PART

7

THE VIHANTI-PYHÄSALMI VMS BELT

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ABSTRACT

The Vihanti-Pyhäsalmi belt contains the most important volcanogenic massive sulfide (VMS) deposits in Finland. The volcano-sedimentary host rocks belong to a 1.93–1.92 Ga island arc that occurs along the northwestern parts of the Raahe-Ladoga shear complex. The stratigraphy in the region is divided into two units, a lower bimodal volcanic unit conforming to the Pyhäsalmi group and an upper volcano-sedimentary association defined as the Vihanti group. The U-Pb zircon ages of the two groups are similar.

The Vihanti-Pyhäsalmi belt hosts two large VMS deposits, Pyhäsalmi in the Pyhäsalmi group and Vihanti in the Vihanti group, as well as a number of small sulfide deposits located around them. The Pyhäsalmi deposit is hosted by rhyolitic and basaltic volcanic rocks, contains 75.7 Mt of pyritic mineralization grading 0.9% Cu, 1.9% Zn, 0.4 g/t Au, and 14.1 g/t Ag, and hosts the only currently producing mine (2014) in the belt. The Vihanti mine operated from 1954–1992, producing 28 Mt at 5.12% Zn, 0.48% Cu, 0.36% Pb, 25 ppm Ag, and 0.49 ppm Au. The Vihanti deposit and three minor satellite mineralizations are hosted in a sequence dominated by intermediate and felsic metavolcanic rocks.

Keywords: stratigraphy; VMS-deposit; Paleoproterozoic; Svecofennian; Pyhäsalmi; Vihanti; Finland.

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REGIONAL GEOLOGY OF THE VIHANTI-PYHÄSALMI BELT

The bedrock of the Vihanti-Pyhäsalmi belt forms the easternmost part of the Paleoproterozoic Svecofennian domain, bordered by Archean basement complexes (3.1–2.6 Ga) in the east and the Central Finland Granitoid Complex and related supracrustal formations (1.93–1.87 Ga) of the Svecofennian domain in the west (Fig. 7.1). The area belongs to the northwest–southeast trending Raahe-Ladoga zone (RLZ) that represents the collisional border of Paleoproterozoic island arcs against Archean terranes (Korsman et al., 1997). The RLZ is considered the main sulfide ore belt in Finland (Kahma, 1973). Table 7.1 shows the production data of the most important deposits.

The Vihanti and Pyhäsalmi volcanogenic massive sulfide (VMS) deposits are genetically related to the Paleoproterozoic island arc that formed in an ocean located on the western side of the Archean basement complex 1.93–1.92 Ga ago (Mäki, 1986; Gaál and Gorbatschev, 1987; Ekdahl, 1993; Lahtinen, 1994; Kousa et al., 1994; Roberts et al., 2004 Eilu et al., 2013). Supracrustal rocks along the RLZ are mainly turbiditic metasedimentary rocks that locally contain abundant graphite-bearing schists and minor mafic metavolcanic interlayers. This sequence is defined as the Näläntöjärvi suite by Laajoki and Luukas (1988) and it has been proposed that it is a depositional basement for the volcanic rocks of the island arc (Kousa, 1997). The volcanic arc-related rocks of the Vihanti-Pyhäsalmi belt contain several separate volcanic centers, which now appear in narrow and discontinuous belts in the western part of the Näläntöjärvi suite (Fig. 7.1). The narrow volcanic configuration is the result of intrusions of voluminous postvolcanic Svecofennian plutons. The bimodal metavolcanic rocks of the Pyhäsalmi group have distinct lithogeochemical signatures on which basis they can be separated from the 1.89–1.88 Ga Ylivieska-type metavolcanic rocks in the west (Mäki, 1986; Rasilainen and Västi, 1989; Kousa et al., 1994). The regional metamorphic grade in the Vihanti-Pyhäsalmi belt is mainly from lower amphibolite facies to upper amphibolite facies. Locally, for example, in the Kiuruvesi area, the metamorphic grade is higher and reaches granulite facies (Korsman et al., 1997).

The volcanic belt appears separated into two blocks by major southwest–northeast and southeast–northwest trending faults, namely the Oulujärvi shear zone (Kärki et al., 1993) and the Revonneva and Ruhaperä shear zones (Luukas, 1997) (Fig. 7.1). Both blocks show distinct lithological features that have been used to define the Vihanti and Pyhäsalmi lithological associations. In the Vihanti block, intermediate and felsic metavolcanic rocks are the dominant protoliths but mafic metavolcanic rocks are minor and sparsely distributed. In the Pyhäsalmi-Kiuruvesi block, a wider range of volcanic compositions exists with a bimodal felsic–mafic metavolcanic association being the most characteristic. We propose a schematic informal lithostratigraphical classification for the Vihanti and Pyhäsalmi groups (Fig. 7.1). This interpretation should be regarded as tentative because of the sparse outcrop relations of the belt and overlapping dating results of the metavolcanic rocks of both groups. Nevertheless, these two different lithological associations indicate at least two different volcanic environments despite their similar age of 1.93–1.92 Ga (Kousa et al., 2013). The Pyhäsalmi group represents a lower bimodal felsic-mafic metavolcanic sequence over which the Vihanti group, a series of felsic and intermediate metavolcanic rocks with calc-silicate and graphite tuffite interlayers, was deposited during continuous evolution of the arc. This stratigraphic succession is based on observations in the Pyhäsalmi-Kiuruvesi-Pielavesi area where the oldest Pyhäsalmi group rocks are exposed in antiformal dome centers and the Vihanti group rocks are exposed in synformal basins between the antiforms.

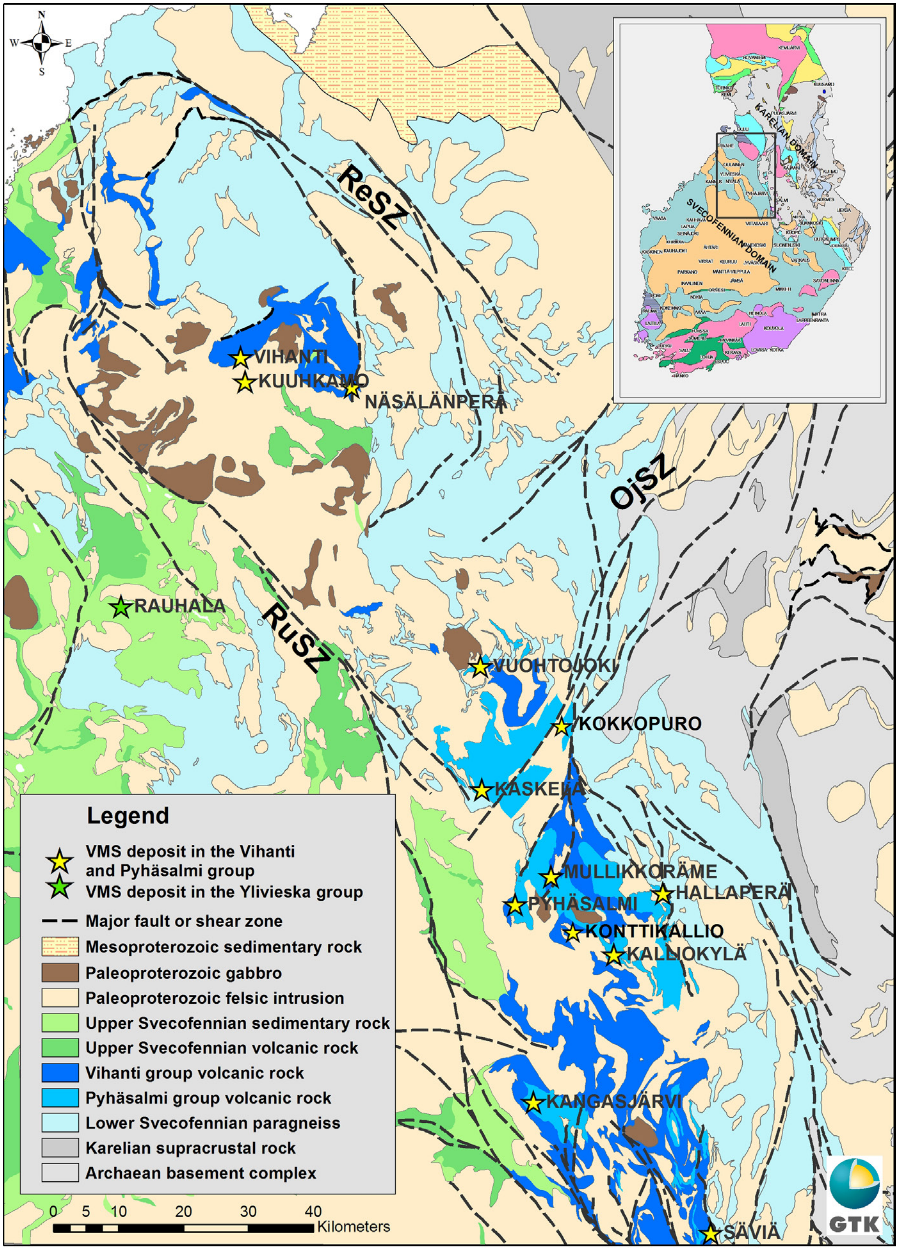

FIGURE 7.1 General geology of the northwestern part of the Raahe-Ladoga zone.

The most important Zn-Cu deposits of the Vihanti and Pyhäsalmi area are shown with stars. The main structural features are represented by black dashed lines (OjSZ = Oulujärvi shear zone, ReSZ = Revonneva shear zone, RuSZ = Ruhaperä shear zone).

Source: *The base map is modified after Bedrock Map of Finland–DigiKP (2013).*

Table 7.1 Production of ore, Pyhäsalmi, Vihanti, and satellite mines, 1962–2012

Deposit	Production (t)	Cu%	Zn%	Pb%	S%	Au g/t	Ag g/t
Pyhäsalmi[a]	58,500,000	0.94	2.38		38	0.4	14
Kangasjärvi[b]	80,000	0.1	5.4		38		
Ruostesuo[b]	240,000	0.4	2.7		30	0.3	10
Mullikkoräme[b]	1,148,000	0.3	6.1	0.9		1	45
Vihanti[b]	28,100,000	0.5	5.1	0.4		0.5	25
Kuuhkamo	150,000		4				
Näsälänperä	100,000		2				15

[a]*Production and reserves*
[b]*Production*

VOLCANOGENIC MASSIVE SULFIDE DEPOSITS OF THE VIHANTI AREA

EXPLORATION AND MINING HISTORY

The Vihanti area covers about 10 × 20 km and contains one major massive sulfide ore deposit with three small uneconomic satellite deposits. The Vihanti mine (known also as the Lampinsaari mine) produced 28.1 Mt (million metric tons) of sulfide ore from 1954–1992. Exploration in the Vihanti area started in 1936 when the first studies were focused on locating the host rock of Zn-rich sulfide boulders. The Geological Survey of Finland (GTK) made the first geological and geophysical maps and drillings in the 1940s and the discovery holes were drilled in 1946 at Lampinsaari. The Outokumpu mining company (Outokumpu) obtained the prospecting rights in 1951 and continued exploration in the area. The Vihanti mine was opened in 1954 when reserves were 6 Mt of 12.5% Zn ore. An underground mine extended down to 800 m depth and the mine was closed in 1992. As a result of intense exploration in the nearby area, Outokumpu discovered the Näsälänperä mineralization further southeast in the Vilminko area in 1978 and the Kuuhkamo mineralization 4 km southeast of the Vihanti mine in 1987.

Once Outokumpu had stopped mining and exploration activities in the Vihanti mine, the GTK restarted geological studies in the district. As a result of these investigations, the Kokkoneva sulfide body was found in 1999 in the Vilminko area (Kousa and Luukas, 2004).

GENERAL GEOLOGY

The 1.92 Ga metavolcano-sedimentary rocks of the Vihanti area belong to the Vilminko formation of the Vihanti group (Fig. 7.2). The Vilminko formation is mainly composed of thick layers of intermediate and felsic metavolcanic rocks and minor interstratified mafic metavolcanic rocks. A distinct calc-silicate horizon is intercalated with dolomites and graphite-bearing felsic metatuffs forming a continuous layer, known as the U-P horizon in reference to the uranium and phosphorous trace components (Rehtijärvi et al., 1979). This intercalation, known also as the Lampinsaari association (Rouhunkoski, 1968), is the key horizon for the massive sulfide deposits in the Vihanti area. The electromagnetic properties of the graphite and sulfide components of this horizon make it easy to delineate on geophysical maps. A massive graywacke sequence forms the uppermost lithological unit

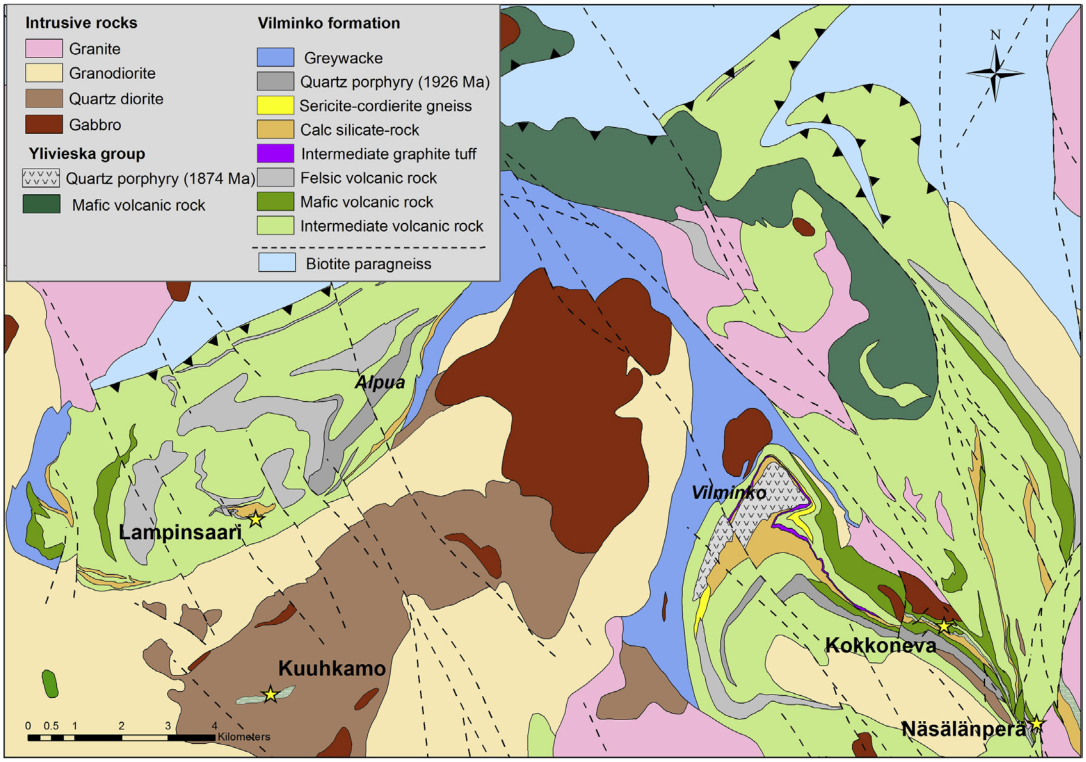

FIGURE 7.2 Geology of the Vihanti area.

Source: *The map is modified after Bedrock of Finland–DigiKP (2013).*

of the Vilminko formation. A younger sequence of volcanic rocks and volcaniclastic sediments (Ylivieska group) were deposited on the Vihanti group rocks at 1.89–1.87 Ga ago (Rasilainen and Västi, 1989; Kousa and Luukas, 2007).

The magmatic history of the Vihanti area covers a timespan from approximately 1.93–1.87 Ga (Vaasjoki and Sakko, 1988; Kousa et al., 2013). In the volcanic sequence, two different porphyry sills have been dated. A quartz-plagioclase porphyry sill (the Kokkoneva porphyry) gives an age of 1926 ± 6 Ma, which is similar to ages of the metavolcanic rocks in the Pyhäsalmi area (Kousa et al., 2013). This sill is identified in the vicinity of the Vihanti, Kuuhkamo, and Vilminko mineralizations. At all locations, the Kokkoneva porphyry is completely or partly altered and contains a remarkable amount of disseminated pyrite. These metamorphosed altered rocks are expressed as quartz rocks or cordierite-sillimanite-sericite rocks. It is suggested that a genetic connection exists between this porphyry type and VMS ore forming processes in the Vihanti area (Nikander et al., 2002; Luukas and Kousa, 2013). A younger quartz porphyry sill (1874 ± 3 Ma) intruded the Vilminko formation in the Vilminko area (Kousa and Luukas, 2007).

Structural interpretations indicate that metavolcanic rocks of the Vilminko formation form an open anticline in the Vihanti mine area and an open syncline in the Näsälänperä area. The stratigraphic model (Fig. 7.3) of the Vihanti group is based on the lithological sequences from the Vilminko area.

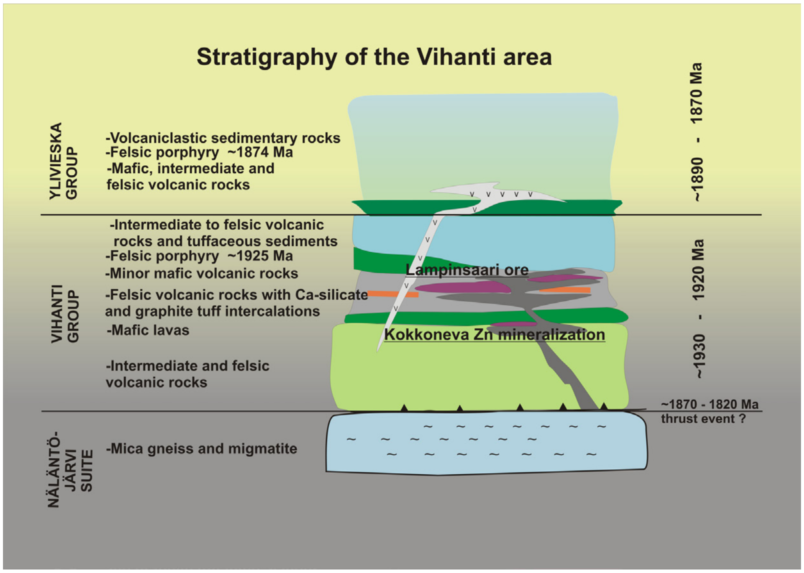

FIGURE 7.3 Stratigraphy of the Vihanti area.

VIHANTI DEPOSIT

The Vihanti Zn-Pb-Ag deposit is situated on the southwestern edge of the antiformal dome of the Lampinsaari-Alpua area (Kousa and Luukas, 2004) (Fig. 7.2). The volcanic sequence is composed of felsic to intermediate metavolcanic rocks with minor mafic metavolcanic rocks. The sequence is intruded by porphyritic granitoids and gabbros to the south. Sulfide mineralization is focused along a more than 100-m-thick and 1500-m-long sequence of altered felsic metavolcanic rocks, calc-silicate rocks, dolomites, and graphite-bearing metatuffs (U-P horizon). The volcanic stratum is cut at a low angle by a 50–100-m-thick altered quartz porphyry sill, causing alteration in the vicinity of Lampinsaari, identified now as cordierite-altered volcanic beds. Mineralized incompetent calcareous rocks and massive sulfide ore lenses have been intensely folded on the southern edge of the Lampinsaari anticline (Fig. 7.4). The lower part of the ore (between +350 and +800 mine levels) forms a fold limb that dips about 45° southward. The general fold axis dips south–southwest.

There are 5 different ore types in the Vihanti deposit and about 20 separate ore bodies that have been mined out. The metal content and size varies greatly between different bodies (Rouhunkoski, 1968). The most important ore types are the Zn ores of which the three largest (Ristonaho, Välisaari, and Lampinsaari) contained about 75% of the total mined ore (Autere et al., 1991). Minor Zn ore bodies were mined out along the southern fold limb down to the +800 mine level. The Zn-ores typically occur in tectonically thickened calc-silicate-dolomite-serpentinite beds in the upper levels of the mine. Although Zn-ores contain some Ag and Au, a separate disseminated Pb-Ag ore type occurs in close connection to the Zn-ores. The best Pb-Ag ores were found in the western part of the mine. Pyrite- or pyrrhotite-rich ores, which are situated in the stratigraphically upper parts of the mineralized horizon, are termed *pyrite ores*. The Hautaräme and Hautakangas ore bodies on the southeasterly dipping limb area are massive pyrite ores hosted by felsic metavolcanic and calc-silicate rocks. Cu ores occur in the felsic metavolcanic rocks. They are disseminated ore types and are closely related to the pyrite ores.

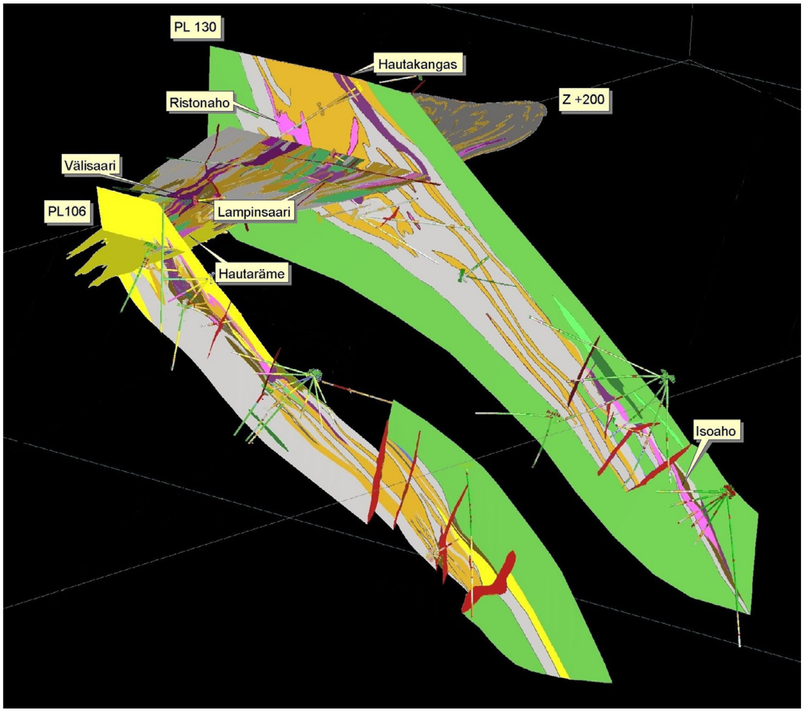

FIGURE 7.4 Geology of the Vihanti mine and its main ore bodies.

Viewing direction is from the south. Rock types: green = intermediate metavolcanic rocks; gray = calc-silicate banded felsic metavolcanic rock; orange = calc-silicate rock, dolomite; lilac = ore; yellow = cordierite-sillimanite gneiss; red = younger dikes. Distance between cross sections 106 and 130 is 600 m.

Source: *Mine level +200 is modified after Rouhunkoski (1968).*

The fifth separate ore type is uranium-phosphorous ore, which occurs as a discontinuous layer in the upper part of the U-P horizon along the southeast-dipping limb area. This unexploited ore type is hosted by banded calc-silicate bearing felsic metavolcanic rocks (Rehtijärvi et al., 1979). The underground production of the Vihanti mine was 28 Mt ore, which contained 5.1% Zn, 0.5% Cu, 0.4% Pb, 25 ppm Ag, and 0.5 ppm Au.

KUUHKAMO MINERALIZATION

In the 1950s, Outokumpu located a Lampinsaari-type lithological sequence at a distinct EM-anomaly located 4 km south of the Vihanti mine. However, the Kuuhkamo zinc mineralization was not discovered until the 1980s. The Kuuhkamo mineralization resembles the Vihanti deposit lithologically. It occurs as a small window of graphite-bearing intermediate metavolcanic rock inside a quartz diorite intrusion (Fig. 7.2). Structurally, the Kuuhkamo mineralization forms a tight east–west trending anticline with a hinge zone that is exposed at the surface (Fig. 7.5). The fold axis plunges westward at an angle of 40°. The total resources of the Kuuhkamo deposit is estimated to be less than 0.25 Mt, of which 0.15 Mt at 4% Zn is in the main lode (http://tupa.gtk.fi/karttasovellus/mdae/raportti/526_Kuuhkamo.pdf, 5.5.2015; Nikander et al., 2005a).

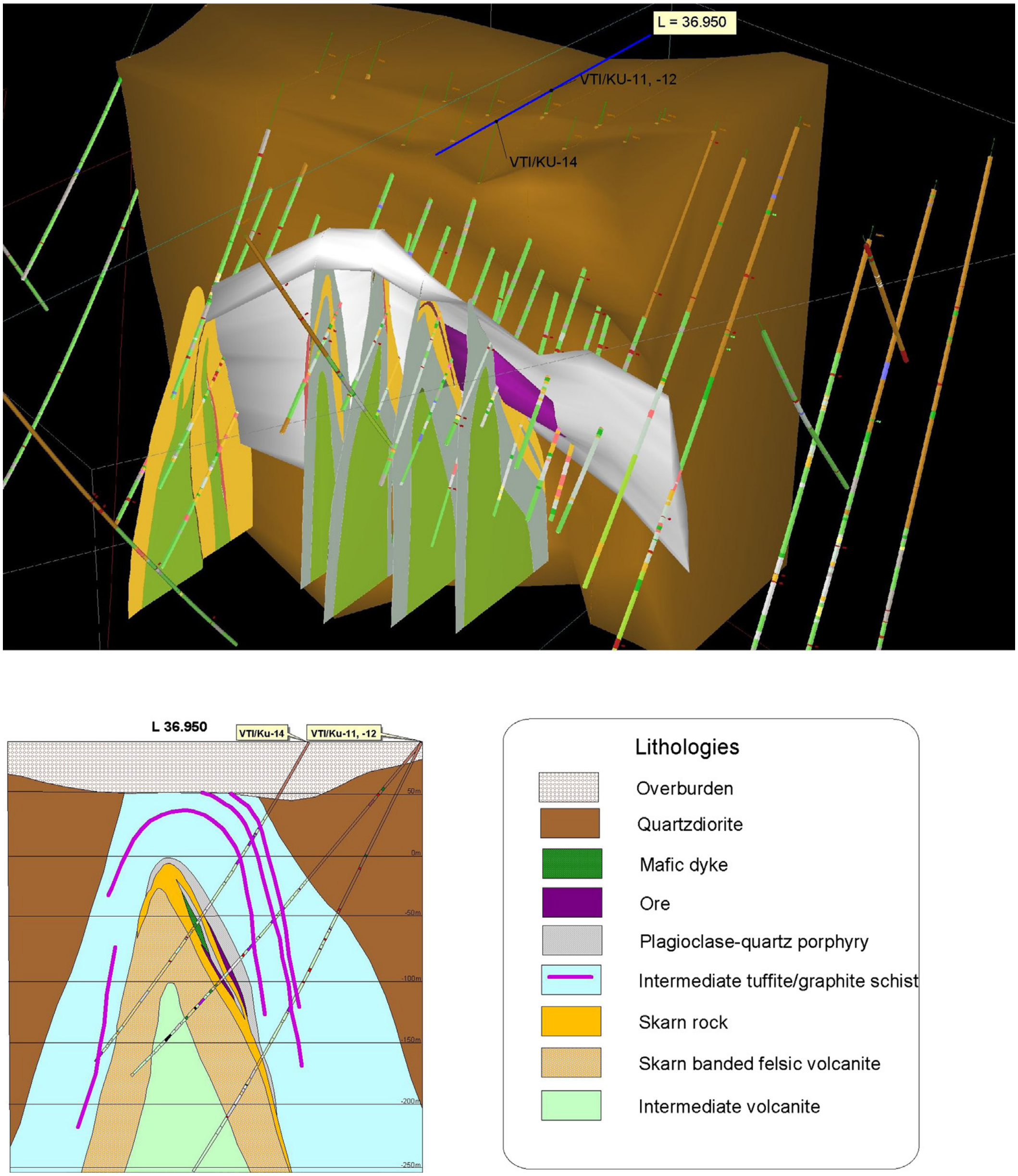

FIGURE 7.5 Geology of the Kuuhkamo deposit and profile.

L = 36.950.

The lowermost part of the volcanic pile consists of intermediate metavolcanic rocks, which are followed by a 10–50-m-thick horizon of felsic metavolcanic rocks, calc-silicate rocks, serpentine dolomites, and minor graphite-bearing metatuffs (U-P horizon). This horizon is covered by a new layer of intermediate metavolcanic rocks and graphite-bearing metatuffites, which are the source of strong electromagnetic anomalies. This volcanic sequence is cut by several 5–20-m-thick quartz porphyry sills that are similar to the Lampinsaari porphyry. The volcanic strata were folded and then cut by voluminous quartz diorite intrusions, the extent of which is also outlined from interpretation of seismic data (Heinonen, 2013).

Mineralization is mainly found on the southern limb of the antiform. The sulfide ore is related to a synvolcanic porphyry sill, a medium-grained quartz plagioclase porphyry that intruded between the U-P horizon and the overlying intermediate metatuffites. In the proximity of the mineralization, the porphyry has been altered and metamorphosed to a cordierite gneiss analogous to that of the Lampinsaari deposit.

MINERALIZATIONS AT VILMINKO-NÄSÄLÄNPERÄ AREA

Two minor sulfide mineralizations are situated in the Vihanti formation in the Vilminko-Näsälänperä area (Fig. 7.2). Lithologically the area resembles the Lampinsaari-Alpua area in the west. Outokumpu located a small zinc mineralization at Näsälänperä in 1978. The highly sheared mineralization is composed of two narrow pyrrhotite-sphalerite bearing ore lodes hosted by calc-silicate bearing felsic metavolcanic rocks. The ore lodes are 1–2 m thick and about 200 m long. The estimated resource is 100,000 t of ore, which contains about 2% Zn and 15 ppm Ag (http://tupa.gtk.fi/karttasovellus/mdae/raportti/528_Näsälänperä.pdf, 5.5.2015).

Another minor sulfide mineralization is situated 2.5 km northwest of Näsälänperä at the southwest limb of the Peuraneva syncline. This Kokkoneva mineralization was found during the GTK's regional studies in the Vihanti area in the late 1990s. Sulfide mineralization is located between the Kokkoneva quartz porphyry sill and mafic metavolcanic rock (Fig. 7.3). According to the stratigraphic model, the subvolcanic porphyry sill has intruded along a contact zone between intermediate and mafic volcanic rock below the calc-silicate bearing U-P horizon. In this respect, the Kokkoneva mineralization represents an example of mineralization under the typical U-P horizon. The total length of the sill is approximately 8 km and the thickness less than 100 m. The upper part of the porphyry sill is altered and metamorphosed to quartz K-feldspar or cordierite-sillimanite rock. The mineralization is mainly disseminated, but breccia ore textures also exist. Typical ore minerals are pyrrhotite, pyrite, sphalerite, chalcopyrite, and magnetite. The mineralization is about 250 m long and at ground surface the thickness is 1–2 m. The wedge-like ore body is cut by faults at 30–40 m depth. The ore is interpreted to have formed by hydrothermal replacement of volcanic strata adjacent to the felsic porphyry sill (Nikander et al., 2002; Nikander et al., 2005b).

ORE MODEL

Rouhunkoski (1968) explained cordierite gneiss and some calc-silicate rocks in Lampinsaari mine as products of extensive Mg-metasomatism by the ore-forming solutions. Recent studies show that an altered quartz porphyry sill, now metamorphosed to cordierite-sillimanite rock, has an important role in the ore-forming processes (Nikander et al., 2002). A two-stage ore-forming process could explain the diversity of ore types in the Vihanti area. The first stage represents primary sulfide ore formation by hydrothermal processes at the seafloor. In the Vihanti area, such primary sulfide deposits could be located in the upper part of the felsic metavolcanic to calc-silicate rock sequence (e.g., Hautaräme and Hautakangas lodes). During the second stage, a felsic subvolcanic sill intruded into mineralized horizons and in some way facilitated the formation of replacement ores in the nearby thick calc-silicate rocks.

VOLCANOGENIC MASSIVE SULFIDE DEPOSITS OF THE PYHÄSALMI AREA

EXPLORATION AND MINING

The Pyhäsalmi area and the surrounding regions have been under intense exploration since the 1950s, mainly by Outokumpu and GTK. The Pyhäsalmi deposit was found in August of 1958 by a local farmer who was digging a well in his yard in the Ruotanen village of the Pyhäjärvi municipality. Soon after discovery, Outokumpu acquired the mineral rights from the family and commenced exploration. The first drilling intersection was 38.5 m of massive sulfide grading 5.7% Zn, 0.9% Cu, and 48% S. The first estimation of reserves in February 1959 indicated 12.2 Mt of ore with 0.81% Cu, 2.93% Zn, and 36.8% S. Mine construction started in August 1959 and production from an open pit commenced on March 1, 1962. Since 1976 all production has been from the underground mine.

The mine has been deepened gradually and reached a depth of 1000 m in 1996 (Fig. 7.6). A new ore body was found in December 1996 and the decision to build a new mine was made in 1998. Production via a new shaft commenced on July 1, 2001. The Canadian mining company Inmet Mining Corporation

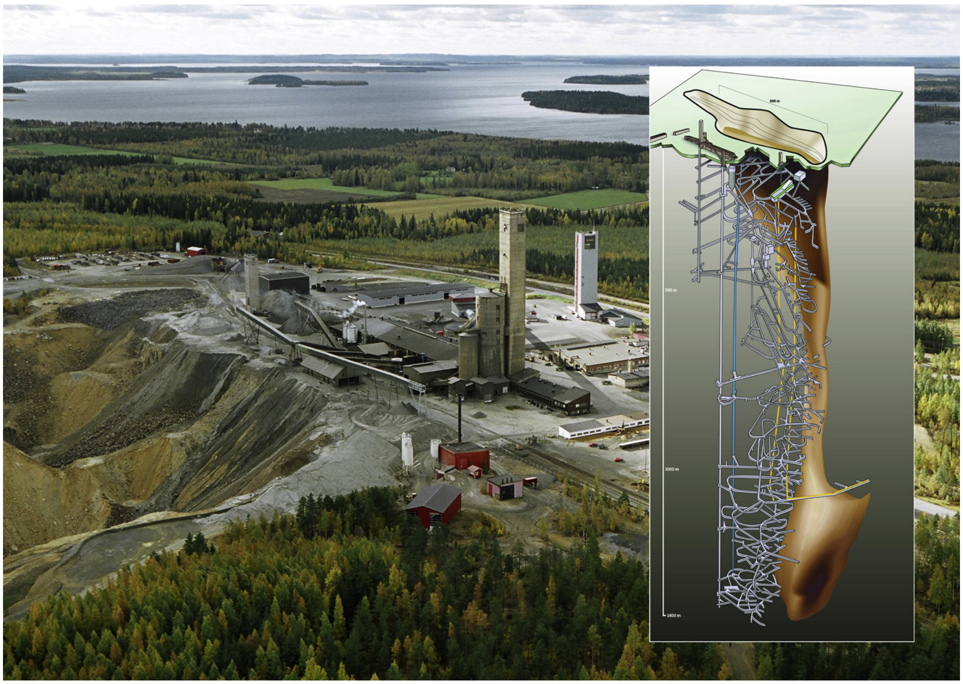

FIGURE 7.6 Aerial and axonometric view of the Pyhäsalmi mine and location map.

acquired the Pyhäsalmi mine in 2002, and in 2013 another Canadian company, First Quantum Minerals, took over Inmet Mining Corporation and also the Pyhäsalmi mine. The Pyhäsalmi mine is one of the most efficient underground mines in its size class. The deepest point of the mine is 1444 m below surface, making it the deepest base metal underground mine in Europe as of 2014.

During the exploration period after the initial opening of the Pyhäsalmi mine, several small massive sulfide deposits (Kalliokylä or Ruostesuo, Kangasjärvi, Hallaperä, Vuohtojoki, and Kokkopuro) were found in the Pyhäsalmi area (Fig. 7.1). The first satellite mine was the Kangasjärvi mine (Fig. 7.1) in Keitele, which GTK discovered in 1964. The second satellite mine was Ruostesuo (Kalliokylä) about 16 km southeast of Pyhäsalmi. The Ruostesuo deposit was discovered by Outokumpu in 1959 and was in production from 1988–1989. The Mullikkoräme deposit (Figs. 7.1 and 7.8), located 10 km to the northeast of Pyhäsalmi, was discovered by Outokumpu in 1987. This satellite mine was in production from 1989–1990 and again from 1996–2000. Three other satellite deposits in the Pyhäsalmi area are the Hallaperä deposit, the Vuohtojoki deposit, and the Kaskela deposit (Fig. 7.1). These massive sulfide deposits have been uneconomic and have not been mined (Ekdahl et al, 1997).

Exploration has continued around the Pyhäsalmi deposit and two new mineralizations have been found: Konttikallio between Pyhäsalmi and the Ruostesuo deposit, and Kokkopuro located 25 km north of Pyhäsalmi (Fig. 7.1). Both are small and uneconomic.

PRODUCTION AND RESOURCES

Total production at Pyhäsalmi since the beginning of mining has been 51 Mt (end of 2013) grading 0.92% Cu, 2.45% Zn, and 37.4% S. The ore also contains, on average, 0.4 g/t Au and 14 g/t Ag. Along with production from the Pyhäsalmi mine, three satellite deposits have also been processed in the

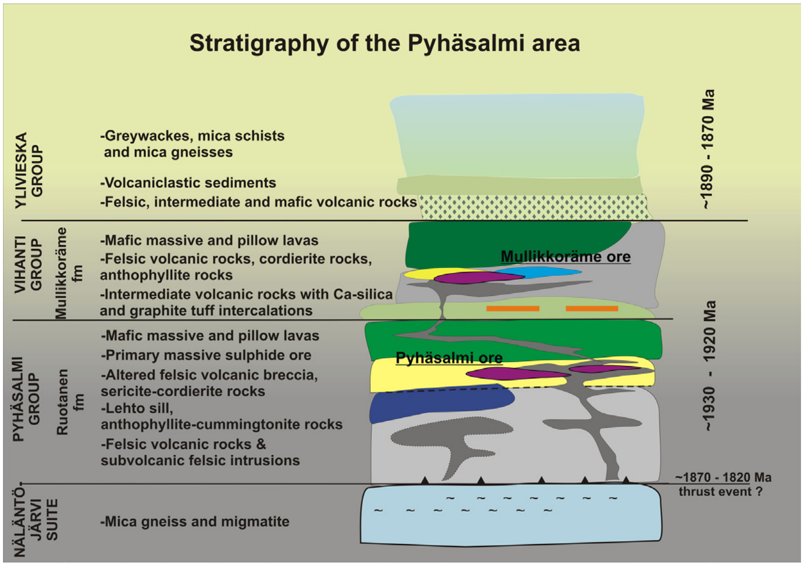

FIGURE 7.7 Stratigraphy of the Pyhäsalmi area.

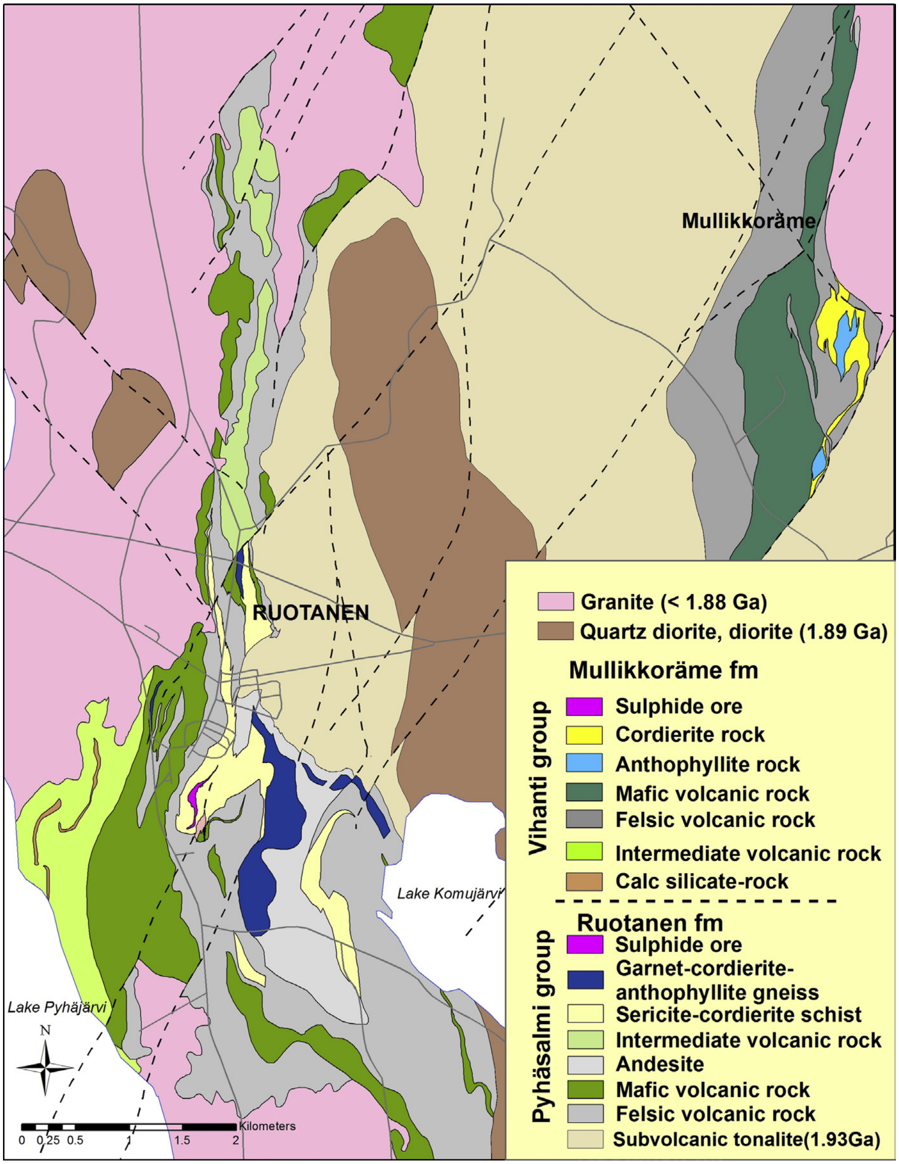

FIGURE 7.8 Geology of the Pyhäsalmi-Mullikkoräme area.

Source: *Map is modified after Bedrock of Finland–DigiKP (2013).*

Pyhäsalmi mill. Ore and concentrate production from Pyhäsalmi and its satellites are shown in Tables 7.1 and 7.2.

Mining of the Pyhäsalmi ore has been challenging because of high horizontal rock stress, which is two times greater than the vertical stress. Amphibolite facies regional metamorphism has led to sulfide recrystallization and formation of very coarse grained, strained, and deleterious-free ore assemblages.

Table 7.2 Production of concentrates and metals, 1962–2012

Product	
Copper concentrate	1,681,627 t
Copper metal	429,629 t
Zinc concentrate	2,307,459 t
Zinc metal	1,205,109 t
Pyrite concentrate	27,138,657 t
Au in copper concentrate	6987 kg
Ag in copper concentrate	349,431 kg

The Pyhäsalmi mine is also a very important pyrite producer and delivers 800,000 t of pyrite concentrate annually (Mäki, 2013). Annual ore hoisting is about 1.4 Mt. According to the latest mineral reserve estimation, the mine will operate until 2019 (Mäki, 2013). New resource exploration inside the mine lease is in progress.

REGIONAL GEOLOGY

The 1.93–1.92 Ga bimodal metavolcanic rocks of the Pyhäsalmi region belong to the Pyhäsalmi group, which is inferred to be the lowermost exposed volcanic unit in the Svecofennian domain. The depositional basement of the Pyhäsalmi group is unknown. The slightly younger or coeval Vihanti group with intermediate to felsic metavolcanics, minor calc-silicate–dolomite interlayers and minor mafic intercalations is deposited on the top of Pyhäsalmi type rocks. A schematic stratigraphic model of the Pyhäsalmi area is presented in Fig. 7.7.

In the present configuration, the metavolcanic rocks of the Pyhäsalmi group are situated in antiformal domes, whereas the overlying metavolcanic and metasedimentary rocks of the Vihanti group occupy synformal basins. A specific intrusion type of subvolcanic tonalite that is situated in the antiformal structure is closely related to the 1.93–1.92 Ga volcanic event. Later in the geological evolution, voluminous Svecofennian intrusive rocks (1.89–1.87 Ga) penetrated the volcanic sequences. The metavolcanic rocks of the Pyhäsalmi group in the Pyhäsalmi mine area belong to the Ruotanen formation (Puustjärvi, 1999). According to the inferred stratigraphy, a voluminous pile of felsic metavolcanic rocks form the lowermost part of the formation. The pinkish gray Na-rich quartz plagioclase-phyric rhyolitic rocks contain abundant mafic dikes.

The Kettuperä gneiss unit (sample A0751 in Helovuori, 1979) in the Pyhäsalmi group is interpreted here as the oldest felsic volcanic member of the Ruotanen formation. A new zircon U-Pb dating gives an age of 1924 ± 3 Ma to this sample, which is considered as a reliable age for the volcanism of the Pyhäsalmi group (Kousa et al., 2013). This unit is overlain by voluminous felsic breccias that are strongly altered and metamorphosed into cordierite-sericite schists. This pyroclastic unit is the host for the main sulfide ore body and presents abundant pyrite dissemination. The felsic metavolcanic rocks are overlain by massive mafic metalavas, which form the uppermost part of the Ruotanen formation. Intermediate metavolcanic rocks with minor calc-silicate interlayers (Vihanti group) overlie the Ruotanen formation.

In the Mullikkoräme area, about 8 km northeast of the Pyhäsalmi mine, the felsic and mafic metavolcanic rocks are named the Mullikkoräme formation, and are proposed to be representatives of the

Vihanti group in the Pyhäsalmi region (Bedrock of Finland–DigiKP, 2013). The zircon U-Pb age of 1921 ± 2 Ma from the Riitavuori metarhyolite and the age of 1925 ± 4 Ma from a metarhyolite at the Mullikkoräme mine area are both from the Mullikkoräme formation. These results indicate that both the Pyhäsalmi group and the Vihanti group were both formed within a short period of only a few million years (Kousa et al., 2013).

The Pyhäsalmi Deposit

The Pyhäsalmi deposit is the largest VMS deposit in the Vihanti-Pyhäsalmi belt. It is hosted in a metamorphosed volcanic sequence composed of lapilli tuffs, coherent lava flows, and sill-shaped intrusions of varied composition (Figs. 7.7 and 7.8). Rhyolitic volcaniclastic rocks are the most common host rock near the sulfide deposit. Voluminous pegmatites are emplaced along the main subvertical foliation near the eastern tectonized contact of the Pyhäsalmi deposit. Further to the east, sericite-altered felsic metavolcanic rocks are gently dipping to the east and at depth they extend under the granitoids (Heinonen, 2013). The upper part of the Pyhäsalmi deposit consists of subvertical intercalations of Zn- and Cu-bearing pyritic ore (Helovuori, 1979). In general, the upper part of the deposit shows a strong sheared character that denotes local tectonic transposition with intercalation of banded massive sulfides, enclaves of altered metavolcanic rocks, and tectonic rafts of country rock separated by sulfide mylonites and shear zones.

Pyrite is the most voluminous sulfide component of the system, whereas variable amounts of sphalerite, chalcopyrite, dolomite, calcite, and barite occur in different ore types (Imaña, 2003). Pyrrhotite is a common sulfide observed in areas of pegmatite contact metamorphism and ductile shear zones. Despite high grade regional metamorphism, secondary pyrrhotite formation has only minimum development along pyrite grain boundaries in the central parts of the deep ore body (Imaña, 2003).

CHEMOSTRATIGRAPHY

Lithogeochemical classification of whole-rock data obtained from systematic drill core sampling has allowed the identification of the chemical protoliths of the altered rocks. The severe obliteration of primary textures due to alteration and metamorphism has made correlations of original lithologies difficult; therefore chemical protolith identification becomes relevant to improve the stratigraphic understanding of the mine area. The Pyhäsalmi massive sulfide deposit and hydrothermally altered rocks are formed within a thick volcanic package of transitional magmatic affinity. The main components are related to felsic protoliths named Rhyolite A and Rhyolite B (Barrett, 2010), an intrusion named Mafic A-2, and andesites (Lehto sill) (Fig. 7.9). In the mine area, the original proximal part of the hanging wall sequence has been removed by faulting and does not appear in direct contact with the mineralized stratigraphy. However, rocks assigned to the hanging wall part of the deposit are interpreted to be formed from a tholeiitic sequence composed of coherent and brecciated mafic volcanic rocks (Mafic A-1). A mineralized unit of tholeiitic affinity (Rhyolite X) occurs within this mafic tholeiitic package (Barrett, 2010). There appears to be no major break in volcanic activity during the VMS formation as there is no evidence of pelagic sedimentation, laterally continuous chemical precipitates, or reworked components at the change from the transitional to tholeiitic volcanic episodes.

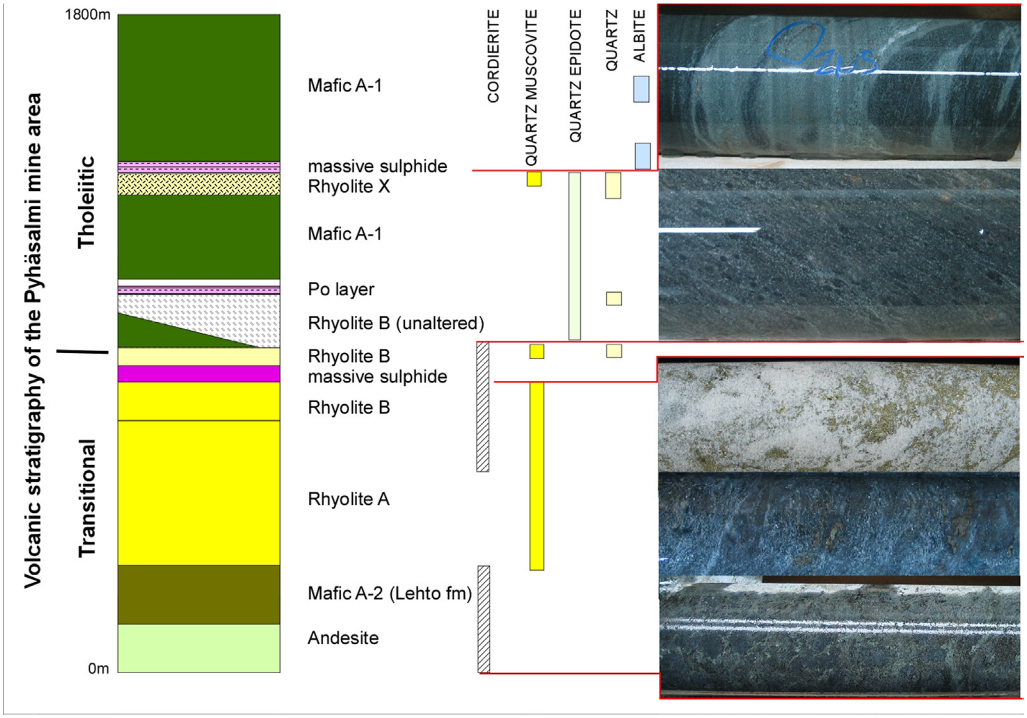

FIGURE 7.9 Chemostratigraphy and alteration of the Pyhäsalmi mine area.

PYHÄSALMI DEPOSIT AND MINERAL ZONATION

Typically, VMS deposits are characterized by well-developed mineral zonation, which normally grade from an inner core consisting of a high temperature pyritic assemblage to Cu-rich sulfide zones and then Zn sulfides in the periphery (Galley et al., 2007). In the upper portion of the Pyhäsalmi deposit, mineral zonation was not observed due to intense deformation and post-VMS tectonic stacking of different parts of the original massive sulfide lens. However, the deep mine ore body, which is located at the end of the upper ore body slab, forms a potato-shaped blob of massive sulfide ore from 1000 m down to 1400 m depth, within which mineral zonation is well preserved (Mäki and Puustjärvi, 2003; Imaña, 2003).

Much of the deep ore body is massive pyrite, which occupies the core of the potato-shaped deposit and contains uneconomic Cu tenors. A Cu-rich pyrite zone occurs around the inner barren pyrite core and is in turn surrounded by a distinct Zn-barite–rich zone toward the periphery of the deposit. The Zn ore surrounds the lower ore body on all sides except the top. This suggests the form of a downward-facing sheath fold with the upper ore body forming the upper limb of the fold. The lower limb of the fold is short and curtailed, giving the overall deposit a hook-shaped geometry in cross section (Lickorish, 2012) (Fig. 7.10). Ore types and mineral assemblages in the deep ore body were described in Imaña, 2003 and are represented in Fig. 7.11.

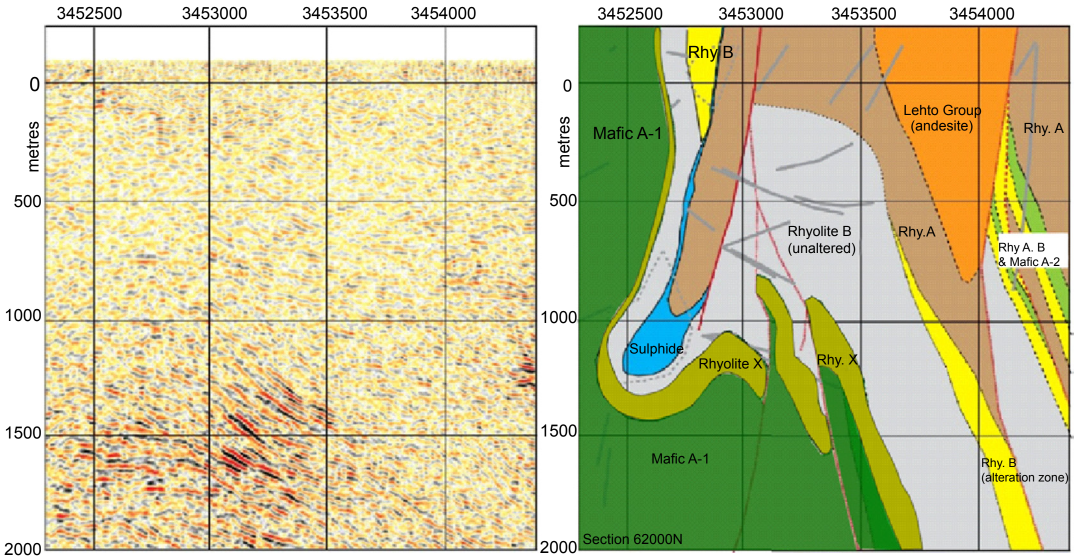

FIGURE 7.10 Seismic profile and simplified geological cross section 62000 N across the middle part of the deep ore body.

The gently dipping reflectors on the seismic profile to the left represent the location of felsic and mafic intercalations of Rhyolite X (and other felsic horizons not shown in the cross section) and Mafic A-1.

Source: *Modified after Lickorish, 2012*.

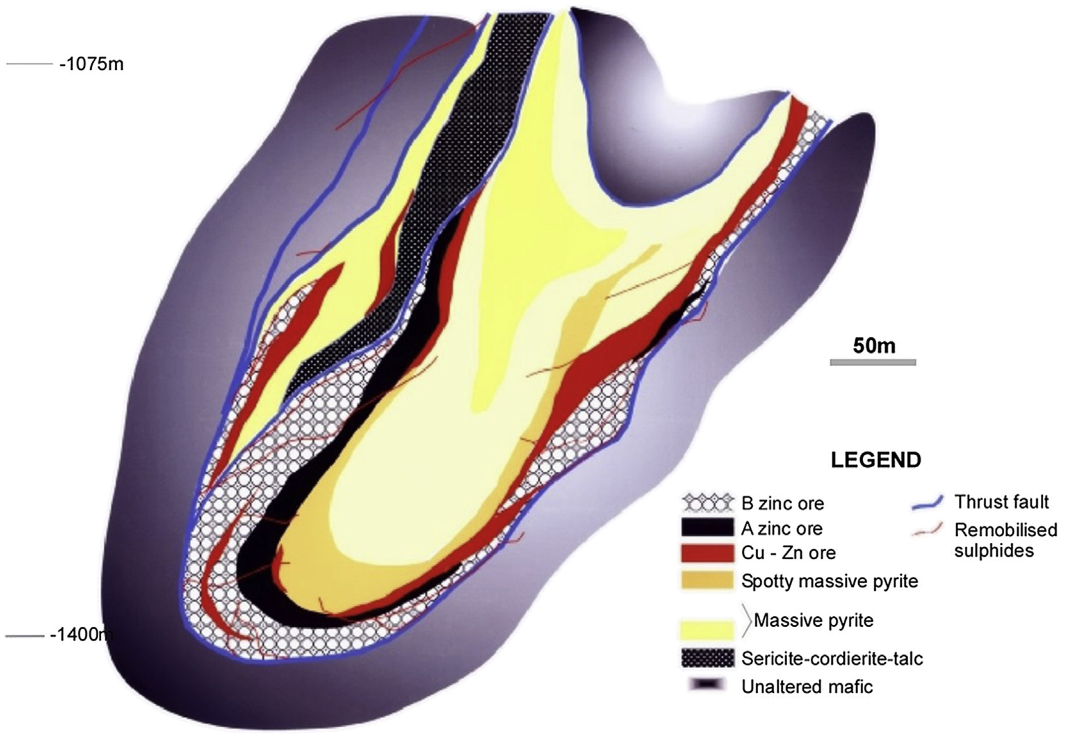

FIGURE 7.11 Ore zonation in the deep ore body (Imaña, 2003).

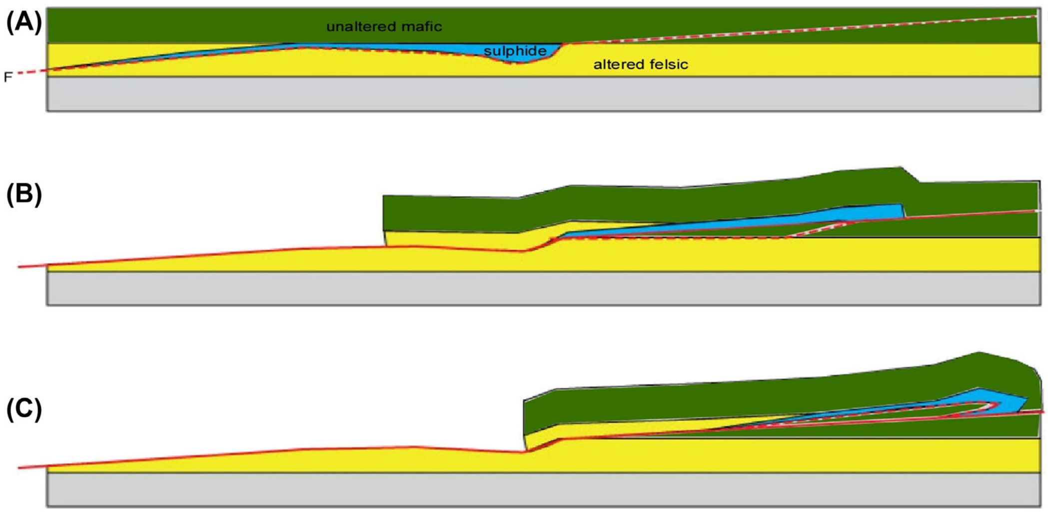

FIGURE 7.12 Separation of the massive sulfide deposit from its host alteration zone by thrusting.

(A) Original stratigraphic template, with incipient thrust fault. (B) Movement on thrust carries sulfide deposit over unaltered material. (C) A small "shortcut" fault in the footwall is all that is needed to introduce some unaltered material into the core of the VMS fold closure.

STRUCTURE AND CROSS SECTIONS

The overall structure in the Pyhäsalmi deposit is controlled by a subvertical, strongly sheared, inverted anticline structure with a sheath fold at its lower end. The sheath fold in the deep ore body is attributed to continuous high strain deformation of folded material of contrasting competency along a shear zone. In Pyhäsalmi, the existence of the massive sulfide lens would have formed a singularity in the stratigraphy that would have concentrated strain, producing a higher amplitude structure that by continual deformation would have stretched out to form a sheath fold localized on the massive sulfide (deep ore body).

Such deformation resulted in the deep ore body being tectonically transposed onto less-altered volcanic rocks of the hanging wall mafic sequence, which by subsequent folding and tilting formed the unusual aspect of a massive sulfide deposit enclosed in unaltered rocks (Fig. 7.12). Shear structures (ore mylonites) are especially common along the periphery of the deep ore body, especially within the Zn ores.

HYDROTHERMAL ALTERATION

Much of the strong sulfide mineralization in Pyhäsalmi occurs within altered parts of Rhyolite B. Alteration within this unit is pervasive and widespread for about 4 km in a north–south direction and to more than 1 km at depth. This unit presents geochemical patterns related to strong alkali depletion and significant enrichment in Fe, K, Mg, Si, and Ba accompanying base metal enrichment. Metamorphism of the original alteration assemblages has resulted in formation of mineral assemblages of muscovite, cordierite, quartz, biotite, and barite. Except for areas where tectonic dislocation has happened (the deep ore body), massive sulfides are spatially associated with this mineral assemblage.

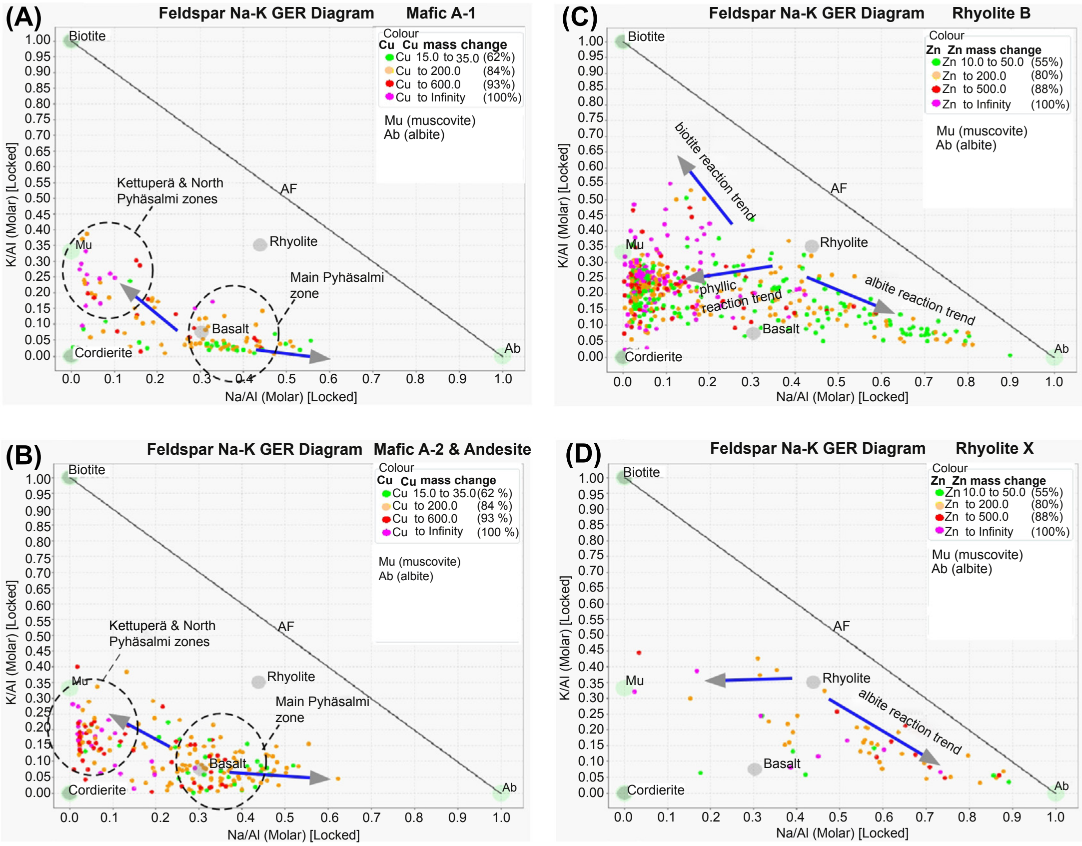

FIGURE 7.13 General element ratio (GER) scatterplots of K/Al vs. Na/Al molar ratios are representing the silicate mineralogy for different volcanic protoliths in the Pyhäsalmi mine area.

The molar plot is colored by net metal mass gains. (A) Cu enrichment in sericitized hanging wall Mafic A-1 unit is significant in the Kettuperä area, but shows very weak Cu gain near the Pyhäsalmi deposit. (B) Basalts and andesites of the Lehto unit are only weakly enriched near the Pyhäsalmi deposit but more enriched and altered in the northern part and Kettuperä zones. (C) Rhyolite B shows distinct alteration trends associated with variable Zn enrichment; stronger metal gains are associated with biotite-, muscovite-, and cordierite-bearing assemblages. (D) Rhyolite X, found near the deep ore body, is mostly albitized with only weak to moderate gains in Zn.

Exhalative style of mineralization is not common in the Pyhäsalmi deposit, however, the exclusively hydrothermal composition of the Zn-rich parts of the deposit (Imaña, 2003) and strong enrichment of barium and silica along certain pyritic horizons could represent hydrothermal precipitates (Barrett, 2010).

The silicate alteration mineralogy has been confirmed by plotting whole-rock assays from different lithologies in a series of K/Al versus Na/Al molar ratio plots. Calculated mass changes of Cu and Zn are also presented in these plots to see the relationship between metal enrichment and hydrothermal alteration (Fig. 7.13). It was shown that the alteration and metal enrichment of altered units are stronger in the northernmost parts of the system, which are located more than 2 km away from the actual ore body position. This separation also confirms the interpretation that the massive sulfides have been detached from their proximal alteration zones in the north during severe thrusting and deformation.

Several late, unaltered mafic dikes cut through the deep massive ore body, with only minor thermal reactions occurring along dike margins. These mafic dikes are generally enriched in Au and As as a consequence of metal remobilization during metamorphism and deformation. A second ore horizon, Rhyolite X contains a widespread and relatively lower-temperature alteration assemblage than altered Rhyolite B. Rhyolite X is replaced by albite and silica and is devoid of Cu, with only minor Zn enrichment. Significant Cu and Zn contents occur within locally sericitized parts.

SUBSEAFLOOR REPLACEMENT

Subseafloor VMS formation is an effective mechanism of retaining large portions of the metalliferous budget within permeable strata before it is expelled onto the seafloor. Favorable conditions and diagnostic evidence of this process were explained by Doyle and Allen (2003).

The Pyhäsalmi ore body is entirely hosted by felsic rocks interpreted to represent rapidly emplaced lapilli tuff and coherent lava flow units. Numerous relicts of altered rock are observed within the massive sulfide, mainly associated with the inner Cu-bearing, barite-poor portions of the ore body. Studies aimed at differentiating and explaining the origin of diverse rock enclaves in the ore body (Miettinen, 2011) found that many enclaves in the deposit were not just tectonic rafts of country rock assimilated during deformation. On the contrary, many enclaves show evidence of being very early relicts of an altered host rock. Lithogeochemical protolith characterization of these enclaves found striking similarities to altered rocks (Rhyolite B) in the main alteration zone outside the ore body. In distal parts of the deposit, drill holes intersect strong hydrothermal alteration that extends 25–30 m both up-hole and down-hole from the pyritic massive sulfide lens.

Altered enclaves of Rhyolite B have not been observed in the Zn ores, so it is conceivable that the Zn-rich sulfides formed by direct venting onto the seafloor. Textural and lithogeochemical evidence demonstrate that the pyrite, Cu ores and Zn ores were subjected to a zone refinement process (Mäki and Puustjärvi, 2003) consisting of successive high temperature infiltration and replacement of permeable volcaniclastic strata.

SATELLITE DEPOSITS

KANGASJÄRVI

The Kangasjärvi deposit occurs 25 km south of the Pyhäsalmi mine. It was mined in 1986 by Outokumpu and was processed in the Pyhäsalmi mill (see Fig. 7.1). Total production from the open pit was 86,000 t of ore grading 5.4% Zn, 0.1% Cu, and 38% S. The ore deposit was found by the GTK in 1964. After production, the Kangasjärvi area was explored by several companies but no new resources have been found (Mäki and Puustjärvi, 2003).

The Kangasjärvi ore and alteration have been described by Rehtijärvi (1984), Rasilainen (1991), and Roberts et al. (2004). The ore deposit is hosted by a succession of altered mafic, intermediate, and felsic metavolcanic rocks. Host rocks include cordierite-sillimanite-garnet-anthophyllite gneisses and cordierite-bearing gneisses (Rasilainen, 1991) (Fig. 7.14). The main ore minerals are pyrite and

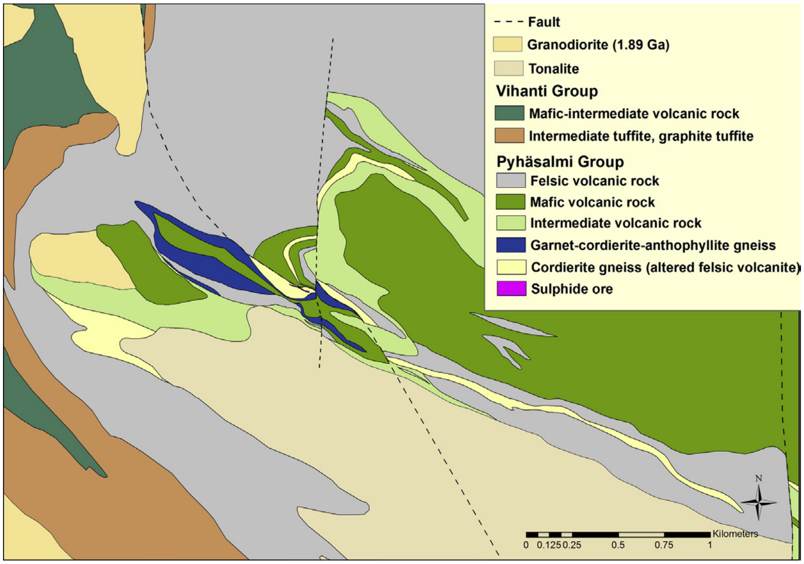

FIGURE 7.14 Geology of the Kangasjärvi area.

Source: *Map is modified after Bedrock of Finland–DigiKP (2013).*

sphalerite and the main gangue minerals are quartz and barite. Magnesium enrichment and the absence of carbonate minerals are consistent with a proximal Kuroko-type environment of deposition (Rehtijärvi, 1984). The Kangasjärvi deposit has similarities to the Pyhäsalmi ore deposit in terms of lithology, alteration, and metal abundance.

RUOSTESUO (KALLIOKYLÄ)

The Ruostesuo Zn-Cu deposit was in production from 1988–1989, and the ore was processed in the Pyhäsalmi mill. The deposit is part of a large mineralized system in the Kalliokylä volcanic formation about 15 km southeast of Pyhäsalmi (Fig.15). The total resource is estimated to be 2.7 Mt grading 1.7% Zn, 0.4% Cu, 10 g/t Ag, and 0.4 g/t Au (Ekdahl et al., 1997). The mineralizations were found by Outokumpu in 1959 using airborne geophysical measurements (Fig. 7.1).

The ores occur in the altered portion of a rock suite that contains felsic, intermediate, and mafic metavolcanic rocks (Fig. 7.15). The sequence is strongly folded and metamorphosed to granulite facies (Huhtala, 1979). Metarhyolites and both Mg-rich and Fe-rich metabasalts are the primary volcanic protolith in the area. Hydrothermal alteration proximal to the sulfide lens is represented by strong depletions of Ca, Na, and K with a characteristic metamorphic orthoamphibole-cordierite-garnet assemblage that grades outwards into Mg- and Fe-rich tholeiitic metabasalts (Roberts, 2002; Roberts et al., 2004). The ores are brecciated or massive pyrite-pyrrhotite occurrences with some chalcopyrite and sphalerite. The ore lodes in the Kalliokylä formation differ from each other geochemically, particularly in their zinc content. In the southeast, ores hosted within cordierite-anthophyllite rocks are poor in Zn, assaying 0.2–0.4% Zn and 0.4–0.6% Cu. In the northeast, the Ruostesuo mine contains ores hosted by felsic metatuffites, amphibolites, and cummingtonite gneisses. These ores assay over 2% Zn and 0.4% Cu (Huhtala, 1979).

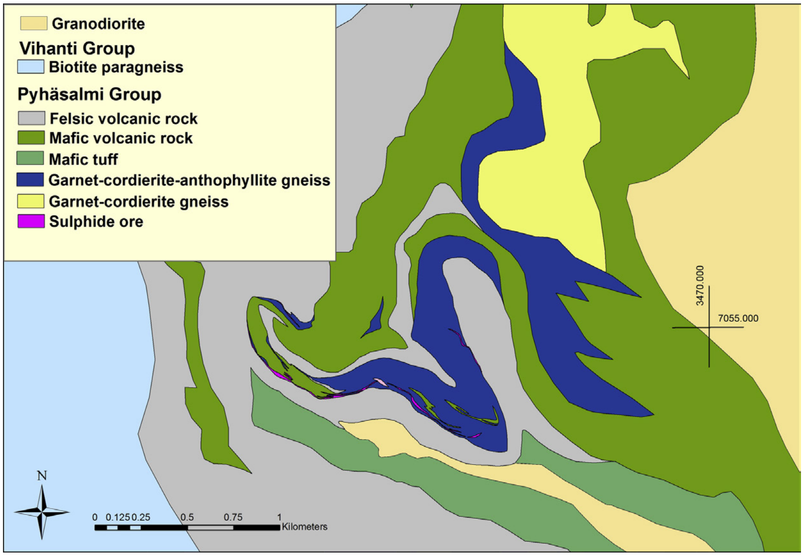

FIGURE 7.15 Geology of the Kalliokylä mine site and Ruostesuo deposit.

Source: *Map is modified after Bedrock of Finland–DigiKP (2013).*

MULLIKKORÄME

In 1983, a research program was commenced by Outokumpu to study lithogeochemical halos around the Pyhäsalmi deposit (Mäki, 1986). According to this study, Outokumpu reevaluated several old exploration targets. The Mullikkoräme deposit was discovered using lithogeochemistry and geophysics in 1987.

The Mullikkoräme formation is located about 10 km northeast of Pyhäsalmi (Fig. 7.1). It is a north–south trending, bimodal volcanic formation composed of basaltic pillow metalavas (west) and rhyolitic felsic metavolcanic rocks (east). The metamorphic grade is lower than in Pyhäsalmi, mostly in greenschist facies. Metamorphic alteration minerals include: chlorite, sericite, phlogopite, talc, quartz, and pyrite (Ekdahl et al., 1997).

The Mullikkoräme deposit is a typical small size polymetallic sulfide deposit. It was in production in two periods, first between 1990 and 1993 and the deeper parts from 1996 to 2000. The total production was 1.15 Mt of 6.1% Zn, 0.3% Cu, 0.9% Pb, 45 ppm Ag, and 1 g/t Au (Pelkonen, 2000). The mineral assemblage of carbonate sphalerite and galena suggests that mineralization in Mullikkoräme represent lower-temperature processes than those in the Pyhäsalmi system. Sulfide lenses are small, Zn and Pb rich, Cu poor and are hosted by hydrothermal carbonates and talc schist. Some ore lenses were massive and pyrite rich but these commonly have very low base metal tenors (Pelkonen, 2000).

SUMMARY

The Vihanti-Pyhäsalmi belt contains the most important volcanogenic massive sulfide (VMS) deposits in Finland. The volcano-sedimentary host rocks belong to a 1.93–1.92 Ga island arc that occurs along the northwestern parts of the Raahe-Ladoga shear complex. The stratigraphy in the region is divided into two units, a lower bimodal volcanic unit forming the Pyhäsalmi group and an upper volcano-sedimentary association defined as the Vihanti group. U-Pb radiometric dating suggests that these two groups have a similar age.

The Vihanti-Pyhäsalmi belt hosts two large VMS deposits and a number of small sulfide deposits located around them. The only currently producing mine (2014) is the Pyhäsalmi deposit, containing 75.7 Mt of pyritic Zn-Cu ore. The Vihanti mine operated from 1954–1992, producing 28 Mt of Zn-Pb-Ag ore. The Vihanti deposit and three minor satellite mineralizations are hosted in a volcanic sequence of the Vihanti group dominated by intermediate and felsic metavolcanic rocks. Recent exploration projects at the old mine sites show that both areas are still very high potential VMS exploration targets. In particular, new exploration techniques, such as deep penetrating EM-measurements, seismic methods, and deep drilling with 3D modeling, will give new ideas for further studies.

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