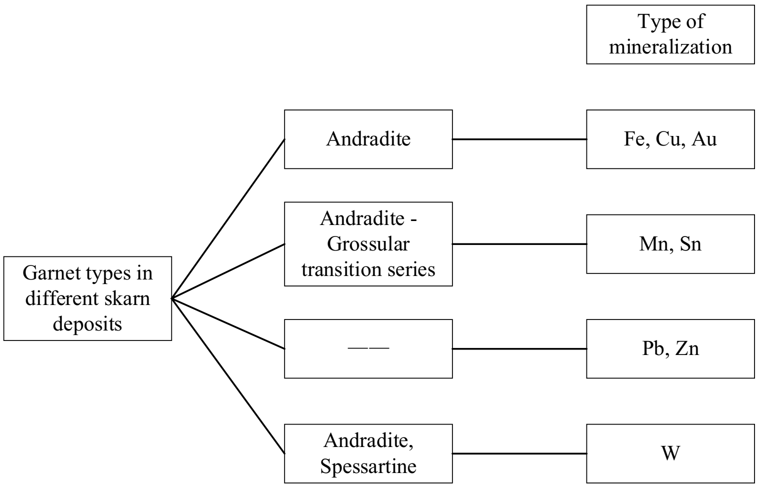

Fig. 2. The relationship between garnet and mineralization in different types of skarn polymetallic deposits.

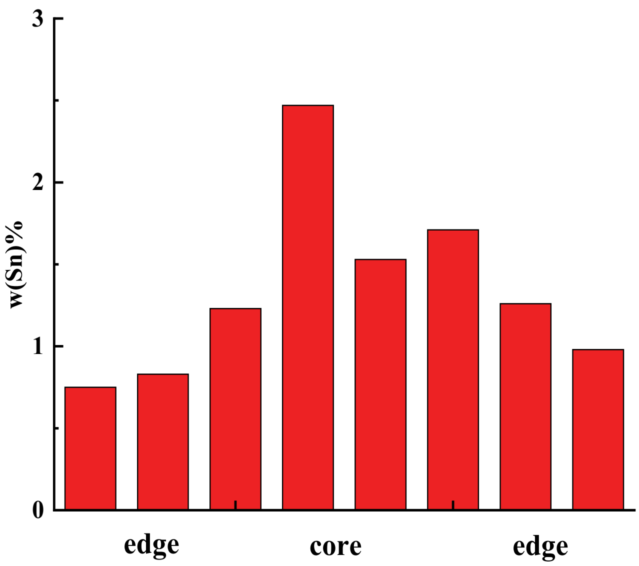

Fig. 3. Sn content in garnet.

Due to the constraints of valence state and ion radius, those entering garnet crystal with isomorphism can only replace divalent cations, and the radius of calcium ion is relatively large. Thereby, it is difficult to be replaced by other iron ions or manganese ions, and the valence conservation should be maintained in the whole isomorphism substitution process [11].

The major elements of garnet are closely related to the geographical environment of skarn polymetallic deposits. Hence, the contents of major and trace elements in two different skarn polymetallic deposits are compared, as shown in Table 3 below.

Table 3 suggests that the contents of major elements in garnets from different two areas are different. The source area of the garnet and the metal elements in the skarn polymetallic deposit can be judged by comparing these values. The content analysis of other trace elements in the deposit reveals that there are great differences in trace elements in various regions, and the content of trace elements fluctuates greatly in a certain range.

Table 3
Major element contents (W%) and trace elements (×10^{-6}) of the deposit

Major element contents	Jiama copper polymetallic ore in Tibet	Dulong tin zinc polymetallic ore
SiO_2	35.7%–36.7%	34.9%–39.2%
CaO	33.4%–35.0%	33.3%–37.6%
FeO	23.9%–29.5%	5.5%–28.3%
Al_2O_3	0–4.0%	0.2%–18.6%
MgO	0.01%–0.2%	0.01%–2.00%
MnO	0–0.4%	0.2%–0.9%
Zn	–	1.0–30
Ti	0.5–5.2	0.1–0.8

Before the implementation of the trace element experiment in garnet, it is also analyzed and inferred based on the mineral chemical characteristics of garnet. Along with the characteristics of garnet mineralogy and skarn deposit, the source of garnet can be inferred, the ore-bearing protolith and ore location can be explored, so as to judge the formation area of the deposit, and indicate prospecting indirectly or directly. In recent years, the element content of garnet in skarn polymetallic deposits has also become an important indicator of mineralization and prospecting as the application of in-situ microanalysis technology, and it has a crucial significance in the whole process [12].

3.3. The significance of skarn and garnet in the metallogenic environment

The results reveal that the chemical composition of garnet in different skarn polymetallic deposits can not only invert the physical and chemical environment of the fluid migration process, but also indicate the mineralization type of the deposit. Most researchers believe that if the skarn deposit is dominated by grossular, there may be W, Mo and

Sn deposits; if it is dominated by andradite, there may be iron ore deposits or polymetallic deposits.

The research data also show that garnet is mainly formed in four different ways: submarine exhalative sedimentation, regional metamorphism, magmatism and hydrothermal metasomatism. The components and characteristics of garnet formed by each way are also different. For example, the formation of garnet under submarine exhalative sedimentation is closely related to the content of Fe and Mn in seawater. The skarn deposits formed are characterized by reverse zoning as long as they are almandine and spessartine-garnet. The endmember of garnets formed by regional metamorphism is primarily categorized as almandine, spessartine-garnet and grossular, and the skarn deposits formed by the same way also have obvious characteristics of positive zoning. Garnet with andradite and grossular as the endmember is formed under hydrothermal metasomatism, and the formation time of the two is different [13].

In the same time period, the dissolution thickness around the injection well is about 1.5 times of the average dissolution thickness in the solution cavity, and the dissolution thickness at the injection well reaches about 0.5 m after 100 h of dissolution. The injection well is approximately more than 70m away from the production well, and the dissolution rate is slow and the cavity becomes narrow near the production well [14]. The dissolution rate around the injection well is about 2~3 times that around the outlet well. With the extension of the dissolution and production time, the dissolution rate of the rock salt layer in the whole dissolution chamber decreases. After nearly 100 h of dissolution and production, the dissolution rate around the outlet well is almost zero [15]. After 300 h of dissolution, the dissolution rate around the injection well decreased to less than 0.1 cm/h. In production, well adjustment should be carried out timely according to the situation of dissolution and recovery, which is not only beneficial to the development of the shape of dissolution cavity, but also can greatly increase the concentration of solution, improve production efficiency and improve the recovery rate of resources [16].

4. Conclusion

The genesis of skarn polymetallic deposit, the characteristics of garnet and the water-soluble mining are comprehensively analyzed and studied. The results show that the garnet minerals are directly or indirectly related to the ore-forming geology of the source region, and can reflect the geological characteristics and mineral-rich deposit information of the source region to a large extent. Deep mining and analysis of the mineralogical information of garnet, study of the mineral chemical characteristics of garnet, can enrich the study of garnet. The dissolution rate around the injection well is about 2~3 times that around the outlet well. With the extension of the dissolution and production time, the dissolution rate of the rock salt layer in the whole dissolution chamber decreases. After nearly 100h of dissolution and production, the dissolution rate around the outlet well is almost zero. After 300 h of dissolution, the dissolution rate around the injection well decreased to less than 0.1 cm/h. It is helpful to trace the formation process, forming conditions and forming location of garnet, and then to determine the location information and mineral content information of skarn deposits, so as to promote the field geological exploration. It can be widely used in the future prospecting process, and continue to play a vital role in the future geological prospecting process.

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