

スウェーデン国シェレフテ地域ボリーデン鉱床含金鉱石の 地球化学的特徴

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要旨

スウェーデン国北部シェレフテ地域東部に位置する含金ボリーデン塊状硫化物鉱床は、18.9～18.5億年の火山弧環境で形成された高含金品位（平均15 ppm）の鉱床として知られている。ボリーデン鉱床からの鉱石の化学的特徴は、鉱物組合せ、原子吸光法、PIXE法、ICP-MS法による化学組成に基づいて検討された。ボリーデン鉱床の鉱石は、二つに区分され、再結晶を被った自形～半自形の硫砒鉄鉱、黄鉄鉱、エレクトラムを伴う鉱石と黄鉄鉱、磁硫鉄鉱、閃亜鉛鉱、黄銅鉱、四面銅鉱、車骨鉱、ライタカ鉱、自然ビスマスからなる硫塩鉱物に富む黄鉄鉱－黄銅鉱－閃亜鉛鉱鉱石である。前者は後者に切られる。鉱石のTiO₂含有量とAu含有量の間には正の相関が認められる。また、ルチル（TiO₂）は、ボリーデン鉱床の石英－紅柱石－カオリナイトからなる酸性変質帯に随伴する。鉱物組合せと鉱石化学組成のデータは、金鉱化作用が酸性熱水流体により引き起こされたことを示す。

Geochemical characteristics of gold-bearing ores of Boliden deposit, Skellefte district, Sweden

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Abstract

The Au-bearing Boliden massive sulfide deposit located in the eastern part of the Skellefte district in northern Sweden was formed in a volcanic arc setting at 1.89-1.85 Ga and well known for its high gold grades (average 15 ppm). Chemical characteristics of ores from Boliden deposit were examined in this study based on the data of mineral assemblage and chemical compositions of ore determined by AAS, PIXE and ICP-MS. The ores of the Boliden deposit are divided into two types, arsenopyrite-rich ore consisting mainly of recrystallized euhedral to subhedral arsenopyrite, pyrite, electrum and rutile and sulfosalt-rich pyrite-chalcopyrite-sphalerite ores consisting of pyrite, pyrrhotite, sphalerite, chalcopyrite, tetrahedrite, bournonite, laitakarite and native bismuth which cut the arsenopyrite ores. TiO₂ and Au contents of the ores show a positive correlation. Rutile is also associated with acidic alteration zone composed of quartz-andalusite-kaolinite of the Boliden deposit. Data of the mineral assemblage and chemical composition of ores suggest that the gold mineralization was caused by acidic hydrothermal activity.

1. Introduction

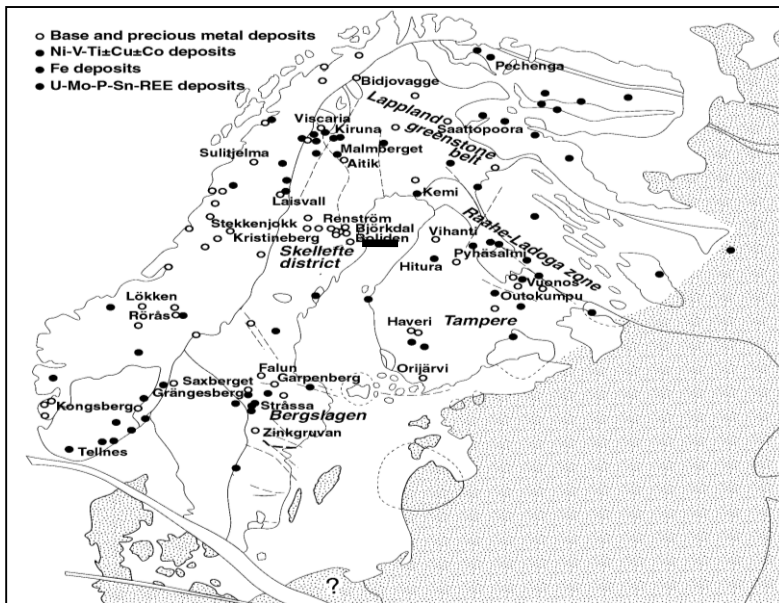


Fig.1 Location of the Boliden deposit in Skellefte district. Modified from Weihed et al. (2005).

The Au-bearing Boliden massive sulfide deposit which was formed in a volcanic arc setting at 1.89-1.85 Ga, is well known for its high gold grades (average 15 ppm) and is characterized by complex mineral assemblages of ore minerals. Earlier studies considered the massive sulfide deposits in the Skellefte district as metamorphosed equivalents of Kuroko-type ores (Rickard and Zweifel, 1975; Vivallo, 1987). In contrast, recent structural and geochemical investigations indicate that the Boliden deposit

may be a high-sulfidation-type epithermal sub-seafloor deposit formed by infiltration and replacement (Allen et al., 1996; Weihed et al., 1996). Particle induced X-ray emission (PIXE) can be used to analyze minute samples smaller than a milligram, not only simultaneously detects elements from Na to U in a short time but also detects major-to-trace elements at the concentration level of ppm (Vaggellia et al., 2003; Saitoh et al., 2002). We examined chemical composition of ores from the Boliden deposit by PIXE and ICP-MS to know the chemical characteristics of the ores based on the relationship between Au concentration and other elements in the ores.

2 Outline of geology

The Boliden deposits are located in the eastern part of the Skellefte district in northern Sweden which has been mined for base and precious metals in the early 1920s (Allen et al., 1996) (Fig. 1). The deposit has mined 8.3 million tons of ore including 128 t of Au, 411 t of Ag, 566,000 t of As, 118,000 t of Cu, and 2.1 Mt of S. The massive sulfide orebodies of the Boliden deposit occur as a set of elongate lenses, obliquely cutting the host rocks structurally. The lenses trend east-west with a roughly vertical dip (Wagner and Jonsson, 2001). Alteration of the Boliden deposit can be classified into two types: sericite-kaolinite-andalusite zone and chlorite zone. The sericite-kaolinite-andalusite zone is surrounded by the chlorite zone. The orebody occurs in the sericite-kaolinite-andalusite alteration zone. The samples used in this study are of upper (Borehole 24) and middle (Borehole 64) positions of orebody.

3 Mineral assemblages of ores

The two different types of ore can be distinguished in the Boliden deposit: arsenopyrite-rich and

sulfosalt-rich pyrite-chalcopyrite-sphalerite ores. The occurrence mode of the sulfosalt-rich pyrite-chalcopyrite-sphalerite ores cutting arsenopyrite ores suggests that the arsenopyrite-rich ores were formed prior to the formation of the sulfosalt-rich ores (Figs. 2B and 2C). The arsenopyrite ores are generally fine-grained (Figs. 2A and 2B). The ores consist mainly of recrystallized euhedral to subhedral arsenopyrite, pyrite, electrum and rutile (Fig. 2A, Table1). The mineral assemblages of sulfosalt-rich ores consist of pyrite, pyrrhotite, sphalerite, chalcopyrite, tetrahedrite, bournonite, laitakarite and native bismuth (Fig. 2D). The gangue minerals are quartz, biotite, muscovite, andalusite, kaolinite, sericite, and chlorite.

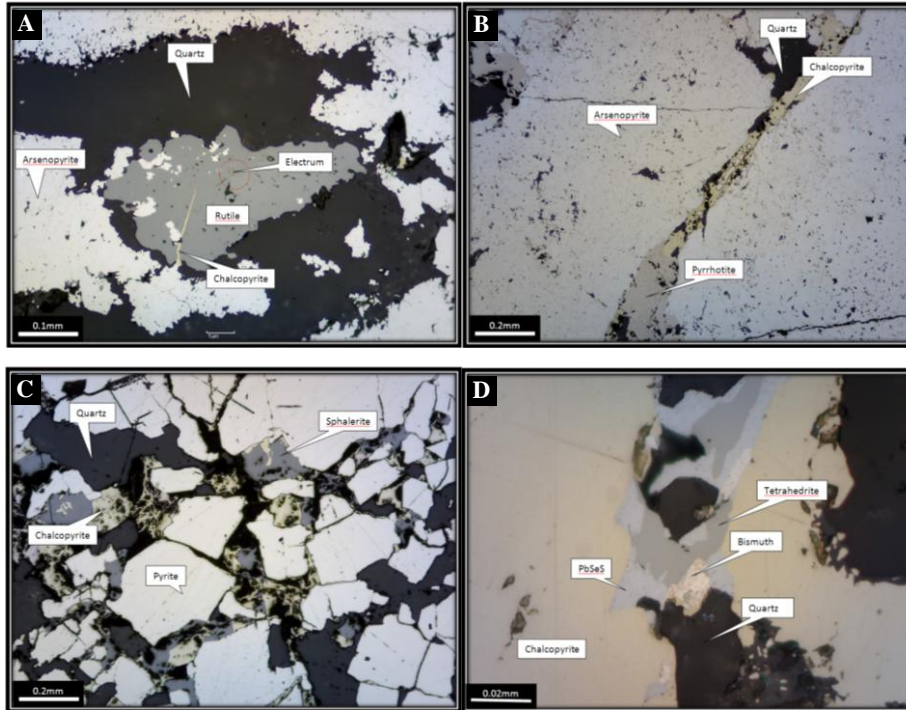


Fig.2. Photomicrographs in reflected light showing representative textural relationship for arsenopyrite-rich ores and sulfosalt-rich ores, Boliden deposit. A. Anhedral rutile crystal enclosing electrum in fine-grained and partially recrystallized arsenopyrite ore. **B.** Typical sulfosalt-rich vein consisting of chalcopyrite and pyrrhotite crosscuts fine-grained massive arsenopyrite containing numerous silicate and sulphide inclusions. **C.** Pyrite porphyroblasts coexisting with sphalerite and chalcopyrite in sulfosalt-rich vein. **D.** The intergrowth of tetrahedrite, bismuth and selenium-galena formed the veinlet occur in massive chalcopyrite.

Table 1. Mineral assemblage of typical ores of Borehole 24 and 64 of the Boliden deposit

Sample	Type of ore	pyrrhotite	pyrite	Arsenopyrite	chalcopyrite	sphalerite	electrum	rutile	quartz
Boliden 24, 99.71-99.73 m	py-cp-rich	+	+++	+	++	++			++
Boliden 24, 138.00 m	py-asp-rich		+++	+	+	+			++
Boliden 64, 14.07-14.09 m	asp-rich			+++	+	+	+	++	++
Boliden 64, 21.80-21.83 m	py-cp-rich	+	+++	++	++	+			++

+++ abundant, ++ moderate, + a few

4 Methods

The rock and ore samples were prepared using PIXE developed by Sera et al., (1999), where the bulk sample was ground into fine powder in an agate mortar. Thin targets were prepared by taking about 0.1 mg of the powder and putting it on a 0.40 μm thick polypropylene film, dropping roughly 1 μl of 10% collodion solution diluted with ethyl alcohol on it to fix the powder, and drying the film through a oven, then keeping the film into the polypropylene bottle. Chemical composition of the samples was determined by PIXE at Nishina Memorial Cyclotron Center (NMCC), Japan Radioisotope Association, using 2.9 MeV protons from a baby cyclotron. Beam currents, the accumulated charge and the typical measuring time were 20-40 nA, 11-19 μC , and 5-10 min, respectively. X-ray spectra were analyzed using the SAPIX program.

Quantitative data were obtained by the combination of data determined by PIXE and Cu and Zn contents of corresponding samples analyzed by AAS. The ore samples examined by PIXE are also analyzed by ICP-MS described by Satoh et al. (1999).

5 Results and Discussion

The analytical results by PIXE and ICP-MS are summarized in Table 2. Ores of the Boliden deposit consist mainly of arsenopyrite. Therefore, Cu, Pb and Zn contents of ores in the Boliden deposit are low and range from 446-19600 ppm, 429-1590 ppm, 28-27200 ppm, respectively. On the other hand, arsenic content of the ores is high for the arsenopyrite-rich ores (maximum content of 249000 ppm), TiO_2 , Ag, Au and Bi contents are also high in the arsenopyrite-rich ores (4940 ppm TiO_2 , 55.0 ppm Ag, 1730 ppm Sb, 36.4ppm Au and 762 ppm Bi). TiO_2 and Au measured by PIXE and ICP-MS shows a positive correlation (Fig. 3). The electrum containing Hg were observed in a rutile crystal in the arsenopyrite-rich ores. The mode of occurrence of electrum accords with the data of TiO_2 and Au contents of the ores. Rutile is also present in altered rocks composed of quartz, andalusite and kaolinite and is thought to be formed by recrystallization of the acidic altered rocks surrounding lenticular orebodies of the Boliden deposit. The positive correlation between TiO_2 and Au suggests that gold mineralization was caused by acidic hydrothermal activity.

Table 2. Chemical composition of ores from the Boliden deposit

Sample	TiO_2	Mn	Co	Cu	Zn	Ga	As	Sr	Mo	Ag	Cd	In	Au	Pb	Bi
Boliden 24, 99.71-99.73 m	39	129	5	7000	27200	33	1860	0.37	2132	4.77	171	14.70	0.31	429	13.2
Boliden 24, 138.00 m	1050	34	184	820	3000	1	6920	1.75	0	8.51	13.5	0.21	7.26	452	13.6
Boliden 64, 14.07-14.09 m	4940	18	480	446	28	2	249000	0.99	645	55	1.55	0.36	36.4	1594	762
Boliden 64, 21.80-21.83 m	718	486	29	19600	1310	21	37900	14.67	0	41.90	12.2	9.96	3.37	453	24.9

TiO_2 , Pb and As contents were determined by the combination PIXE and AAS, concentration of other elements were determined by ICP-MS. unit: ppm

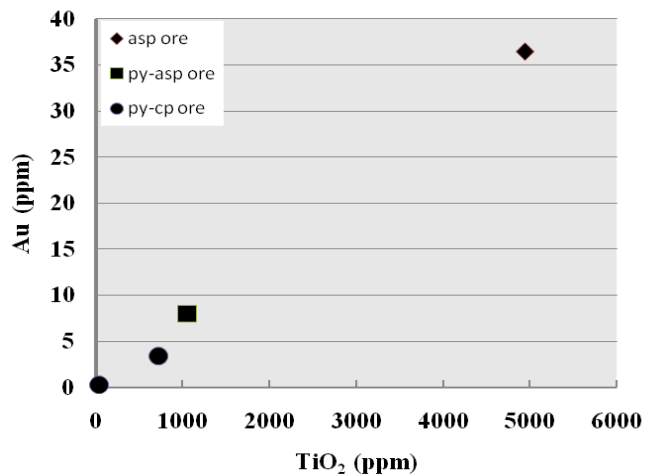


Fig.3 Relationship between Au and TiO₂ contents of different ore types,
Solid diamond: arsenopyrite ore; Solid square: pyrite-arsenopyrite

6 Conclusion

The geochemical characteristics of ores from the Boliden deposit examined on the basis of mineral assemblage and chemical compositions of the ores. The two different ore types can be distinguished in the Boliden deposit: arsenopyrite-rich and sulfosalt-rich ores. The arsenopyrite-rich ores consist mainly of recrystallized euhedral to subhedral arsenopyrite, pyrite, electrum and rutile. The mineral assemblage of sulfosalt ores consist of pyrite, pyrrhotite, sphalerite, chalcopyrite, tetrahedrite, bournonite, laitarite and native bismuth. The positive correlation between TiO₂ and Au contents suggests that gold mineralization was caused by acidic hydrothermal activity.

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