CHAPTER

THE TAIVALJÄRVI Ag-Au-Zn DEPOSIT IN THE ARCHEAN TIPASJÄRVI GREENSTONE BELT, EASTERN FINLAND

9.3

T. Lindborg, H. Papunen, J. Parkkinen, I. Tuokko

ABSTRACT

The Taivaljärvi Ag-Au-Zn deposit is associated with felsic metavolcanic rocks in the Archean Tipasjärvi greenstone belt of eastern Finland. The current owner, Sotkamo Silver Oy, has named it the Silver Mine deposit. The deposit is stratiform and consists of four mineralized layers: the A, B, C, and D bodies. The deposit contains 3.34 Mt of ore reserves (according to the JORC 2012 code) with 0.71% Zn, 0.34% Pb, 102 g/t Ag, and 0.29 g/t Au, as part of 3.5 Mt measured and indicated resource. The content of sulfide ore minerals is low, 5% on average. The main ore minerals are sphalerite, galena, chalcopyrite, pyrite and pyrrhotite, dyscrasite, freibergite, electrum, and native Ag. The deposit displays disseminated and vein-type ore textures. The volcanic host rocks are deformed and metamorphosed at upper amphibolite facies conditions, and the metamorphic mineral assemblages reflect the variation in chemical compositions of the rock sequence. The intense hydrothermal alteration associated with mineralization predated the regional metamorphism, but it can still be recognized in the chemical compositions of the rock sequence. The $\delta^{34}S$ values fluctuate from 2.0–3.8 per mil, indicating a volcanic origin of sulfur. The deposit is a product of hydrothermal activity associated with volcanoclastic felsic eruption, and the type of deposition is assumed to be epithermal in character.

Keywords: Taivaljärvi; Sotkamo; silver; epithermal; Archean; greenstone.

INTRODUCTION

The Taivaljärvi Silver Mine Ag-Au-Zn deposit in eastern Finland is located in the Archean Tipasjärvi greenstone belt (Fig. 9.3.1), in the southern part of a north-trending, about 200-km long and from 3–5 km wide, Tipasjärvi-Kuhmo-Suomussalmi greenstone complex that is a part of the Archean Kianta terrane (Sorjonen-Ward and Luukkonen, 2005). Several studies discuss the geology and geochemistry of the Tipasjärvi belt (e.g., Vartiainen, 1970; Blais et al., 1978; Martin et al., 1983; Taipale, 1983; Martin and Querre, 1984; Luukkonen, 1985, 1988; Piirainen, 1985; Luukkonen and Lukkarinen, 1986; Sorjonen-Ward and Luukkonen, 2005; Papunen et al., 2009; Pietikäinen et al., 2008). Isotope geology and radiometric ages of the area are included in the works of Vaasjoki et al. (1999) and Huhma et al. (2012a).

Mineral Deposits of Finland. http://dx.doi.org/10.1016/B978-0-12-410438-9.00024-8

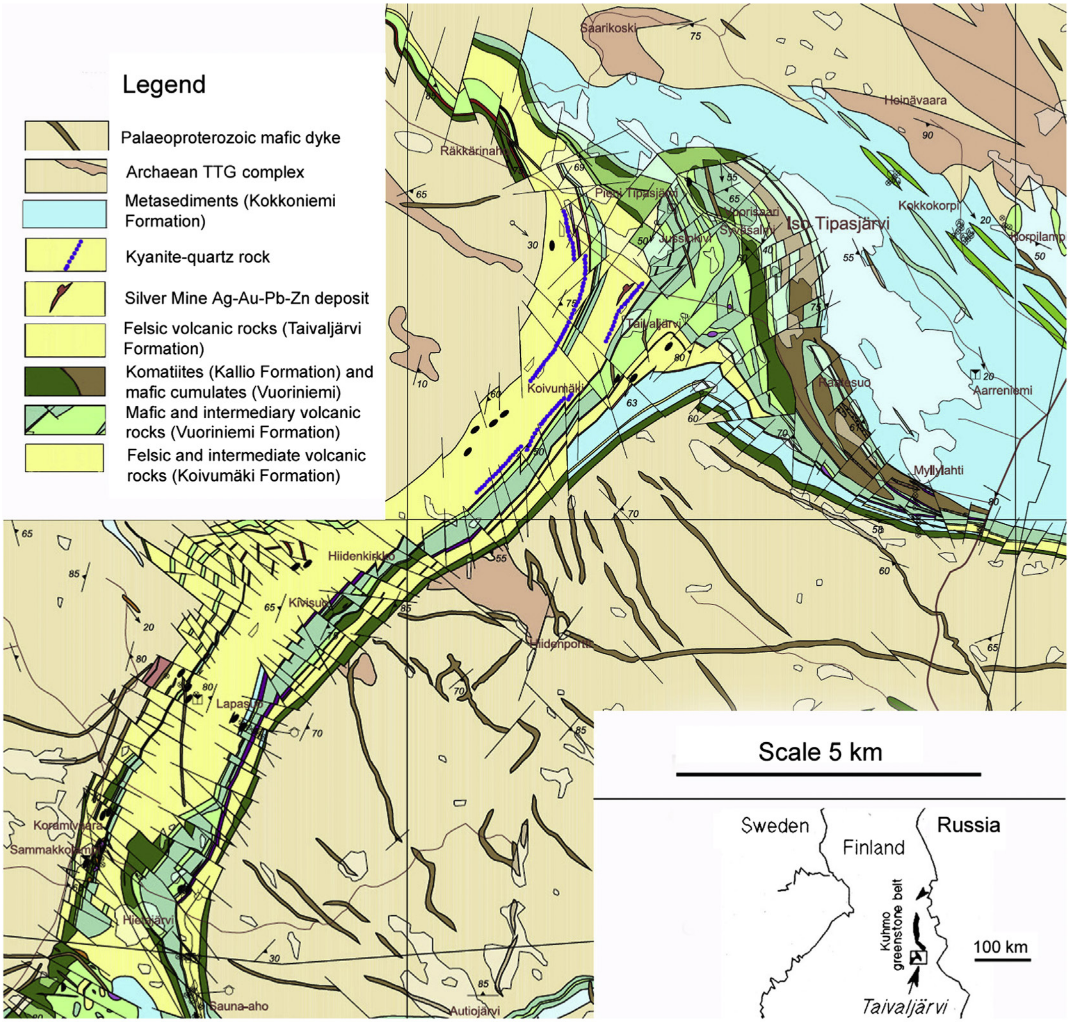


FIGURE 9.3.1 Geology of the Tipasjärvi area and location of the Taivaljärvi Silver Mine deposit.

Source: *The map is from Pietikäinen et al. (2008), with the legend and location of quartz-kyanite rocks added by the authors.*

As late as in the 1970s, the geology and metallogeny of the Archean areas in Finland were poorly known. To initiate further mineral exploration, the Ministry of Trade and Industry financed a research program at Oulu University targeted to basic geological and geochemical studies on the Finnish Archean greenstone belts. During the 1980 summer field season, several sphalerite- and galena-bearing glacial boulders were discovered in the Tipasjärvi area, and shortly thereafter a mineralized subcrop was found in the up-ice direction from the glacial float. At the time of this discovery, the exploration department of Kajaani Oy conducted a geochemical exploration program in the Tipasjärvi area and noted local Zn anomalies in the till. A combination of the boulder and mineralized outcrop information with the geochemical anomaly data guided Kajaani Oy to start diamond drilling, which soon led to the discovery of the deposit. The 400-m-long and up to 110-m-wide subcrop of the Taivaljärvi Zn-Au-Ag ore body was nearly completely covered with till and bog.

In 1988, the prospect was transferred to a joint venture between UPM-Kymmene and Outokumpu Mining Oy, called *Taivalhopea*. From 1988–1991, the Joint Venture (JV) performed additional inventory drilling, concentration tests, mine planning, and completed a feasibility study. To test the beneficiation processes, the JV also constructed a 2600-m-long production decline down to a depth level of 350 m and opened a ventilation shaft to the 340-m level. Due to low metal prices in 1991, the project was put on hold.

In 2005, Silver Resources Oy (at present, Sotkamo Silver Oy) was established. The company acquired the mineral rights and all previous investigation material. It performed additional surface and underground drilling, which now totals approximately 51 km. The company also performed pilot processing tests with excellent results and completed the mineral resource estimate. The mining license was granted in 2011, the environmental permit in 2013, and the detailed technical mine planning is now underway. Production is anticipated to start in 2016. With updated mineral resources, the present owner named the occurrence the Silver Mine deposit.

The area around the Silver Mine deposit is potential for further exploration. From 2005–2007, the Geological Survey of Finland (GTK) performed an extensive exploration program in the Tipasjärvi greenstone belt (Fig. 9.3.1; Pietikäinen et al., 2008). It pinpointed a number of prospects in the voluminous felsic rocks along the western margin of the Tipasjärvi greenstone belt. The Kokkokorpi gold occurrence, the Sauna-Aho zinc occurrence, and the Hiidenkirkko Zn-rich ore boulders and geochemical gold anomalies were considered as the most promising.

REGIONAL GEOLOGY

The Archean granitoid area around the greenstone belt (Fig. 9.3.1) is heterogeneous, varying from stromatic and nebulitic migmatitic gneisses to discrete felsic plutons from tonalite to trondhjemite and monzogranite in composition (Sorjonen-Ward and Luukkonen, 2005). Traditionally, the tonalite-trondhjemite-gneiss (TTG) and granodiorite-granite associations, which surround the Tipasjärvi greenstone belt, have been considered as the basement of greenstone-belt rocks, although they have been reworked and remobilized during metamorphism and deformation (e.g., Taipale, 1983; Papunen et al. 2009; Fig. 9.3.2). However, single-crystal zircon and monazite U-Pb analyses performed with secondary ion mass spectrometry (SIMS) and laser ablation multi-collector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) together with multigrain thermal ionization mass spectrometry (TIMS), have recently become available from the greenstone belts (Huhma et al., 2012a). It is now evident that the bulk of granitoids are younger than the greenstone belt. Signs of older crust have been obtained from migmatitic gneisses at Lylyvaara, east of the Kuhmo greenstone belt (Luukkonen, 1985; Käpyaho et al., 2007). The Sm-Nd data available on the greenstone belt and most granitoid rocks suggest a relatively short crustal residence time for the granitoids (Huhma et al., 2012b).

The greenstone belt was metamorphosed and deformed in several phases, the youngest phase being Proterozoic. Although the rock-forming mineral assemblages are metamorphic, the primary textures are preserved to such an extent that the primary character of the rocks can still be determined. About 80% of the greenstone belt is composed of mafic, ultramafic, and felsic volcanic rocks. The rest is metasedimentary rocks, mica gneisses, banded iron formation, black schists, and mafic–ultramafic intrusive rocks (Piirainen, 1985).

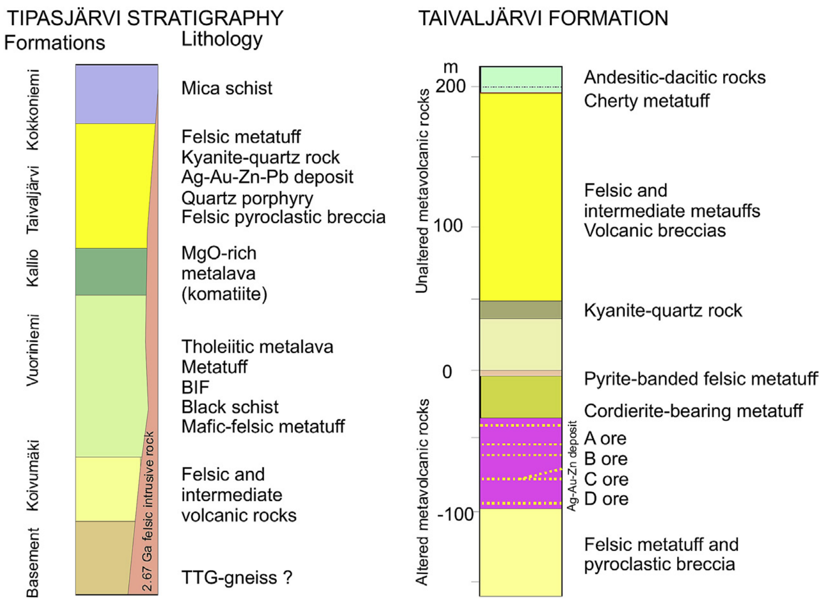


FIGURE 9.3.2 Stratigraphic scheme of the Tipasjärvi greenstone belt and lithologic succession of the Taivaljärvi formation.

The Tipasjärvi section of the greenstone belt was traditionally divided into four lithostratigraphic formations (Taipale, 1983; Papunen et al., 1989, 2009). The lowermost formation, mainly composed of felsic metatuffs, is called the Koivumäki formation, where also the Taivaljärvi felsic volcanics were included (Fig. 9.3.2). The Vuoriniemi formation overlies it, and its lithologic composition varies within a broad range from tholeiitic metatuffs and lavas to banded iron-formation, graphitic black schists, rare dacitic metatuffs, and minor amounts of mafic metalavas. The Kallio formation, characterized by ultramafic komatiitic lavas, overlies the Vuoriniemi formation. The uppermost Kokkoniemi formation is composed of mica schists interpreted as weathering products of the underlying volcanic rocks. This stratigraphic scheme was based on field observations on structures of stratified lithologic units and interpretation of the successive deformation phases (Luukkonen, 1985).

The present (TIMS) U-Pb ages from zircons (Huhma et al., 2012a) set the limits for the stratigraphic succession. The oldest unit dated at 2828 ± 3 Ma is the felsic Koivumäki formation dated from samples from the southern part of the Tipasjärvi belt (Huhma et al., 2012a), and the maximum age of the Kokkoniemi sedimentary unit is set at 2.75 Ga. However, a quite extensive felsic volcanic unit of the belt is dated at 2798 ± 2 Ma, and this unit is considered to be younger than the mafic–ultramafic volcanic rock suite. It terminated the volcanic succession of the greenstone belt and this age group also includes the felsic volcanics of the Taivaljärvi area that host the Ag-Au-Zn deposit. In the stratigraphic scheme, this radiometric age places this felsic formation between the mafic and ultramafic Kallio formation and the sedimentary Kokkoniemi formations and in the present context it is tentatively called the Taivaljärvi formation.

The rocks of the Taivaljärvi formation are either massive quartz-porphyries or, more commonly, volcanic breccias, as well as layered felsic tuffs and tuffites indicating shallow water or subaerial eruption (Taipale, 1983). The layering of the folded sequence is now subvertical to steeply dipping eastwards, and the few available observations of graded bedding in drill cores indicate an eastward younging direction. The Silver Mine Ag-Au-Zn deposit is located in the middle part of the volcanic succession where a number of quartz veins characterize the ore zone. Papunen et al. (1989) divided the deposit into four mineralized layers with different base and precious metal ratios. These layers are roughly parallel to primary stratigraphic layering. However, Parkkinen (2012) indicated in the mining area that the sequence is intensely isoclinally folded, and that the fold structures may control the metal ratios of the deposit.

Geochemistry and mineralogy of the host rocks prove potassic and magnesian hydrothermal alteration. An extensive quartz-kyanite rock layer is present some 100 m stratigraphically above the mineralized zone. The felsic rocks between the silver deposit and the layer of quartz-kyanite rock are K-Mg altered, whereas such alteration is not present in the volcanic rocks stratigraphically above (to the east of) the quartz-kyanite rock. The quartz-kyanite rock is interpreted as the metamorphic equivalent of an intensely leached cap-rock developed in an epithermal hydrothermal system (Papunen et al., 1989). The upper contact of the Taivaljärvi formation is tectonic, and the intense isoclinal folding and overthrusting has brought the older greenstone rocks into the upper contact of the Taivaljärvi succession.

The basal contact of the Taivaljärvi formation with the underlying TTG gneisses is not exposed in outcrop, but drilling reveals that the felsic fragmentary succession is underlain by homogenous felsic porphyry, which grades transitionally into TTG granitoid.

The Juurikkaniemi felsic volcanics in the southern part of the Kuhmo greenstone belt 23 km to the north of Taivaljärvi are lithologically very similar to the Taivaljärvi formation. The multigrain U-Pb zircon age of the felsic volcanic rock of Juurikkaniemi (Katerma) is 2798 ± 15 Ma (Hyppönen, 1983).

THE SILVER DEPOSIT AS A PART OF THE TAIVALJÄRVI FORMATION

LITHOLOGY OF THE FOOTWALL SEQUENCE

Graded bedding with an eastward stratigraphic top direction was locally observed in the drill cores of fine-grained volcanoclastic rocks. This indicates that the basement of the sequence is to the west of the deposit. The footwall of the ore consists of a homogenous, weakly mineralized and, at least, 150-m-thick unit of felsic volcanic rock (metarhyolite) containing quartz, sericite, and biotite as main minerals with thin bands containing garnet and tremolite and locally ankerite together with sulfides. Accessory minerals are chlorite, epidote, cordierite, and rutile. The texture is porphyritic with quartz as phenocrysts (2–4 mm). To the west of the deposit, the footwall rock is intensely foliated but northward it is more massive.

THE ORE DEPOSIT

The till-covered subcrop of the deposit is 400 m long and from 5–110 m wide, averaging 40 m. The deposit dips at 65° to the southeast, plunges 60° to the south-southwest, and drilling-indicated ore extends to a depth of at least 600 m (Fig. 9.3.3). Geophysical deep-penetrating “Sampo” surveys, conducted in spring 2013 by GTK (Niskanen, 2013), indicate that the mineralized zone continues down to 1.5 or even a 2 km depth. This interpretation and the synthesis of geophysics and structural observations of the depth extension were done by Parkkinen (2013).

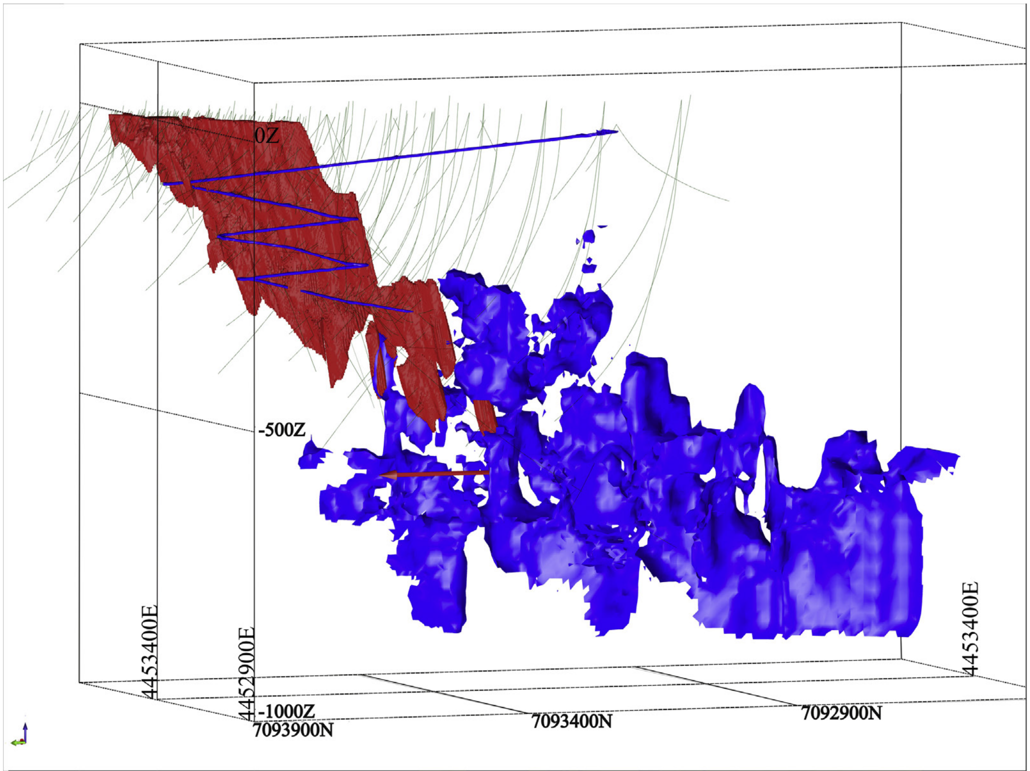


FIGURE 9.3.3 3D model of the Taivaljärvi Silver Mine deposit looking southeast.

Measured, indicated, and inferred resource is red, while cyan is the extension of mineralization inferred with Sampo soundings. Mine decline is blue. Green thin lines indicate drill hole traces. A 200-m-long red arrow points to the north. Finnish National Coordinate System (KKJ) in meters.

Source: *Modified from Niskanen (2012).*

Wardell Armstrong International (2012) performed for Sotkamo Silver Oy a feasibility study of the deposit, and Parkkinen (2013) updated the estimate of mineral resources according to the Australian Code for reporting of exploration results, mineral resources and ore reserves (JORC-code 2012); on this basis Engtec (2014) updated the feasibility study. With a cutoff grade of 50 g/t Ag (eq), the deposit contains 3.52 Mt of measured and indicated resource with 0.71% Zn, 0.34% Pb, 102 g/t Ag, and 0.29 g/t Au. An additional inferred resource contains 1.5 Mt with equal composition. The total inferred mineral resource calculated according to the national instrument for the standards of disclosure for mineral projects within Canada (NI-43101) with a cutoff grade of 30 g/t Ag is 13 Mt of mineralized rock with 0.5% Zn, 0.2% Pb, 65 g/t Ag, and 0.2 g/t Au. Ag accounts for 75–80% of the total commercial value of the deposit, the rest being due to Au, Zn, and Pb.

According to Kopperoinen and Tuokko (1988) and Papunen et al. (1989), the heterogeneous mineralized section is composed of several parallel mineralized layers named from the footwall upward the D, C, B, and A layers, each having specific compositions and metal ratios (Fig. 9.3.4). However, they vary

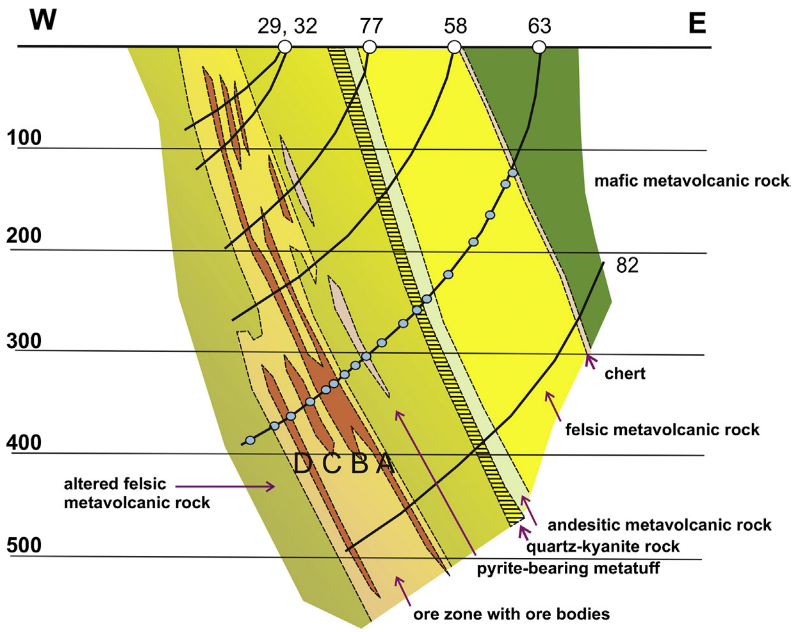


FIGURE 9.3.4 A section across the Taivaljärvi Silver Mine deposit looking northeast.

Locations of the analyzed samples in Table 9.3.1 indicated in the drill core 63 trace.

laterally in thickness and locally join up with the neighboring zones. Parkkinen (2012, 2013) interpreted the deposit as a tightly folded single layer (Fig. 9.3.5), but recently (CTS Engtec, 2014) he suggested a modification of the model with six layers (Fig. 9.3.6). The model needs further justification. The rocks between the mineralised layers are not are not totally barren, but contain a weak dissemination of ore minerals, and the mineable ore contains parts of the entire mineralized section (Fig. 9.3.6). Thick zones are more heterogeneous than thin ones. In addition to quartz and sericite, the felsic metavolcanic host rock close to the footwall contains abundant garnet and biotite, but the abundance of these minerals diminishes toward the hanging wall, and the rock passes to light-colored quartz-sericite rock. Abundant carbonate minerals, forming both disseminations and veins, characterize the deposit (Fig. 9.3.7(A)). Accessory minerals are chlorite, tourmaline, rutile, barite, epidote, and tremolite, which occur locally as bands.

The main layers forming the mineable ore are the A and B zones. The A layer is stratigraphically the uppermost mineralized zone. The thickness varies from 4 to 8 m but locally attains 15 m. It is discontinuous and has a break at a depth of 150–200 m. At the northern edge, close to the surface, the body is banded and Zn-Pb rich with a high amount of iron sulfides. As a whole, however, the ore body is Ag rich, has lower tenors of Zn and Pb compared to other mineralized layers, and contains abundant quartz and ankerite veins.

The B layer is 4–8 m thick, locally attaining a thickness of 16 m. On the surface it is relatively uniform, has a minor break at a depth of 50–100 m, and then continues to a depth of 500 m. The host rock is banded quartz-sericite schist with abundant quartz-carbonate veins (20–30%). Sphalerite and galena occur as banded dissemination together with pyrite and pyrrhotite in quartz-ankerite veins. Fig. 9.3.7(B) represents these structures in the test tunnel mined through B ore layer at level +150.

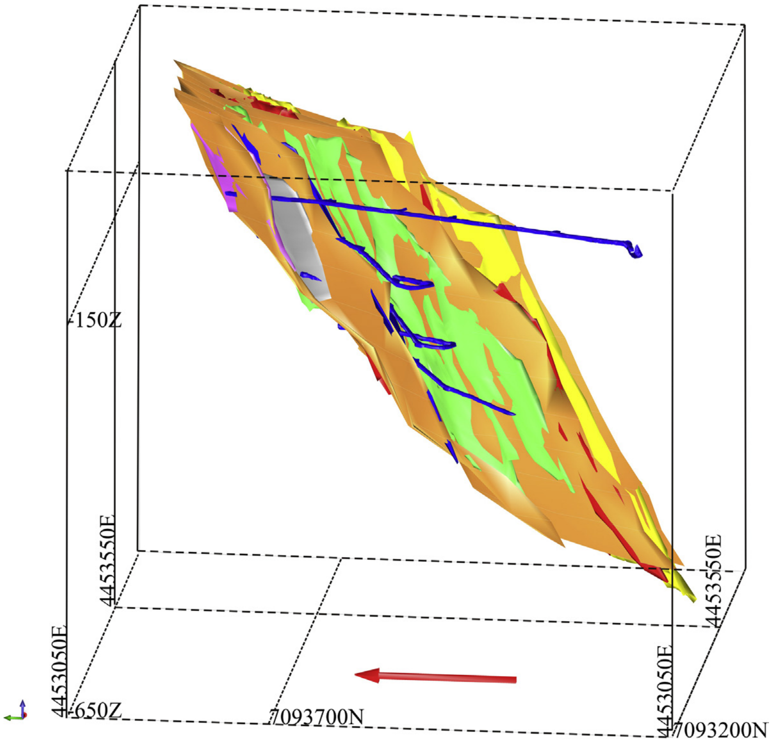


FIGURE 9.3.5 3D model of the isoclinally folded pattern of the Taivaljärvi Silver Mine ore deposit looking east-northeast.

The anticipated six ore layers are indicated with purple, gray, blue, green, red, and yellow colors and the proposed fold with brown color; mine decline is blue. The red arrow represents 200-m length and points to the north. Finnish National Coordinate System (KKJ) in meters.

Source: *From Parkkinen (2012).*

The C layer is on average 5 m thick, but is not as widespread as the other zones. Here the sulfides occur mostly as thin bands. Stratigraphically, the lowermost mineralized D layer is up to 5 m thick and characterized by calc-silicate bands and relatively abundant sulfide minerals, sphalerite, pyrrhotite, chalcopyrite, galena, and pyrite. The main gangue minerals are quartz, carbonates, tremolite, garnet, and biotite.

Deformation has been limited to intense small-scale folding and pinch and swell structures of the layers. Probably simultaneous to the folding, a generation of quartz veins was formed, in places mineralized. This phase was followed by brittle deformation with another generation of barren quartz veins. The geometry of quartz-bearing veins, faults, and shear fractures, which deviate from the directions of bedding and foliation, may indicate a minimum principal stress in northeast-southwest direction (Fig. 9.3.8), or they may also reflect the predeformation orientation of hydrothermal quartz veins across the primary layering.

A structural analysis was focused on the geometry of bedding, foliation, and fold axis observations measured in the 2.5-km-long mine decline in 1990–1991. According to Parkkinen (2012, 2013), the

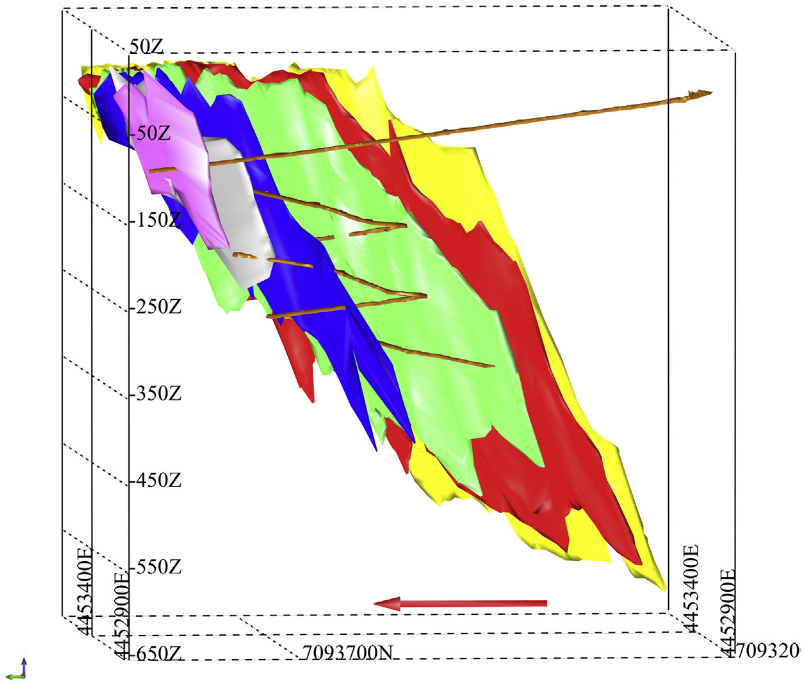


FIGURE 9.3.6 3D model of the Taivaljärvi Silver Mine looking northeast.

Six ore layers, indicated with different colors, and the mine decline (brown). The red arrow represents 200-m length and points to the north. Finnish National Coordinate System (KKJ) in meters.

structural elements give a uniform and simple geometry illustrated in stereographic projections (Fig. 9.3.8). They indicate that the latest foliation phase (local S_2) both parallels the bedding and also forms on average a 10° angle clockwise to bedding. This might be interpreted as sinistral folding within the deposit.

The structural analysis proves that the deposit follows the direction of lineation, and that that direction has a major potential to find extensions of the deposit (Parkkinen, 2010, 2012). Geophysical deep-penetrating Sampo surveys, which GTK conducted in 2011 (Niskanen, 2012) and 2013 (Niskanen, 2013), confirmed the idea, and the potential for the deposit to extend to the depth of 1.5 km (Parkkinen, 2013).

LITHOLOGY OF THE HANGING WALL

The hanging-wall contact of the deposit is almost a plane. It is overlain by a quartz-sericite rock with quartz phenocrysts. Carbonates, which are the main minerals in the ore zone, are very rare above the ore zone. Some layers contain local, ghostlike, fragments suggestive of lapilli tuff or agglomerate. Iron sulfide bands and veins are common, having local tenors of Zn, Pb, and Ag slightly above the background level. Cordierite is present as pinitized porphyroblasts in some layers.

A layer above the ore deposit proper is characterized by abundant pyrite and pinitized cordierite porphyroblasts, and is marked with a zero in the stratigraphic column (refer to Figs 9.3.2 and to 9.3.9

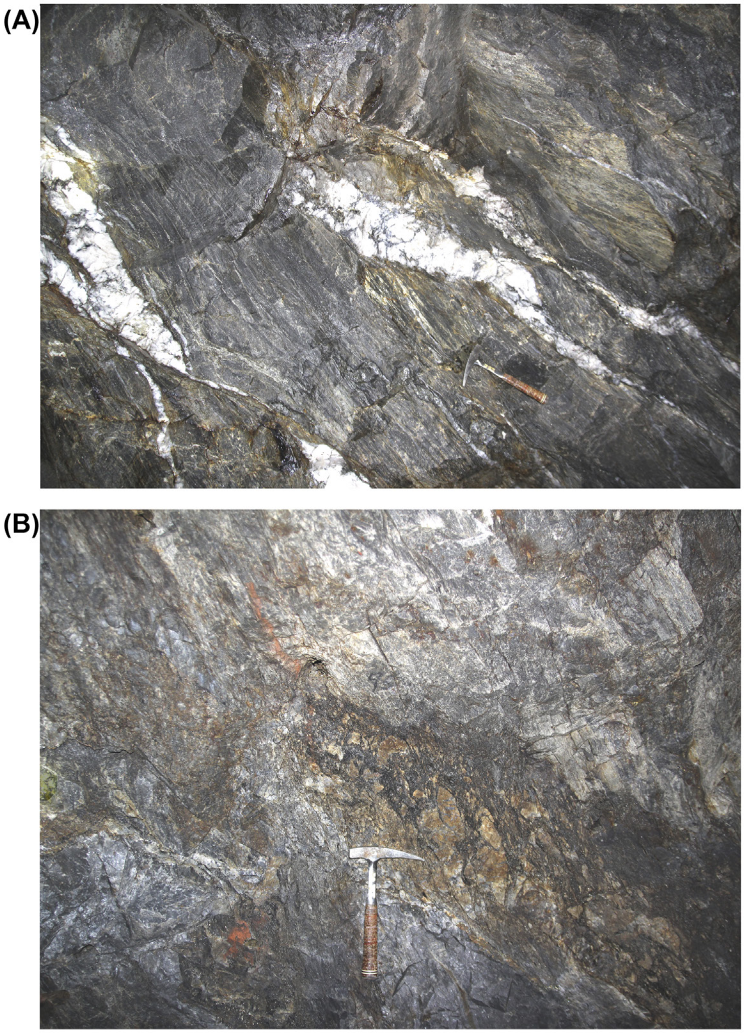


FIGURE 9.3.7 Structure of the ore deposit.

(A) Ore in test tunnel level +150 m; quartz-carbonate veins with sulfide bands; sphalerite and galena accumulation in the upper part of the photo. (B) Ore in test tunnel level +265 m; massive carbonate-sulfide breccias.

later in this section). In addition to pyrite and cordierite, the layer contains sericite, phlogopite, and tourmaline. To the east of this layer, the abundances of K-feldspar and plagioclase increase gradually; to the west, plagioclase is totally absent. The first indications of plagioclase are remnants of plagioclase phenocrysts, which are almost totally altered to K feldspar and sericite. Such remnants are relatively common above the pyrite-banded cordierite-rich layer.

A layer composed of Al silicates, mainly kyanite and quartz, exists about 80–90 m above the Ag-Au-Zn ore. Layers of this rock type are very extensive in the Taivaljärvi formation, south of the deposit, in

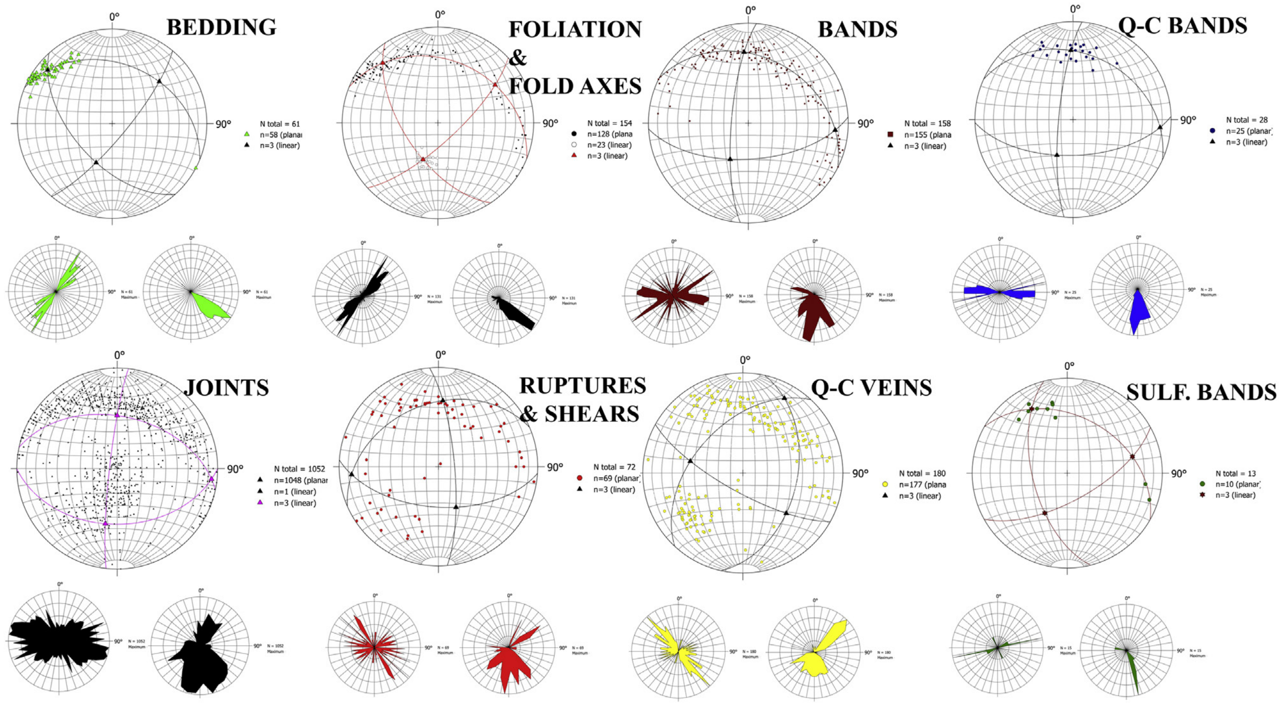


FIGURE 9.3.8 Stereographic projections (Stereo 32, lower hemisphere, equal area) of the Taivaljärvi Silver Mine bedding, foliation and fold axes, banding, quartz-carbonate bands (Q-C BANDS), joints, ruptures and shears, quartz-carbonate veins (Q-C VEINS), and sulfide bands.

Small projections depict the distribution of strike and dip of the elements. The elements were measured from the decline tunnel.

the Kivisuo area where it locally attains a thickness of 80 m; in the Taivaljärvi section, the quartz-kyanite rock is only 5–25 m thick. The quartz-kyanite rocks are characterized not only by quartz and kyanite but also by sillimanite and, locally, by staurolite, cordierite, muscovite, tourmaline, rutile, chlorite and chloritoid, zircon, and apatite. The structure of the original fragmental felsic volcanic rock is still visible on the weathered surface in some of the outcrops.

The rock sequence to the east of the quartz-kyanite rock of the Taivaljärvi formation comprises intermediate and felsic metavolcanic rocks with quartz and plagioclase phenocrysts. In contrast to the felsic metatuffs to the west of the quartz-kyanite rock, the plagioclase phenocrysts are not corroded or replaced by potassic feldspar. A 15–25-m-thick interlayer of intermediate (dacitic) metatuff above the quartz-kyanite rock is characterized by garnet porphyroblasts and abundant magnetite, which is rare elsewhere in the sequence. The total thickness of the intermediate-felsic sequence east of the quartz-kyanite layer is about 90 m and, before the mafic rocks of the Vuoriniemi formation, it terminates in a 10–15-m-thick layer of a cherty metatuff. This quartz-rich rock is very fine-grained and contains bands of disseminated pyrite.

MINERALOGY OF THE DEPOSIT

The following sections on mineralogy and geochemistry are based on the works of Kopperoinen and Tuokko (1988), Papunen et al. (1989), and Laukkanen (2011).

CARBONATE MINERALS

Carbonates occur in intersecting quartz-carbonate-sulfide veins and conformable bands of the A and B zones, in calc-silicate interlayers of the D zone, and in the footwall. In the A and B zones, the content of carbonates varies from 6–8%, and in the C and D zones from 1–2%.

According to microprobe analyses (Papunen et al., 1989), most of the carbonates are manganoankerites with MnO contents of 3–6 wt%. The FeO content of manganoankerite increases from the A zone toward the footwall: in the A zone FeO is 5.27 wt%, in the D zone, 6.42 wt%, and in the footwall, 7.55 wt%; the MgO content decreases correspondingly. Manganocalcite with 3 wt% MnO is associated with ore minerals in the quartz-carbonate veins in the B zone.

ORE MINERALS

The most important ore minerals are freibergite, dyscrasite, pyrargyrite, native silver, electrum, sphalerite, galena, and chalcopyrite. The following minerals have also been identified: pyrite, pyrrhotite, arsenopyrite, cubanite, covellite, gudmundite, acanthite, miargyrite, freieslebenite, bournonite, scheelite, native Sb, and native Bi. The grain size of the common sulfides varies from 0.1–0.5 mm and that of the Ag-bearing minerals from 0.01–0.1 mm. Galena and the associated Ag minerals are more abundant in the stratigraphically uppermost ore zones, where they occur in quartz-carbonate veins and bands. The sulfide content in the ore varies between 5 and 8%, and more than 50% of them are iron sulfides pyrite and pyrrhotite. Silver mineralogy stays basically constant in the whole deposit: more than 95% of silver is in sulfides and antimonides, but in silver-rich parts of the ore, galena contains about 0.1 wt% silver and also native silver and silver-gold alloys occur. Since native silver is quite a rare mineral, a grade of >700 g/t was used as the upper cutoff grade for silver to control the nugget effect in the resource estimates.

Iron sulfides and arsenopyrite

Pyrite is the dominant iron sulfide mineral. It occurs in all ore types and in the wall rock as euhedral cubes. In the quartz-ankerite veins and in the C and D ores, pyrrhotite is an important sulfide mineral. Arsenopyrite occasionally occurs as banded disseminations. It does not show any correlation with the gold content.

Sphalerite

The grain size of sphalerite varies from 0.05–0.3 mm, in places up to 0.5 mm. The mineral exists throughout the deposit, mainly as bands together with iron sulfides and minor galena, and in quartz-ankerite veins together with galena and other ore minerals. Three grains of sphalerite analyzed by microprobe contained 5–7 wt% Fe and 0.26–0.35 wt% Cd (Papunen et al., 1989).

Galena

This occurs mainly as dissemination in quartz-ankerite veins and in bands together with sphalerite, chalcopyrite, and iron sulfides. Galena commonly fills the cracks between the other minerals or occurs as inclusions in ankerite. In the Ag-rich part of the ore body, galena contains inclusions and intergrowths of dyscrasite, freibergite, native Ag, antimony, freieslebenite, and bournonite. The Ag content of galena varies from 0.01–1.7 wt%, the galena in the D ore being poorest in Ag (Papunen et al., 1989). High Ag values are due to submicroscopic inclusions of Ag-bearing minerals.

Chalcopyrite

This is a common accessory ore mineral throughout the deposit. The grain size varies from 0.02 to 0.1 mm. It occurs in Ag-rich parts of the ore intergrown with Ag minerals and in the calc-silicate layers together with pyrrhotite, sphalerite, and galena. Some of the chalcopyrite grains in the Ag-rich part of the ore tarnish green, blue, or gray soon after polishing. The tarnished mineral assays up to 6.8 wt% Ag (Papunen et al., 1989). Chen et al. (1980) described a similar phenomenon and attributed it to Ag diffusion onto the surface of polished Ag-rich chalcopyrite, where it forms a thin layer of acanthite, (Ag2S).

Freibergite [$(Ag,Cu)_{12}(Sb,As)_4S_{13}$] and Dyscrasite [$Ag_3Sb$]

Freibergite is the most common Ag mineral in the deposit. It occurs together with galena in disseminated ore or as intergrowths with galena and dyscrasite in the quartz-ankerite veins. It has also been found in veins together with galena and native Ag as a coating on the grains of galena. The grain size is between 0.03 and 0.06 mm. The Ag content varies from 20–50 wt% (Papunen et al., 1989), the lowest concentrations being in freibergites of the C zone. Silver replaces copper in freibergite-tetrahedrite series, that is, when Ag increases, the Cu content decreases. The Ag-rich freibergites of the B zone plot in the Riley (1974) diagram close to the pure Ag end-member of the tetrahedrite-freibergite series (Papunen et al., 1989). Ag-rich freibergites (up to 50 wt% Ag) occur in the B zone intergrown with normal freibergite (22–25 wt% Ag). Together with freibergite, dyscrasite is the most important carrier of Ag in all ore types. It commonly occurs in grain clusters with galena, freibergite, chalcopyrite, and native Sb in the quartz-ankerite veins and as inclusions in ankerite. Dyscrasite exists throughout the deposit together with galena and the other Ag minerals. The grain size varies from 0.01–0.1 mm. Analyses of dyscrasites are presented in Papunen et al. (1989). The dyscrasite of sample D H55/136.50 contains 0.66 wt% As, which possibly replaces Sb in the mineral.

Freieslebenite (PbAgSb3)

This is a rare Ag mineral and has been recognized only in the A and B ores as inclusions in galena. The chemical compositions of freieslebenite indicate obvious Ag-Cu replacement (Papunen et al., 1989).

Pyrargyrite (Ag3SbS3)

Pyrargyrite exists as thin coatings on the fracture surfaces of the galena-ankerite-quartz veins. The red color typical of the mineral makes it easy to detect, even with the naked eye. The grain size varies between 0.01 and 0.03 mm. The mineral also occurs as inclusions in and along the grain boundaries of galena.

Native Ag and Ag-dominant intermetallic alloys with Au and Sb

As with the other constituents these are common accessories in the ore (Papunen et al., 1989). The alloys commonly occur together with galena and the other Ag minerals, but they also fill the fractures between the other ore minerals or exist as fine-grained dust in carbonate. The grain size is between 0.01 and 0.05 mm. A couple of 1- to 2-mm-thick native Ag veins filling tension cracks have been observed in drill cores; native Ag in the footwall D layer contains 94.1 wt% Ag, 4.8 wt% Sb, and 0.19 wt% Au. Electrum is a rare mineral and has been found as inclusions in pyrite and sphalerite. In the analyzed grains, the concentration of silver exceeds that of gold (51.7 wt% Ag, 43.4 wt% Au). The minerals called "dyscrasite" and "Au-bearing dyscrasite" in Papunen et al. (1989) are complicated intergrowths of different phases of Ag-Sb-Au minerals.

GEOCHEMISTRY OF THE SEQUENCE

The major and trace element compositions of the felsic lithologic sequence of the Taivaljärvi formation are presented according to Papunen et al. (1989) in Table 9.3.1 and Fig. 9.3.9. Geochemically, the rocks can be divided into two major units: the rocks to the east of the kyanite-quartz rock and those in and to the west of the layer. On the basis of the SiO_2 content, the felsic metavolcanic rocks in the eastern part of the sequence range in composition from felsic to intermediate with numerous interlayers of dacites and chert, although their TiO_2 contents are too high for average Archean dacites and rhyolites (Condie, 1981). The rocks of the eastern part of the sequence differ in composition from the corresponding rocks of the western part, having slightly higher MgO, Ba, U, and Th contents but lower TiO_2, $Al2O_3$, Na_2O, P_2O_5, Co, Sr, CaO, Cr, V, Sc, Li, Cs, and Y contents (Fig. 9.3.9). However, the western part of the Taivaljärvi formation contains several rock units, for example, the mineralized rocks, the quartz-kyanite rocks, and the pyrite-banded metatuff, which have specific geochemical characteristics differing from those of the pyroclastic metavolcanic rocks.

The tenors of Cu, Sb, and Au are highest in the D ore body, near the western footwall, in the stratigraphically lower mineralized portion of the Ag-Zn deposit. The central part of the deposit, the B and C ore bodies, are characterized by high tenors of Ag, Zn, As, Se, Pb, and Cu, and the A ore body close to the hanging wall contains abundant carbonates, Ag, and Zn. The content of Ni is also highest in the hanging wall part, although the values are only twice the average background. The contents of Mn, Mg, and Ca show clear positive correlations with that of CO_3.

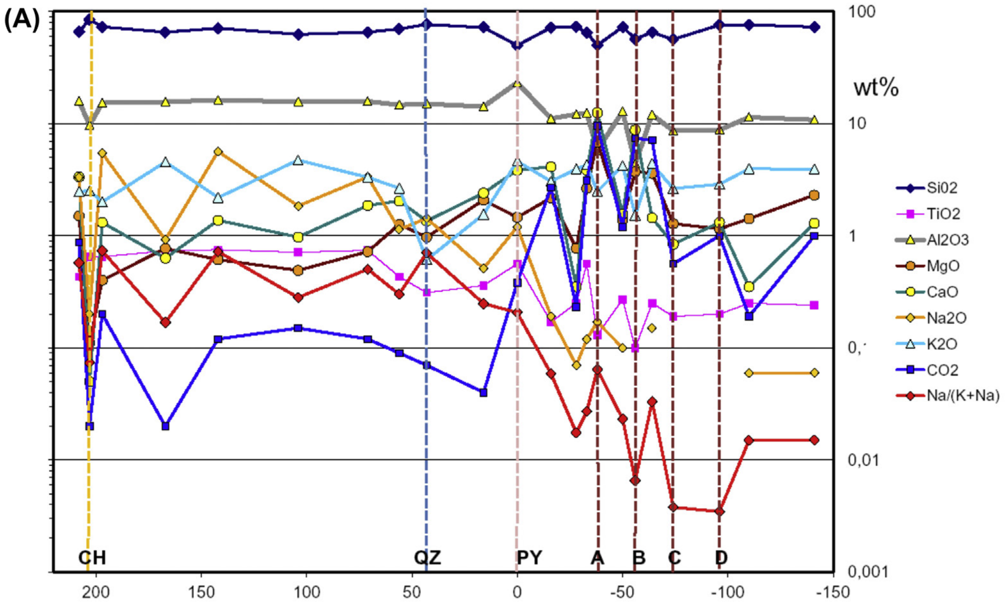
Table 9.3.1 Stratigraphic heights, rock types and chemical compositions of the samples collected from the Taivaljärvi Formation

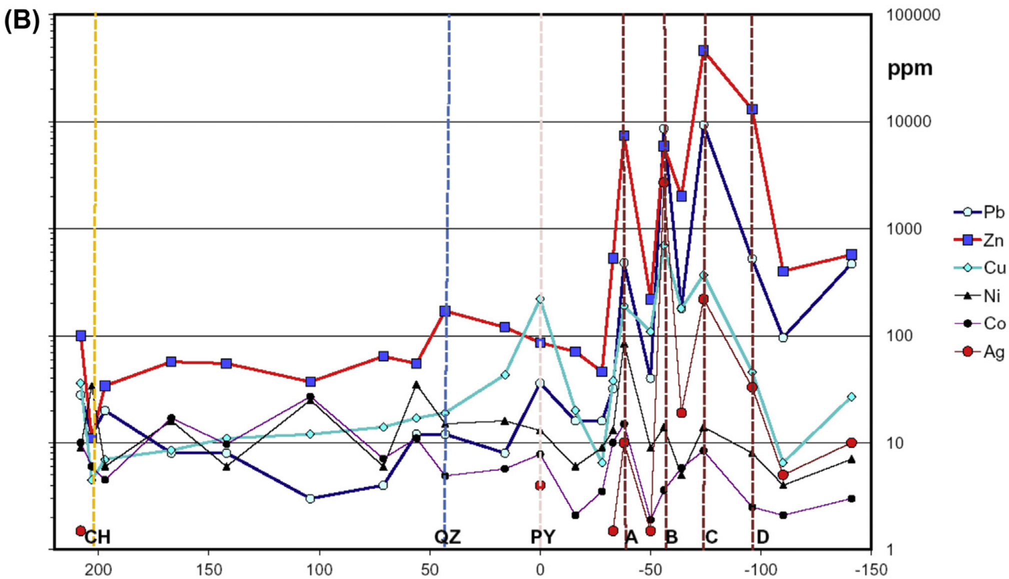
Nr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Height	208	203	197	167	142	104	71	56	43	16	0	−16	−28	−33	−38	−50	−56	−64	−74	−96	−110	−141
Rock	andes	chert	dacite	dacite	dacite	andes	andes	dacite	k-qz-r	rhyol	py-tuff	crd-tuff	rhyol	crd-tuff	A ore	felsic	B ore	felsic	C ore	D ore	rhyol	rhyol
(wt %)																						
SiO_2	66.10	84.90	73.00	65.40	71.00	62.50	65.40	70.00	76.60	72.10	49.80	72.00	73.30	64.70	50.00	72.70	57.10	65.20	56.50	75.90	76.20	72.90
TiO_2	0.43	0.65	0.65	0.73	0.75	0.71	0.74	0.43	0.31	0.36	0.56	0.17	0.25	0.56	0.13	0.27	0.10	0.25	0.19	0.20	0.25	0.24
Al_2O_3	15.80	9.69	15.30	15.60	16.20	15.70	15.80	14.70	15.00	14.20	23.20	11.10	12.10	12.40	5.79	12.80	4.37	12.00	8.64	8.81	11.40	10.80
Fe_2O_3	4.34	0.83	0.72	6.05	1.13	7.87	7.64	3.78	1.88	3.15	8.10	2.50	4.72	5.61	8.35	3.10	7.09	<0.01	11.40	2.93	3.20	4.64
MnO	0.11	<0.02	<0.02	<0.02	0.02	0.07	0.11	0.14	0.02	0.06	0.06	0.21	0.06	0.44	0.80	0.36	1.48	0.49	0.56	0.14	0.28	0.31
MgO	1.50	0.11	0.40	0.77	0.61	0.49	0.72	1.26	0.97	2.08	1.46	2.17	0.77	2.65	6.84	1.38	3.73	3.60	1.28	1.15	1.42	2.30
CaO	3.34	0.05	1.31	0.63	1.37	0.97	1.86	2.04	1.35	2.40	3.84	4.12	0.35	3.82	12.50	1.56	8.78	1.44	0.84	1.31	0.35	1.29
Na_2O	3.30	0.20	5.44	0.92	5.65	1.84	3.34	1.14	1.43	0.51	1.20	0.19	0.07	0.12	0.17	0.10	<0.01	0.15	<0.01	<0.01	0.06	0.06
K_2O	2.48	2.51	2.00	4.55	2.19	4.72	3.32	2.65	0.61	1.55	4.62	3.05	3.93	4.31	2.48	4.21	1.52	4.37	2.63	2.88	3.95	3.92
P_2O_5	0.12	0.14	0.14	0.16	0.14	0.16	0.17	0.10	0.03	0.07	0.08	0.03	0.06	0.11	0.07	0.05	0.03	0.06	0.06	0.06	0.06	0.06
L.O.I.	1.60	1.10	1.10	5.00	1.10	4.40	1.10	3.10	2.00	2.60	7.20	2.50	3.80	3.30	5.30	2.40	4.50	2.70	6.30	2.70	2.20	2.00
CO_2	0.87	0.02	0.20	0.02	0.12	0.15	0.12	0.09	0.07	0.04	0.38	2.70	0.23	3.10	9.60	1.20	7.40	7.10	0.56	1.00	0.19	1.00
Na/(K+Na)	0.571	0.074	0.731	0.168	0.721	0.280	0.502	0.301	0.701	0.248	0.206	0.059	0.018	0.027	0.064	0.023	0.007	0.033	0.004	0.003	0.015	0.015
(ppm)																						
Ag	1.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	4	<0.5	<0.5	1.5	10.0	1.5	2700	19.0	220.0	33.0	5.0	10.0
Au (ppb)	15	<5	<5	<5	<5	<5	<5	<5	<5	<5	45	<5	5	15	33	<5	16000	220	530	500	18	57
Sb	0.6	0.3	1.8	1.4	2	0.3	0.5	0.8	1.3	1.2	1.8	0.4	0.7	1.7	8.7	0.8	390	7.4	230	15	2.9	9.6
As	<I	26	4	17	2	16	2	21	120	10	120	18	77	74	30	9	950	13	88	23	16	6
Bi	1.9	<0.1	<0.1	<0.1	0.3	<0.1	0.4	<0.1	<0.1	1.8	0.4	<0.1	<0.1	<0,1	<0.1	<0.1	1.7	<0.1	2.1	<0.1	0.2	0.4
Se	<0.7	<0.7	1.4	2.6	<1.2	<1.3	3.8	<0.7	<0.7	1.1	3.3	2.9	<1.7	3.5	2.9	<1.0	21	2.3	12	<0.6	1	<0.5
Cd	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	1.2	34	<0.2	32	8.8	240	68	1.2	2
Pb	28	12	20	8	8	3	4	12	12	8	36	16	16	32	480	40	8600	180	9300	520	96	470
Zn	100	11	34	57	55	37	64	55	170	120	86	71	46	530	7400	220	5900	2000	46000	13000	400	570
Cu	36	4.5	7	8.5	11	12	14	17	19	43	220	20	6.5	38	190	110	700	180	370	46	6.5	27
Ni	9	34	6	16	6	25	6	35	15	16	13	6	9	13	85	9	14	5	14	8	4	7
Co	10	6	4.5	17	9.7	27	7.1	11	4.9	5.7	7.8	2.1	3.5	10	15	1.9	3.6	5.8	8.4	2.5	2.1	3
Cr	7.8	0.8	4.5	8.4	6.7	6.2	7	23	10	9.2	7.1	<0.5	1.2	4	<0.5	<0.5	7.5	2.8	3.1	2.3	<0.5	2
V	66	4	36	44	40	42	42	46	28	40	38	12	10	32	14	6	8	8	6	8	6	6
Sc	6.94	3.42	8.32	9.97	8.69	8.45	9.33	7.77	5.55	7.41	12.3	3.87	6.57	7.1	3.69	6.72	3.56	6.11	4.83	3.22	6.1	5.58
Y	10	20	30	40	30	30	30	30	50	40	50	20	50	50	<10	<10	<10	10	<10	<10	40	<10

Continued

Table 9.3.1 Stratigraphic heights, rock types and chemical compositions of the samples collected from the Taivaljärvi Formation—cont'd

Nr	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Zr	70	210	200	240	210	230	200	190	170	170	470	140	260	170	90	270	70	270	160	200	270	240
Hf	3.2	7	5.6	7.3	6.6	6.6	6.3	6.6	7.3	5.6	14	5.5	8.4	5.9	3.8	8.6	3.4	6.5	4.9	4.8	6.5	5.9
Nb	<10	10	10	10	10	20	30	<10	20	10	30	20	10	<10	20	10	30	20	50	20	20	20
Ta	<0.5	0.8	1.4	<0.5	<0.5	<0.5	0.6	0.7	0.9	0.6	1.3	0.8	0.8	0.8	<0.5	0.7	<0.5	0.6	<0.5	0.7	0.6	0.7
Th	2.1	7.9	6.8	6.9	7.3	6.9	7.7	6.5	10	8.7	13	11	9.3	7	4.4	10	3.5	9.7	7.6	7.1	11	9.5
U	0.5	2.2	2.1	1.9	2	2.2	0.8	1.8	3.5	2	4.1	3.5	2.9	1.9	2.4	3.3	1.4	2.6	3.2	2.5	3.1	2.8
Li	18	6	14	26	17	22	18	14	20	30	12	14	10	14	16	12	16	18	13	14	12	14
Rb	100	60	90	150	70	130	120	70	20	60	200	140	140	160	120	149	10	160	120	100	140	150
Cs	8	1.8	2.6	8.4	2.9	2.3	7.3	2.8	1	1.8	6.3	3.5	2.7	5.3	6.5	2.5	3.2	6.1	2.9	1.1	1.9	2.8
Be	2	2	2	3	2	4	3	2	2	2	4	3	3	3	2	1	2	3	4	1	3	2
Sr	230	50	130	40	130	120	160	60	110	60	50	<10	<10	40	60	20	30	10	<10	10	<10	20
Ba	480	200	420	490	400	500	540	300	100	160	560	410	760	630	240	830	200	500	630	580	1100	920
B	20	20	40	30	20	20	20	30	170	20	460	30	20	40	<10	20	<10	30	90	90	20	20
Cl	<50	50	50	<50	<50	150	<50	<50	<50	<50	50	50	50	200	50	50	50	<50	<50	50	50	<50
Br	2.3	<0.5	0.5	<0.5	<0.5	0.6	1.4	<0.5	<0.5	<0.5	<0.5	0.5	0.5	1.2	0.6	<0.5	<0.5	<0.5	0.5	<0.5	0.5	0.6
La	14	25.5	33.9	33.5	31.5	35.7	37.6	28.1	37.2	30.6	24.3	37.6	42.8	27.2	25	42.2	24	39.1	29.2	24.8	33.5	29
Ce	27	46	58	60	52	62	65	48	67	53	44	66	72	48	39	76	25	78	61	47	70	59
Nd	10	20	26	26	25	27	27	19	25	19	17	26	31	22	17	28	10	30	23	20	27	25
Sm	2.2	4.52	5.07	5.09	4.63	5.18	5.02	3.67	5.92	4.5	3.87	5.55	6.1	4.28	3.98	6.41	2.32	6.22	4.96	3.95	5.64	4.93
Eu	0.77	0.58	0.68	0.52	0.68	0.68	0.132	0.74	0.48	0.33	1.01	0.71	0.88	0.57	0.78	0.66	1.29	1.31	1.22	0.73	0.85	0.83
Tb	0.3	0.7	1	0.9	0.6	0.9	0.8	0.5	1.1	0.7	1.1	1.2	1.1	0.6	0.9	1.1	0.5	0.9	1.1	0.5	0.9	0.7
Yb	0.64	2.06	1.99	2.88	2.08	2.26	2.41	1.95	3.19	2.12	6.39	2.93	2.79	2.46	2.82	3.42	1.87	3.51	6.51	1.39	4.43	2.05
Lu	0.11	0.33	0.33	0.48	0.34	0.4	0.42	0.34	0.57	0.36	1.12	0.52	0.48	0.41	0.49	0.58	0.26	0.57	1	0.22	0.74	0.36


(A)
wt%
100
10
1
0,1
0,01
0,001
Si02
TiO2
Al2O3
MgO
CaO
Na2O
K2O
CO2
Na/(K+Na)
CH
QZ
PY
A
B
C
D
200
150
100
50
0
-50
-100
-150


(B)
ppm
100000
10000
1000
100
10
1
Pb
Zn
Cu
Ni
Co
Ag
CH
QZ
PY
A
B
C
D
200
150
100
50
0
-50
-100
-150

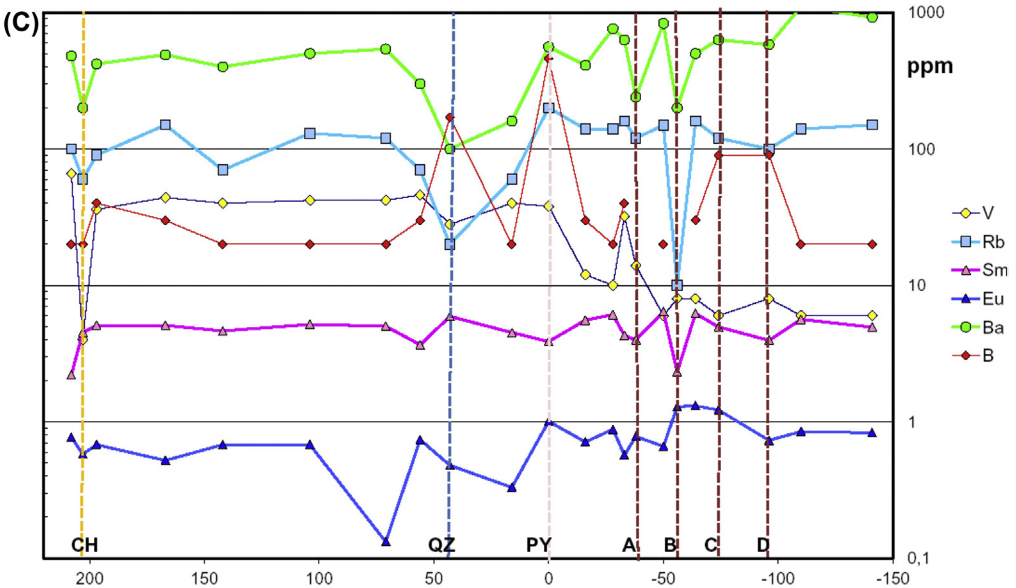


FIGURE 9.3.9 Variation of the chemical compositions versus stratigraphic height at Taivaljärvi.

Table 9.3.1 and Figs. 9.3.2 and 9.3.4 are referred to for the location of the samples in stratigraphic scheme. (A) Variation of the main elements; (B) the ore elements; (C) trace elements. CH = chert layer; QZ = quartz-kyanite layer; PY = pyrite-bearing metatuff; A, B, C, D = ore layers.

Of the mineralogically distinct layers of the sequence, the pyrite-banded felsic metatuff, about 30 m above the A ore body, is characterized by higher Al and K and lower Si contents than the felsic metatuffs on average. The concentrations of ore elements Cu, As, Pb, and Sb are enriched in this layer relative to the barren metavolcanic rocks, and the high Fe content and loss on ignition are due to pyrite dissemination. Also the abundances of the trace elements Zr, Hf, Sc, and B are elevated in this layer.

The quartz-kyanite rock (QZ in Fig. 9.3.9) is characterized by low abundances of all the main elements except SiO_2 and $Al2O_3$. Of the trace elements, only Y and B show slightly higher contents in this rock type than in the average felsic volcanic rock; the contents of all the other elements are reduced. Cr has the highest peak in the felsic metatuff just above the quartz-kyanite rock.

The chert layer at the eastern contact of the Taivaljärvi formation against the Vuoriniemi formation displays a high SiO_2 content, but the contents of all the other major elements are lower than in the felsic metavolcanics of the upper part of the formation. The abundances of Ti and P and of the trace elements Mo, Y, Zr, Hf, Th, and U are at about the same level as in the felsic metavolcanic rocks, but all the other trace elements display lower contents.

There are no marked differences in the total rare earth element contents between the felsic metavolcanic rocks from the lower and upper parts. Fractionation of rare earth elements is somewhat more advanced in the upper part than in the lower part of the sequence, the La/Yb ratios being 14.9 and 12.1, respectively. Rare earth element distributions correspond well to the F2 type of Archean felsic volcanic rocks described by Condie (1981). Most of the samples display a negative Eu anomaly in the chondrite-normalized distribution pattern but, in the mineralized part of the sequence, the anomaly is not as prominent as in the felsic metavolcanic rocks stratigraphically above and below it (Papunen et al., 1989). In terms of Eu/Eu* ratio, the negative anomaly is largest in the dacitic metavolcanic rock about 50 m above the quartz-kyanite rock. The intermediate metavolcanic rock in the eastern part of the Taivaljärvi formation displays a positive Eu anomaly and lower total rare earth element contents than the felsic rocks of the Taivaljärvi formation.

Papunen et al. (1989) presented sulfur isotope compositions for 11 pyrite samples extracted from the Taivaljärvi formation. The samples represent the mineralized parts of the formation and the barren iron sulfide layers above the ore deposit. The $\delta^{34}S$ values vary from 2.0–3.8 per mil, with the largest variation in the ore deposit. The average value is 2.64 per mil. Pyrites of the felsic metavolcanic rocks display upward-decreasing values, although the differences among the samples are very small.

MINERAL PROCESSING, METALLURGY, AND MINING

First metallurgical research and processing tests of the Taivaljärvi Silver Mine ore were undertaken as a part of the feasibility study completed in 1991. The processing tests were performed in the 1980s on a laboratory scale at the State Technical Research Centre, VTT; this laboratory at Outokumpu is now called the Mineral Processing Laboratory of the Geological Survey of Finland, or GTK MinTek. The results of the early tests generally demonstrated that the ore is amenable to concentrate with standard flotation techniques. Early in 2007, GTK MinTek was commissioned to do a review and upgrade of historic metallurgical tests and mineral processing flow charts for Sotkamo Silver Oy. An updated report was received at the end of August 2007. Connected with the feasibility study, GTK MinTek conducted additional metallurgical tests of the Ag-Au-Zn ore in the spring 2011 at the Mini Pilot scale (Peltoniemi, 2011).

According to the tests, the Ag-Au-Zn ore is amenable to flotation processing to achieve silver-lead and zinc concentrates at acceptable recoveries from a grind size of 80% passing 75 μm. Gravity processing does not give any significant advantages over flotation. In the locked cycle test, the total recovery of silver was 76.2% and 90% for gold. Approximately 7% of the silver was recovered in the zinc concentrate grading 544 g/t Ag. Zinc recovery of 90.8% was achieved in a concentrate grading 51 wt% Zn. With the production of a pyrite concentrate, the sulfur content of the tailings could be reduced from 0.7–1.1 wt% to 0.1–0.2 wt% S, which is beneficial for the tailings disposal. Silver grade in the sulfur (pyrite) concentrate ranged from 200 to 300 g/t Ag and the recovery of Ag in pyrite concentrate is about 6%. GTK MinTek concluded that the ore is, in general, easily amenable to concentrating using simple processes and reasonable reagent consumptions. Fair concentrate grades can be yielded with satisfactory recoveries. Based on the pilot plant tests, the silver recovery in the feasibility study was readjusted to 86–91%.

Ore processing is planned to be a traditional crushing-grinding-flotation-filtering scheme, and the underground mining will be a sublevel stoping with backfill.

DISCUSSION AND SUMMARY

ORIGIN OF THE ROCK TYPES

Despite regional metamorphism and deformation, the Taivaljärvi formation shows fragmentary and layered structures typical of pyroclastic felsic volcanic rocks. The primary porphyritic textures of the rocks are still visible locally, providing support for the volcanic origin of the sequence. The silicate mineral assemblages (kyanite, staurolite, cordierite, garnet) indicate medium to upper amphibolite facies conditions of metamorphism. In this context, metamorphism is considered isochemical and the metamorphic mineral assemblages reflect the chemical compositions caused by premetamorphic processes.

The interdependence of the chemical composition of the rock and metamorphic mineral assemblage is clearly visible. For example, the Al_2O_3 excess, which is necessary for the formation of kyanite in the quartz-kyanite rock, is a result of depletion of alkalies and all major elements except Al, which remained unchanged. Correspondingly, the cordierite in the metatuff above the ore deposit crystallized in a rock that contained more MgO than felsic volcanic rocks on average.

On the basis of SiO_2 versus Zr/Ti diagrams by Winchester and Floyd (1977), the felsic metavolcanic rocks in the upper (eastern) part of the Taivaljärvi formation have andesitic to dacitic compositions, and the alkali ratios correspond to those of primary volcanic rocks (Hughes, 1973). In contrast, the metavolcanic rocks stratigraphically below the quartz-kyanite rock are rhyolitic, and the Na/K ratios are far from magmatic (Hughes, 1973). TiO_2 contents correspond well to the andesitic to dacitic primary composition of the upper part, and the rhyolitic composition of the lower part. The felsic metavolcanic rocks have average compositions of Archean rhyolites and dacites, and the rare earth element distribution patterns indicate Fe_2-type felsic volcanic rocks in the classification of Condie (1981). However, the total variation in the Na/K ratios cannot be attributed to magmatic processes alone, and in the following section, the chemical compositions are examined in terms of hydrothermal alteration.

Certain primary textures can survive the recrystallization associated with regional metamorphism. For example, relics of plagioclase phenocrysts are common in the upper, dacitic part of the sequence above the pyrite-banded metatuff, where the abundance of plagioclase phenocrysts increases upward (to the east) parallel to the Na content of the rock. Plagioclase phenocrysts do not exist in the lower, rhyolitic part of the sequence. This is because the plagioclase phenocrysts either were lacking initially or were destroyed before metamorphism by hydrothermal decomposition. The best explanation for the anomalously low Na/K ratio in the lower part of the section is the decomposition of the primary plagioclase and dissolution of its components, particularly Na^+ and Ca^{++} under low pH conditions with muscovite as a stable mineral (Helgeson et al., 1978). On a wide scale, hydrothermal potassic alteration was more intense in the rhyolitic lowermost (western) part of the Taivaljärvi formation.

In the upper part of the section, only certain layers of the sequence are intensely altered. For example, the pyrite-banded felsic metatuff is depleted in silica but enriched in ore elements, especially Fe and S, and Al, K, Sc, Zr, Hf, and B if compared with the metavolcanic rocks above and below the metatuff layer. The variation in composition may be a result of premetamorphic hydrothermal alteration of the tuff layer to clay minerals, especially to K micas (sericite alteration), which may absorb trace elements—for example, boron—on account of their ion exchange capability (Potter et al., 1963). High concentration of pyrite and the ore elements indicate conditions similar to in the ore layers, as do also the peaks of Eu and Yb. High concentrations of Zr and Hf may indicate accumulation of zircon as a residual heavy mineral.

A relative increase in Mg is seen in the cordierite-bearing felsic metavolcanic rock layers above the deposit. High concentrations of Mg exist also above and below the pyrite-banded metatuff. Although in the upper part of the ore deposit Mg, Mn, and Ca are mainly incorporated in carbonates, the existence of abundant garnet, cordierite, and amphibole minerals indicates redistribution of Mg and Fe and suggests a premetamorphic, altered Mg-Fe mineral assemblage (chlorite alteration) in the rocks of the ore zone.

The quartz-kyanite rock is depleted in all major elements except SiO_2 and $Al2O_3$. Of the trace elements, there is a slight increase in Y, Th, U, and B. The probable premetamorphic minerals, silica and kaolinite, were deposited as a result of intense leaching by an acidic fluid (low pH). The peak of Cr in the Taivaljärvi sequence close to the kyanite-quartz rock layer (sample 8) is of interest. Schreyer (1982) considers that the fuchsite-aluminum silicate rocks in the Archean greenstone belts of Zimbabwe and Western Australia represent metamorphosed alunite-bearing deposits, where Cr was primarily incorporated in the alunite and clay minerals. An alunitic origin can well be postulated also for the Taivaljärvi quartz-kyanite rocks. The quartz-kyanite rock, an extensive key unit of the sequence, has been found in a stratigraphically similar position as much as 8 km southwest of the Taivaljärvi Silver Mine deposit. It could be interpreted as the cap rock of a hydrothermally altered pyroclastic sequence in which acid vapor leached all the minerals and deposited alunite, kaolinite, and silica.

On exsolution from magma, an aqueous fluid can consist of a single phase of intermediate salinity and density (Hedenquist and Taran, 2013). During ascent to a low-pressure regime, the fluid may intersect its solvus, where a low-salinity vapor and dense, hypersaline liquid separate. At this point, the solubility of the elements carried in the fluid changes, leading to precipitation of minerals such as carbonates and sulfides, depending on the primary anion concentrations. The saline fluid also causes alteration of the host rock to hydrous minerals (kaolinite, chlorite, montmorillonite, etc.).

Permeable lithologic units guide the condensates of magmatic vapor that contain SO_2 and HCl to flow laterally and form a subhorizontal blanket of alteration zones (Hedenquist and Henley, 1985; Hedenquist and Taran, 2013). As a lithocap, the advanced hydrothermal argillic alteration can extend to wide areas and provide a guide to districts where near-surface boiling zones may host precious and base-metal deposits. The dacitic volcanic rocks overlying the quartz-kyanite rock did not experience as intense hydrothermal alteration as did the underlying sequence, as the vapors causing the alteration were channeled laterally along the permeable layer and prevented from reacting with the rocks above. The quartz-rich layer at the top of the Taivaljärvi formation shows enrichment of silica and some lithophile elements. The rock could be interpreted as chemical sediment, chert, in origin.

The incompatible elements have often been classified as immobile (e.g., LREE, Ti, Zr, Y, Hf) and mobile (e.g., U, Th, Rb, Cs) in relation to hydrothermal processes. In altered volcanic rocks, Ti and Al are considered to be largely unaffected by regional alteration (Bence and Taylor, 1985) and their trends reflect magmatic processes. In the Taivaljärvi formation, the volcanic suite was originally heterogenous, varying from rhyolitic to andesitic-dacitic in composition. The marked difference in Ti content between the lower, altered part and the upper part of the Taivaljärvi formation is ascribed to this primary compositional difference. The upper part could have been primarily intermediate in composition, but secondary hydrothermal enrichment of SiO_2 altered the rocks, making them more silicic in composition yet not changing the primary high Ti content. The marked depletion of Y and Ti in the host rocks of the deposit indicates reactions caused by hydrothermal fluids.

Lemiére et al. (1986) have observed partial leaching of Y and Nb and total leaching of Mg, Ca, Na, K, and P_2O_5 in aluminous rocks formed by acid leaching. This finding may well apply to quartz-kyanite rocks, too. In the volcanic suite of the Taivaljärvi formation the altered rocks are slightly depleted in light relative to heavy rare earth elements. Michard et al. (1983) noted enrichment of light over heavy rare earth elements by a factor of ten in 13°N East Pacific Rise hydrothermal fluids. Preferential extraction of light rare earth elements can thus cause fractionation of rare earth elements. The negative Eu anomaly observed in the chondrite-normalized distribution patterns in the volcanic suite could be ascribed to plagioclase fractionation from the melt.

Bence and Taylor (1985), however, have noted that negative Eu anomalies can be generated during prograde alteration reactions, and positive Eu anomalies during retrograde reactions when the temperature drops and hydrothermal phases are precipitated. Eu enrichment has been observed in the active hydrothermal vents at 13°N on the East Pacific Rise (Michard et al., 1983). Bence and Taylor (1985) observed Eu enrichment relative to the adjacent rare earth elements in the vent alteration zone of the Balaklala mine, Shasta district, California. This is in harmony with the Taivaljärvi rare earth element distribution in which the negative Eu anomalies in the mineralized rocks are not as prominent as in other altered metavolcanic rocks.

ORIGIN OF THE DEPOSIT

The silver deposit is stratiform, with well-developed compositional layering. The geochemistry of the host rocks indicates zoning of premetamorphic hydrothermal potassic, chloritic, sericitic, and argillic alteration. Sulfides and other ore minerals characterize the ore zone as stratiform bands, dissemination, and fracture fillings. The carbonates in the upper part of the ore zone mainly fill fractures in the rock, and abundant Ca, Fe, Mn, and Mg characterize the geochemistry of this part. The observed carbonate mineral species, manganocalcite and manganoankerite, explain well the interdependence between the elements. The ore zone is depleted in the trace elements Sc and Y but enriched in Nb, W, and Mo. The barren interlayers in the deposit exhibit high silica contents and low carbonate contents.

From the anomalous ore metal contents, the ore layer can be traced laterally along the sequence to a considerable distance from the actual ore deposit, thus referring to the stratabound character of the ore. Carbonate minerals were deposited together with sulfides, sphalerite, and chalcopyrite, in particular, in the fractures of the upper part of the ore deposit. The existence of ore minerals and carbonates in the fractures of the metamorphosed host rock indicate late remobilization of sulfides and carbonates, but some observations also demonstrate that the fractures were folded together with the host rock and hence the fracture filling could partly be syngenetic with premetamorphic hydrothermal processes.

According to Kopperoinen and Tuokko (1988) and Papunen et al. (1989), mineralization took place during periods of hydrothermal activity following cycles of explosive volcanism. The fluids separated from the magma reservoir below the felsic volcanic rocks carried metal ions together with sulfur and carbonate species, and were homogenous at the time of separation from magma. During ascent as a hydrothermal plume along rock fractures to lower pressure levels, the fluids attained the boiling level where an acidic vapor separated from the fluid, escaped along permeable layers, and along these channel ways caused intense leaching of host rock. Due to boiling, the solubility of the ions in the primary fluid was reduced, and resulted in precipitation of sulfides and carbonates in the fractures. Precipitation of hydrothermal minerals healed the rock fractures that acted as channel ways for the hot mineralizing fluids and formed a network of sulfides, carbonates, and quartz.

Sulfur isotopes are generally similar throughout the sequence with the slight decrease in $\delta^{34}S$ values upward attributed to the temperature differences in the fluids between the ore horizons and the overlying sequences. The $\delta^{34}S$ values correspond well with those observed in the volcanic environment and, thus, the sulfur may be volcanic in origin.

Structural analysis by Parkkinen (2012) indicates that the ore deposit is located in a tightly isoclinally folded synclinorium structure, and the minor fold structures control the distribution of ore minerals. The geophysically indicated deep extension of the ore deposit may follow the fold structure, which plunges southwest, but at deep levels the plunge turns almost horizontal.

The deposit as a whole displays geochemical signatures that can be observed also in the pyrite-bearing metatuff layer east of the main ore. Unfortunately, sulfur was not analyzed from exactly the same samples as the trace elements and, thus, the S/Se ratios were approximated from the ore analyses.

In the deposit, the S/Se ratio fluctuates between 1400 and 4800, but in the barren pyrite-bearing metavolcanic rocks above the ore bodies, the ratio is between 15,000 and 18,000. The relationship is about the same as that observed by Auclair et al. (1987) between the high-temperature hydrothermal base-metal sulfides and the iron-rich sulfides of the low-temperature regime in the recent seafloor hydrothermal sulfide deposits at 13°N East Pacific Rise. Hence, the pyrite-banded metatuff might be of the same stratigraphic layer as the ore deposit, but more distal and of a low-temperature regime. In the folded sequence, a minor anticlinorium can be constructed to the east of the ore-bearing syncline, raising the possibility that the pyrite-bearing metatuff may be the same primary strata as the ore layer. The compositional difference is due to lateral difference between the proximal (ore) and distal (pyritic tuff) locations in a primary hydrothermal fluid plume.

The ore type can be defined on the basis of the data presented earlier. The association with felsic pyroclastic rocks, the stratiform setting, and the compositional alteration features around the deposit are consistent with a low-sulfidation epithermal deposit associated with a geothermal system. Also, the other features such as the scarcity of iron sulfides, the disseminated and stringer-vein-type ore textures, the abundant carbonate gangue minerals, the vertical arrangement of alteration zones with potassic alteration at the lowest stratigraphic levels overlain by chloritic and sericitic zones, and, finally, the zone of advanced argillic or acid-leached type of alteration above the ore deposit are all typical of the epithermal deposit type (Henley and Hedenquist, 1986). The quartz-kyanite rock represents the primary argillic lithocap alteration zone that formed along a permeable lithology suitable for the leaching of the host rock by acidic vapors, and left residual silica, aluminous clays, and alunite that recrystallized to quartz and kyanite during metamorphism.

The wide extent of the quartz-kyanite rock in the area is typical for lithocaps related to hydrothermal alteration plumes above felsic intrusions. In this sense, it is worth noting the observation (Papunen et al., 1989) that in drill cores, the Taivaljärvi volcanic sequence grades westwards to a homogenous felsic porphyry, which further turns to a felsic plutonic rock. In the magnetic map, an oval anomaly to the west of Taivaljärvi could indicate a partly magnetized intrusion. It is an open question whether the felsic volcanic rocks are associated with this intrusion, and if the Silver Mine deposit is related to a porphyry type system.

ACKNOWLEDGMENTS

The authors thank Hannu Huhma, Hugh O'Brien, and an anonymous reviewer for thorough reviews and improvements on the text.

REFERENCES

Auclair, G., Fouquet, Y., Bohn, M., 1987. Distribution of selenium in high-temperature hydrothermal sulfide deposits at 13° north, East Pacific Rise. Canadian Mineralogist 25, 577–587.

Bence, A.E., Taylor, B.E., 1985. Rare earth element systematics of the West Shasta metavolcanic rocks: Petrogeneis and hydrothermal alteration. Economic Geology 80, 2164–2176.

Blais, S., Auvray, B., Capdevila, R., et al., 1978. The Archaean greenstone belts of Karelia (Eastern Finland) and their komatiitic and tholeiitic series. In: Windley, B.F., Naqvi, S.M. (Eds.), Archaean Geochemistry. Elsevier, Amsterdam, p. 87–107.

Chen, T.T., Dutrizac, J.E., Owens, D.R., Lafiamme, J.H.G., 1980. Accelerated tarnishing of some chalcopyrite and tetrahedrite specimens. Canadian Mineralogist 18, 173–180.

Condie, K.C., 1981. Archean greenstone belts. Developments of Precambrian Geology 3, 434.

Engtec, C.T.S., 2014. Bankable Feasibility Study Sotkamo Silver Mine, p. 137. Accessible online at www.silver.fi.

Hedenquist, J.W., Henley, R.W., 1985. Hydrothermal eruptions in the Waiotapu geothermal system, New Zealand: Their origin, associated breccias and relation to precious metal mineralization. Economic Geology 80, 1640–1668.

Hedenquist, J.W., Taran, Y.A., 2013. Modeling the formation of advanced argillic lithocaps: volcanic vapor condensation above porphyry intrusions. Economic Geology 108, 1523–1540.

Helgeson, H.C., Delany, J.M., Nesbitt, H.W., Bird, D.K., 1978. Summary and critique of the thermodynamic properties of rock-forming minerals: American Journal of Science 278A, 1–229.

Henley, R.W., Hedenquist, J.W., 1986. Introduction to the geochemistry of active and fossil geothermal systems. Berlin-Stuttgart, Borntrager. Mineral Deposits Monograph 6, 1–22.

Hughes, C.J., 1973. Spilites, keratophyres and the igneous spectrum. Geology Magazine 109, 513–527.

Huhma, H., Mänttäri, I., Peltonen, P., et al., 2012a. The age of the Archaean greenstone belts in Finland. In: Hölttä, P. (Ed.), The Archaean of the Karelia Province in Finland. Geological Survey of Finland, Special Paper 54, 74–175.

Huhma, H., Kontinen, A., Mikkola, P., et al., 2012b. Nd isotopic evidence for Archaean crustal growth in Finland. In: Hölttä, P. (Ed.), The Archaean of the Karelia Province in Finland. Geological Survey of Finland, Special Paper 54, 176–213.

Hyppönen, V., 1983. Explanation to the maps of pre-Quaternary rocks, sheets 4411 Ontojoki, 4412 Hiisjärvi, and 4413 Kuhmo. Geological Map of Finland 1:100 000. Geological Survey of Finland, p. 60.

Käpyaho, A., Hölttä, P., Whitehouse, M.J., 2007. U-Pb zircon geochronology of selected Archaean migmatites in eastern Finland. Bulletin of the Geological Society of Finland 79 (1), 95–115.

Kopperoinen, T., Tuokko, I., 1988. The Ala-Luoma and Taivaljärvi Zn-Pb-Ag-Au deposits, eastern Finland. Geological Survey of Finland, Special Paper 4, 131–144.

Laukkanen, J., 2011. Silver mineralogy of the locked cycle products of Taivaljärvi silver deposit. Geological Survey of Finland, Report C/MT/2011XX, p. 20.

Lemiére, B., Delfour, J., Maine, B., et al., 1986. Hydrothermal alteration and the formation of aluminous haloes around sulfide deposits. Mineralium Deposita 21, 147–155.

Luukkonen, E.J., 1985. Structural and U-Pb isotopic study of late Archaean migmatitic gneisses of the Presvecokarelides, Lylyvaara, eastern Finland. Royal Society Edinburgh Earth Science Transactions 76, 401–410.

Luukkonen, E.J., 1988. The structure and stratigraphy of the northern part of the late Archaean Kuhmo greenstone belt, eastern Finland. Geological Survey of Finland, Special Paper 4, 71–96.

Luukkonen, E., Lukkarinen, H., 1986. Explanation to the stratigraphic map of middle Finland. Geological Survey of Finland, Report of Investigations 74, p. 47.

Martin, H., Querrè, G., 1984. A 2.5 Ga reworked sialic crust: Rb-Sr ages and isotopic geochemistry of late Archaean volcanic and plutonic rocks from eastern Finland. Contributions to Mineralogy and Petrology 85, 292–299.

Martin, H., Chauvel, C., Jahn, B.M., 1983. Major and trace element geochemistry and crustal evolution of Archaean granodioritic rocks from eastern Finland. Precambrian Research 21, 159–180.

Michard, A., Albarede, F., Michard, G., et al., 1983. Rare earth elements and uranium in high-temperature solutions from the East Pacific Rise hydrothermal vent field (13°N). Nature 303, 795–797.

Niskanen, M., 2012. Electromagnetic SAMPO soundings at Taivaljärvi 2011. Geological Survey of Finland Report M185K2011.

Niskanen, M., 2013. Electromagnetic SAMPO soundings at Taivaljärvi 2013. Geological Survey of Finland Report M178K2012.

Papunen, H., Kopperoinen, T., Tuokko, I., 1989. The Taivaljärvi Ag-Zn deposit in the Archean greenstone belt, eastern Finland. Economic Geology 84, 1262–1276.

Papunen, H., Halkoaho, T., Luukkonen, E., 2009. Archaean evolution of the Tipasjärvi-Kuhmo-Suomussalmi greenstone complex, Finland. Geological Survey of Finland, Bulletin 403, p. 68.

Parkkinen, J., 2010. Rakenneanalyysin ja geostatistiikan synteesi (English summary: Taivaljärvi Ag-Zn-Pb-Au deposit, Synthesis of structural analysis and geostatistics). Geologi, Helsinki. 62, 238–243.

Parkkinen, J., 2012. Unfolding Taivaljärvi. Geologi, Helsinki. 64, 70–74.

Parkkinen, J., 2013. Silver Mine Deposit at Sotkamo: Geological Model of EM Sampo Soundings. Accessible online at www.silver.fi.

Peltoniemi, S., 2011. Pilot Plant on Taivaljärvi ore. GTK Mintek Research Report, p. 47.

Pietikäinen, K., Halkoaho, T., Hartikainen, A., 2008. Tipasjärven vihreäkivivyöhykkeen malmivarojen kartoitushankkeen (2901006) toiminta vuosina 2005–2007 Sotkamon, Valtimon, Kuhmon ja Nurmeksen alueilla. Geological Survey of Finland. Report M10.4/4322/2008/27, p. 65. (in Finnish).

Piirainen, T. (Ed.), 1985. Arkeeisten alueiden malmiprojektin loppuraportti (Progress report on the ore research project on the Archaean areas). University of Oulu, Department of Geology. Report 28, p. 183 (in Finnish).

Potter, P.E., Shrimp, N.E., Whitter, J., 1963. Trace elements in marine and fresh-water argillaceous sediments. Geochimica et Cosmochimica Acta 27, 669–694.

Riley, J.F., 1974. The tertahedrite-freibergite series, with reference to the Mt. Isa Pb-Zn-Ag orebody. Mineralium Deposita 9, 117–124.

Schreyer, W., 1982. Fuchsite-aluminium silicate rocks in Archaean greenstone belts: Are they metamorphosed alunite deposits? Geologische Rundschau 71, 347–360.

Sorjonen-Ward, P., Luukkonen, E.J., 2005. Archaean rocks. In: Lehtinen, M., Nurmi, P.A., Rämö, O.T. (Eds.), Precambrian Geology of Finland: Key to the Evolution of the Fennoscandian Shield. Elsevier., Amsterdam, pp. 19–99.

Taipale, K., 1983. The geology and geochemistry of the Archaean Kuhmo greenstone-granite terrain in the Tipasjärvi area, eastern Finland. Acta Universitatis Ouluensis, Ser A5, 98.

Vaasjoki, M., Taipale, K., Tuokko, I., 1999. Radiometric ages and other isotopic data bearing on the evolution of Archaean crust and ores in the Kuhmo-Suomussalmi area, eastern Finland. Bulletin of the Geological Society of Finland 71, 155–176.

Vartiainen, H., 1970. Schist belt of Tipasjärvi in the parish of Sotkamo, Finland. Bulletin of the Geological Society of Finland 42, 13–22.

Wardell Armstrong International, 2012. Taivaljärvi mine bankable feasibility study, summary. Accessible online at www.silver.fi.

Winchester, J.A., Floyd, P.A., 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology 20, 325–343.