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Advances in Skarn Type Gold Deposits

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Abstract: The distribution of skarn type gold deposit, ore-controlling tectonic setting, ore deposit classification, mineralization alteration zoning and some research methods of ore deposit geochemical are reviewed. Most of skarn type gold deposits located in the Pacific rim, The main ore-controlling tectonic setting are high Angle convergent subduction plate on island arc orogenic belt and craton activation area associated with deep fracture zone. As a major magmatic hydrothermal deposit, Skarn type gold deposits, have the typical phenomenon of ore deposit scale mineralized alteration zoning and the band structure of a single mineral scale. The former has the important instruction significance to guide the prospecting exploration and the latter, which is to understand the evolution of ore-forming fluid and deposit genesis, has great significance. Now, the research for the geochemical characteristic of skarn type deposit gold deposit focuses on mineral phase equilibrium, fluid inclusions, stable isotope and trace element research. The purpose of this paper is to through the analysis of these developments, sets up a study framework of skarn type gold ore deposit.

Keywords: *Skarn type gold deposits, Metallogenic tectonic background, Deposit classification, Mineralized alteration zonation, Geochemistry*

1. Introduction

Skarn is an old term for silicate gangue. These deposits were formed at elevated temperatures with the addition and subtraction of material. They are developed most often, but not invariably, at the contact of intrusive plutons and carbonate country rocks. The latter are converted to marbles, calc-silicate hornfelses and/or skarns by contact metamorphic effects. The calc-silicate minerals, such as diopside, andradite and wollastonite, which are often the principal minerals in these ore-bearing skarns, attest to the high temperatures involved, and various lines of evidence suggest a range of 650-400°C for initial skarn formation, but in some skarns, particularly Zn-Pb, lower temperatures appear to have obtained.[1-3] The pressures at the time of formation were very variable as the depths of formation were probably from one to several kilometres. heavy metals in soil and environmental evaluation has the urgency and realistic necessity.

The mineralizing time of skarn gold deposit is mainly of late Mesozoic, contcmporancous with the collision orogencsis occurred in the mainland of China; the gold orcbodics emplaced in the late stage of the collision orogenesis. Almost all the skarn gold deposits distributed in the collision orogenic belts, fault-magmatic belts and marginal mobile belts, especially in the Lower Yangtze River district. Their metallogenie geodynamic background was the compression-extension transition stage of collision orogenesis. The geological and the geochemical characteristics of the skarn gold deposits and their related igneous intrusions are exclusively coincident with the metallogenic model for collision orogensis or for A-type subduction. It shows that the metallogenic model for collision orogenesis is the oreforming models for the most of the skarn gold deposits, China.[4]

2. The Distribution and Metallogenic Tectonic Background

Skarn (or skarn-type) gold deposits can be divided into gold only, copper–(gold), copper–iron–(gold) and lead–zinc–(gold), with gold only skarn as the most attractive exploration target. Each compositional type has a distinctive set of characteristics and tectonic setting. The bulk of gold probably entered the skarn system during retrograde alteration, concurrent with the main stage of sulphide mineralisation. Skarn gold deposits in China are distributed in various tectonic provinces (Fig. 1) and are hosted in rocks ranging in age from the Palaeoproterozoic to the Triassic. However, the available geochronological data indicate that ore-forming processes took place from the Permian to the Cenozoic (Table 1). The importance of the skarn gold, together with the discrepancy between the age of the host rocks and the spatial–temporal distribution of the skarn deposits, requires detailed studies of ore genesis and of the geodynamic setting(s) of the skarn gold deposits.

3. Genesis of skarn deposits

A common pattern in the evolution of proximal skarns (skarns near or at an igneous contact) has been recognized which takes the form of (1) initial isochemical metamorphism, (2) multiple stages of metasomatism, and (3) retrograde alteration

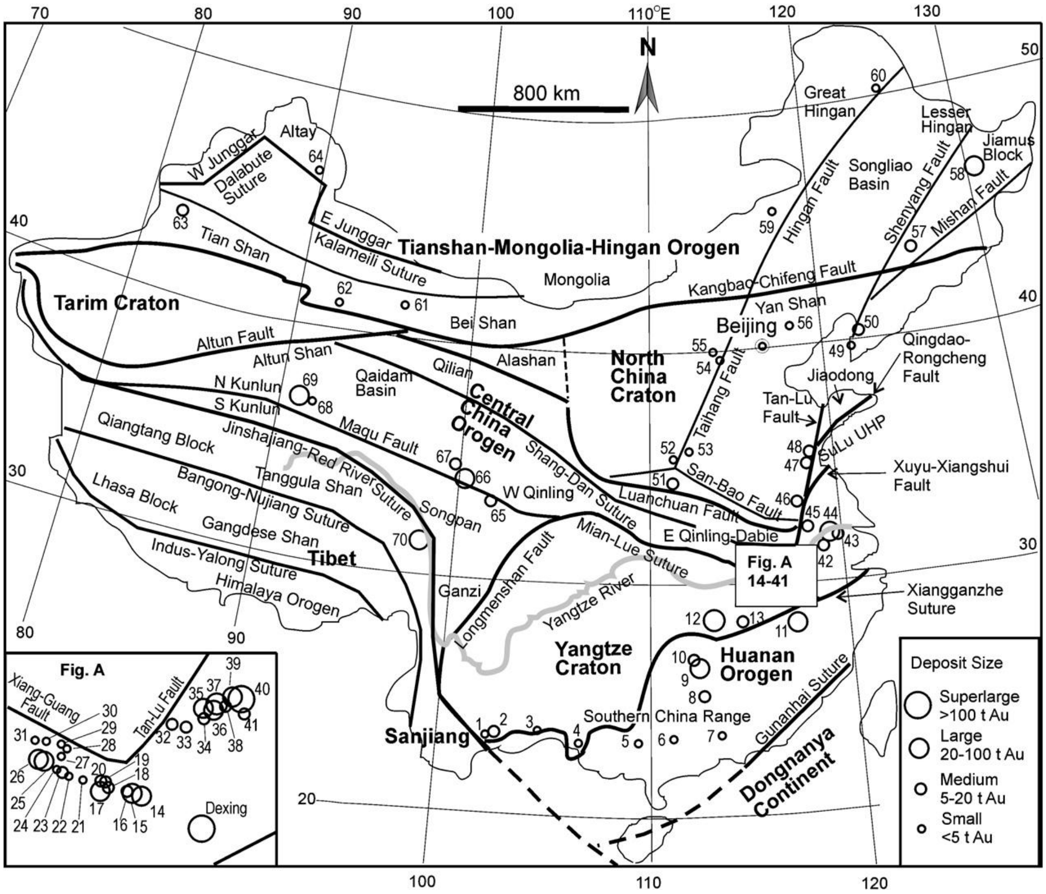

Fig. 1.*Simplified map of mainland China showing tectonic provinces and distribution of 70 skarn gold deposits (Yan-Jing Chen., 2007)*

Stage 1

This involves the recrystallization of the country rocks around the causative intrusion, producing marble from limestone, hornfels from shales, quartzites from sandstones, etc. Reaction skarns may form along lithological contacts. If the marbles are impure then various calcium and magnesian silicates may form and we have a calc-silicate hornfels that might contain minerals of economic interest, such as talc and wollastonite. The principal process involved in this isochemical metamorphism is diffusion of elements in what can be an essentially stationary fluid, apart from the driving out of some metamorphic water. The rocks as a whole may become more brittle and more susceptible to the infiltration of fluids in stage 2.

Stage 2

The infiltration of the contact rocks by hydrothermal-magmatic fluids leads to the conversion of pure and impure marbles, and other roek types, into skarns and the modification of calc-silicate hornfelses of stage 1. This is a prograde metamorphic and metasomatic process operating at temperatures of about 800-400·C [6] during which an ore fluid evolves, initial ore deposition takes place and the pluton begins to cool. The new minerals developed are dominantly anhydrous. Deposition of oxides (magnetite, cassiterite) and sulphides commences late in this stage hut generally peaks during stage 3.

Stage 3

This is a retrograde (destructive) stage accompanying cooling of the associated pluton and involving the hydrous alteration of early skarn minerals and parts of the intrusion by circulating meleOlic waler. Calcium tends to be leached and volatiles introduced with the development of minerals such as low-iron epidote, chlorite, actinolite, etc. Declining temperatures lead to the precipitation of sulphides. The alteration is usually structurally controlled and cuts across earlier skarn patterns with the sulphide deposition often extending beyond the skarn boundaries into marble or hornfels. Here reactions at the marble contact may lead to neutralization of the hydrothermal solutions and the development of high grade sulphide ores. In distal skarns, stage I, or even stage 2, may not be developed and fluid inclusion work suggests formational temperatures of 350-210°C [7]. As some scholars [8] pointed out the degree to which a particular stage is developed in a particular skarn will depend upon its geological environment. The metamorphism during stages 1 and 2 is likely to be more extensive and higher grade around a skarn developed at deep crustal levels than one formed at shallow depths. Conversely retrograde alteration during cooling and the possible influx of meteoric water (stage 3) will probably be more intense at shallow rather than at deeper levels. The origin of all the introduced material in certain skarns, e.g. vast tonnages of iron, has been much debated. The great majority of workers who have investigated these deposits consider that in most cases the pluton responsible for the contact metamorphism was also the source of the metasomatizing solutions. Whilst it is conceivable that a granitic pluton might supply much silica, it might be thought unlikely that it could have supplied the amount of iron that is present in some deposits. However, Whitney have shown that it is probable that in natural magmatic systems, the concentration of iron in chloride solutions coexisting with magnetite or biotite is very high. This high solubility may explain the large quantities of iron in some skarns associated with granitic intrusions. On the other hand, where the pluton concerned is basic, the supply of iron does not present such great problems. These difficulties do become insurmountable, however, for the small class of pyrometasomatic deposits, such as the Ausable Magnetite District, New York State, which have no associated intrusions. Perhaps the main function of the intrusion in some examples is that of a heat engine.

4. Mineral assemblage and alteration zoning

Host rocks these deposits are in carbonate rocks, including limestone or marble, dolomite, and calcareous and dolomitic marble, pelite, argillite, shale, graywacke, and other clastic rocks. In terms of the bedrock type classification of Glass and others [11], most host rocks for these deposit types are type IV; they are highly calcareous sedimentary rocks or metamorphosed calcareous sedimentary rocks that have extensive buffering capacity. Less common host rocks include chert, volcanic flows and volcaniclastic rocks, and metamorphic rocks such as slate or phyllite, quartzite, and amphibolite. These less common host rocks provide low to medium buffering capacity. At the Beal Mountain, Mont., gold deposit, gold-bearing rock is entirely in calcsilicate-bearing hornfels in clastic, quartz-rich host rocks. This deposit is atypical of skarns and may represent a distinct, but related type of disseminated gold deposit in contact metamorphosed rocks.

Although many skarn minerals are typical rock-forming minerals, some are less abundant and most have compositional variations which can yield significant information about the environment of formation Some minerals, such as quartz and calcite, are present in almost all skarns. Other minerals, such as humite, periclase, phlogopite, talc, serpentine, and brucite are typica The advent of modern analytical techniques such as elec-tron microprobe analysis (EMPA) and laser ablation inductively coupled plasma mass spectroscopy (LA-ICPMS) makesit relatively easy to determine accurate in situ mineral com-positions and consequently, to use precise mineralogicalnames. In the study of skarns it is important that mineralogi-cal names are used correctly so as not to imply more than isknown about the mineral composition. For example, the se-quence pyroxene, clinopyroxene, calcic clinopyroxene, diop-sidic pyroxene, and diopside are increasingly more specificterms with defined meanings. Unfortunately, it is all too com-mon in the geologic literature for specific end-member terms,such as diopside, to be used when all that is known about themineral in question is that it might be pyroxene. Wall rock is altered to hornfels (quite widespread in places, and present throughout areas as large as 15 to 20 km), marble, bleached limestone, and skarn zones; potassic, sericitic, argillic, propylitic alteration assemblages are developed and plutons may contain endoskarn. Silica and marble "fronts" (sharp boundaries between unreplaced rock and altered rock) may be present. Ore minerals may be present in massive, stratiform, vein, and (or) disseminated form; grain size is highly variable and ranges from fine to very coarse. Ore may be present in sulfide mineral zones, oxide zones, and in supergene, clay-rich oxidized zones. Sulfide minerals and gold generally are deposited during late, retrograde alteration within zones characterized by hydrous calcsilicates. Retrograde alteration may be best developed along faults cutting paragenetically earlier assemblages. Gold is commonly associated with a late pyrite + quartz assemblage (veins or disseminated).

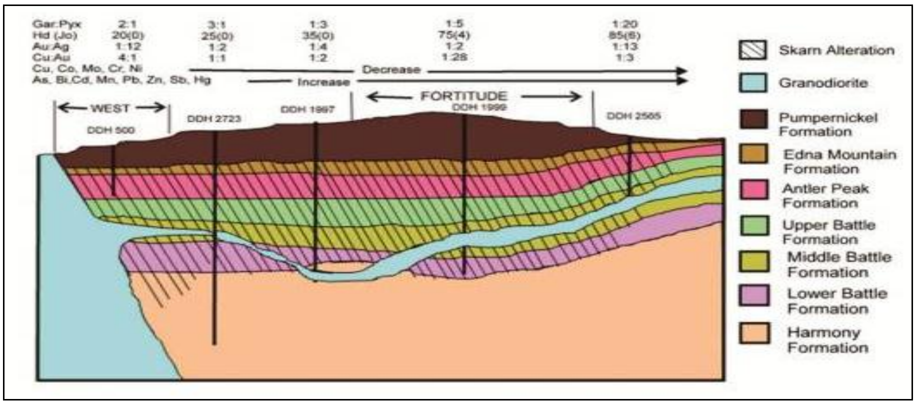

Fig. 2.*The Zonation in Skarn Gold Deposits(Myers and Meinert., 1991)*

Skarn deposits exhibit temporal and spatial zoning that reflects various stages of skarn development. Early formed prograde mineral assemblages are variably overprinted and crosscut by retrograde assemblages. Initial metamorphism forms marble and hornfels, which may be present in extensive surrounding halos. Subsequent metasomatism forms high-temperature, anhydrous calcsilicate assemblages that may be overprinted or cut by lower temperature hydrous assemblages including sulfide minerals (mainly pyrite) deposited under conditions of increased sulfur concentrations.

Prograde-Garnet (andradite-grossular), pyroxene (diopside-hedenbergite), idocrase, wollastonite. Retrograde-Epidote, amphibole, chlorite, prehnite, scapolite, boron minerals, potassium feldspar, clay, siderite. Ore-Gold (electrum), pyrite,pyrrhotite, chalcopyrite, arsenopyrite, magnetite, hematite (specularite), sphalerite, galena, bismuthinite or native bismuth, hedleyite, telluride minerals, molybdenite, and scheelite; gold is present as native gold or electrum associated with pyrrhotite, chalcopyrite, or with quartz-pyrite assemblages.

5. Geochemistry of skarn deposits

Skarn formation spans almost the complete range of potential ore-forming environments. Most geochemical studies of skarn deposits have focused on mineral phase equilibria, fluid inclusions, isotopic investigations of fluid sources and pathways, and determination of exploration anomaly and background levels. Experimental phase equilibria studies are essential for understanding individual mineral reactions. Such studies can be extended using thermodynamic data to include variable compositions). Another approach is to use a self-consistent thermodynamic database to model potential skarn-forming solutions [12-15]. Fractionation of elements between minerals also can be used to estimate conditions of skarn formation. A general review of phase equilibria applicable to skarn systems is presented by Bowman. A more specialized treatment of the vector representation of skarn mineral stabilities is presented by Burt. Recent work has incorporated standard phase equilbria treatment of skarn mineralogy along with fluid dynamics to model the metasomatic evolution of skarn systems Fluid inclusion studies of many ore deposit types focus on minerals such as quartz, carbonate, and fluorite which contain numerous fluid inclusions, are relatively transparent, and are stable over a broad T-P-X range. However, this broad T-P-X range can cause problems in interpretation of fluid inclusion data, because these minerals may grow and continue to trap fluids from early high temperature events through late low temperature events[16-18]. In contrast, high temperature skarn minerals such as forsterite, diopside, etc. are unlikely to trap later low temperature fluids (beyond the host mineral's stability range) without visible evidence of alteration. Thus, fluid inclusions in skarn minerals provide a relatively unambiguous opportunity to measure temperature, pressure, and composition of skarn-forming fluids. Salinities in most skarn fluid inclusions are high; documented daughter minerals in skarn minerals include NaCl, KCl, CaCl2, FeCl2, CaCO3, CaF2, C, NaAlCO3(OH)2, Fe2O3, Fe3O4, AsFeS, CuFeS2, and ZnS .some experts describe systematic variations in NaCl:KCl:CaCl2 ratios in fluid inclusions from different skarns reflecting differences in the fluid source and the degree of mixing of magmatic, connate, and meteoric fluids. In general, magmatic fluids have KCl>CaCl2 whereas high-CaCl2 fluids appear to have interacted more with sedimentary wall rocks.In gold skarns, prograde garnet and pyroxene homogenization temperatures are up to 730¡C and 695¡C, respectively, with salinities up to 33 wt. % NaCl equivalent. In contrast, scapolite, epidote, and actinolite from these skarns have homogenization temperatures of 320-400¡C, 255-320¡C, and 320-350¡C, respectively. In tungsten skarns, prograde garnet and pyroxene homogenization temperatures are up to 800¡C and 600¡C, respectively, with salinities up to 52 wt. % NaCl equivalent. In contrast, amphibole and quartz from these skarns have homogenization temperatures of 250-380¡C and 290-380¡C, respectively with salinities of 12-28 and 2.5-10.5 wt. % NaCl equivalent

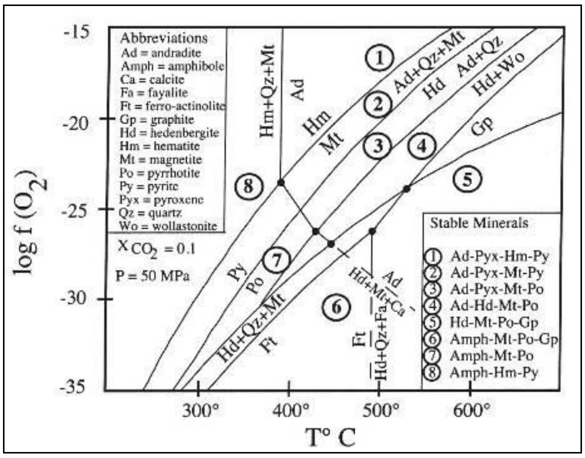

Fig.3. *Temperature-log oxygen fugacity diagram, showing the stability fields of major skarn silicate, oxide, and sulfide minerals(Meinert., 1998)*

Oxidized skarns typically contain associations 1, 2, and 8. Reduced skarns typically contain associations 3, 4, and 7. Metamorphic skarns typically contain associations 4, 5, 6, and 7. Associations 5 and 6 are not stable in oxidized skarns due to the presence of graphite. Associations 1 and 8 are not stable in metamorphic skarns due to the presence of hematite.

Isotopic investigations, particularly the stable isotopes of C, O, H, and S, have been critically important in documenting the multiple fluids present in most large skarn systems The pioneering study of Taylor and

O'Neill demonstrated the importance of both magmatic and meteoric waters in the evolution of the Osgood Mountain W skarns. Bowman et al.[24] demonstrated that in high temperature W skarns, even some of the hydrous minerals such as biotite and amphibole can form at relatively high temperatures from water with a significant magmatic component.

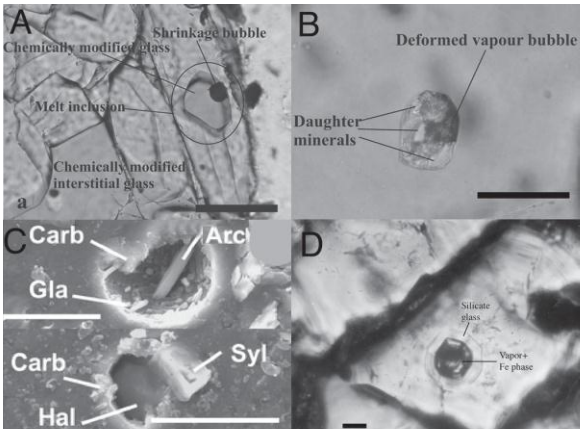

Fig. 5 *Melt inclusions in skarn minerals (Meinert., 2005)*

A. Silicate two-phase (glass + shrinkage bubble) melt inclusion in clinopyroxene from magmatic skarn from 1944 eruption of Mt. Vesuvius, Italy. B. Multiphase (daughter minerals and a deformed vapor bubble) hydrosaline melt inclusion in endoskarn from 472 AD eruption of Mt. Vesuvius, Italy. C. Scanning electron microscope image of exposed melt inclusions similar to (B) containing chlorides (halite [Hal] and sylvite [Syl]), sulfates (glaserite [Gla], and arcanite [Arc]), and Na-Ca carbonate (Carb) D. Melt inclusion in garnet from Tongguanshan, China Fe-Cu skarn

Sulfur isotopic studies on a variety of sulfide minerals (including pyrite, pyrrhotite, molybdenite, chalcopyrite, sphalerite, bornite, arsenopyrite, and galena) from the skarn deposits summarized in Table 2 indicate a very narrow range of ^{34}S values, consistent with precipitation from magmatic fluids. For some of the more distal zinc skarns, sulfur isotopic studies indicate that the mineralizing fluids acquired some of their sulfur from sedimentary rocks (including evaporites) along the fluid flow path.

4. Conclusion

In the past decade, great progress hasbeen made in the exploration and investigation of gold skarn deposits in the world and many large deposits have been discovered. Au-bearing skarn deposits are distributed mainly in the Circum-Pacific metallogenic belt. According to their tectonic settings may be divided into three types: the Mesozoic /Cenozoic fold belts, the Paleo-zoic fold belts, and the shield/platformal areas. The Au-bearing skarns are hosted mainly by Carboniferous-Permian and Triassic carbonate clastic pyroclastic formations, subordinately Tertiary, Cambrian, and et al. The related intrusives are mainly hypabyssal calc-alkaline intermediate and intermediate-acid diorite, quartz monzodiorite, quartz monzonite, granodiorite andthe rocks of their hypabyssal facies. Most of them are of Yanshanian and Himalayan, locally, are of Caledonian or Uariscan. The Au-bearing skarns are chiefly calcic, only a few are magne-sian. The later occurs in the mobile platform or shield. Most of the Au-bearing skarns occur-ring in the island-arc setting consist mainly of hedenbergites and belong to the reducing-type, but in the mobile platform, the Au-bearing skarns are chiefly composed of andradite and diopside, and belong to the oxidizing-type.In the ores, gold is often intimately associated with arsenides, bismuthide, and tellurides. In many Au-skarns occurring in the mobile platforms, the selenides are identified. Therefore, Cu, Au, As, Bi, Te, Ag, Co(Se) are more specific metallic elements for Au-bearing skarns, and referred to as an important geochemical ore-searching indicators. In many gold skarn deposits the mineralized zone is very clear. The comprehensive zonal model from intrusive to carbonate wall rocks is : Cu(Mo)yCu(Fe)yCu(Au)yAuyAu (Pb,Zn,Ag).

The common methods for studying of skarns and skarn deposits both mac-roscopically and microcosmically is including remote sensing interpretation, physical geographical prospect-ing, field geological mapping, petrography (or mineralogy) and mineralogy, mineral phase equilibrium, fluid inclusion and stable isotope, the newmeans developed recently such as remote sensing interpretationand quantitive calculation formineral phase equilibrium are introduced especially. The consideration of in-tegration of macroscopic and microcosmic methods and constant introduction of newmeans in the skarn de-posit studies have important significance in further revealing the formation and distribution of skarn deposits, and understanding their petrogenic and metallogenic mechanism.

5. Perspective

Skarn deposits that enter production today cannot be compared with skarn deposits worked a hundred, or even twenty, years ago. Many currently active mining or exploration projects involving skarn deposits operated at some time in the past at a smaller scale and are currently being re-evaluated for different metals (gold, silver) than were sought in past enterprises. Many abandoned or inactive skarn deposits are the focus of recent exploration because of economic changes or development of modern technology that allows previously uneconomic ore to be mined. For example, skarns that were mined in the past for base metals or tungsten may now constitute exploration targets for gold. Known or potential environmental hazards from historic mining can, in some cases, be mitigated by reopening the site to mining activity that involves reprocessing historic tailings using modern mining practices.

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