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MINERAL DEPOSITS OF LAPLAND: EXCURSION GUIDE OF THE MONTANUNIVERSITÄT LEOBEN

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Preface

From September 12-21, the main excursion of the geologists of the Montanuniversität Leoben took place in Lapland, northern Finland & Sweden. Thanks to the organisation of Prof. Melcher and Prof. Prochaska and especially with the support of Dr. Kari Niiranen (LKAB) the excursion covered interesting spots for economic geologists and mineralogists alike. We The biggest operating mines, Kemi (Cr), Aitik (Cu, Au), Kiruna (Fe) and Kittilä (Au) have been visited. Furthermore, Europe's oldest rocks (TTG complex), the enigmatic IOCG deposits (Hannukainen) and orogenic gold deposits of the Central Lapland Greenstone Belt have been explored. The excursion stops are displayed in Figure 1.

Geology & Metallogeny

The Fennoscandian shield in the north-westernmost part of the East European Craton consists of three crustal segments: Fennoscandia (northwest), Volgo-Uralia (east) and Sarmatia (south). It represents the largest exposed area of Precambrian rocks in Europe and constitutes large parts of Fennoscandia in Finland, NW Russia, Norway and Sweden (Figure 2).

Archean crust occurs in the east and north of Fennoscandia. The western and eastern parts of the Karelian Province comprise Mesoarchean 2.8-3.0 Ga lithologies, but rocks older than 3.0 Ga have also been found. The central part of the Karelian province is mainly Neoarchean, consisting of plutonic and volcanic rocks of 2.75-2.70 Ga in age. The Belomorian province is dominated by 2.9-2.7 Ga granitoids and volcanic rocks, as well as Neoarchean ophiolite-like rocks and eclogites. The Kola province comprises Mesoarchean and Neoarchean units, together with some Palaeoproterozoic components. The Archaean part of the Norrbotten province is dominantly covered by younger rocks and thus data is quite scarce. Rifting of the Archaean crust in the Fennoscandian shield began in north-eastern Fennoscandia and became more dominant after the emplacement of 2.50-2.44 Ga, plume-related, layered intrusions and dyke swarms. Erosion and deep weathering after 2.44 Ga was followed by the Huronian glaciation. Rifting events at 2.4-2.1 Ga are associated with mostly tholeiitic mafic dykes and sills and fluvial to shallow-water sedi-

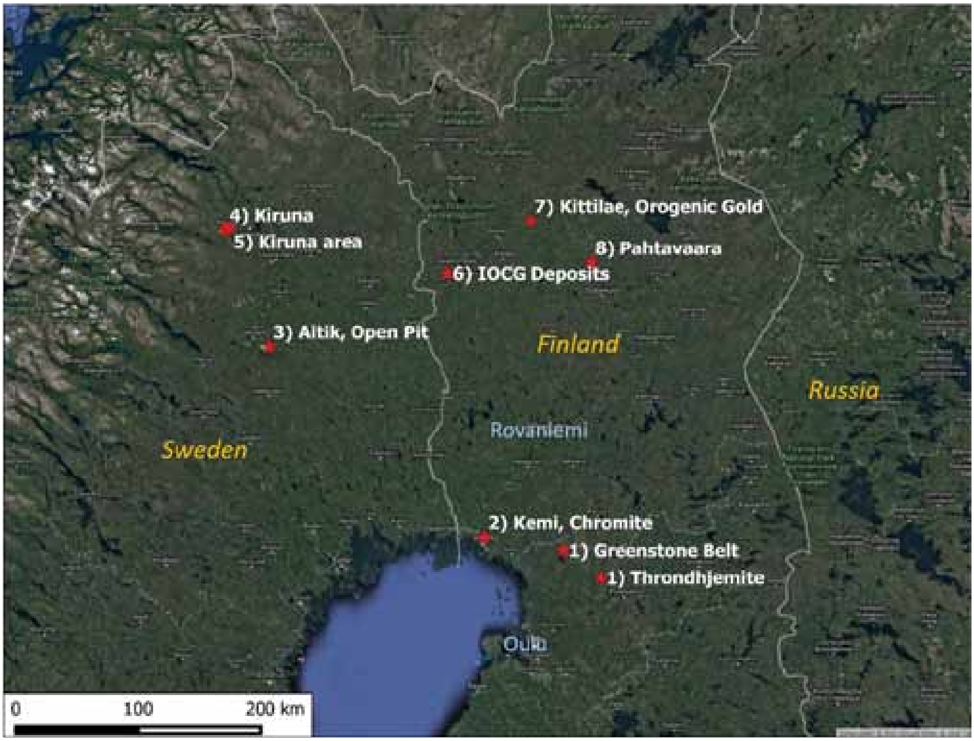

Figure 1: The excursion days (numbers in brackets) and their topics. Map created with QGIS and Google plugin.

mentary rocks. Local shallow-marine environments were marked by deposition of carbonates at 2.2-2.1 Ga. The Palaeoproterozoic orogenic evolution of Fennoscandia can be divided into the Lapland-Kola orogen at 1.94-1.86 Ga and the composite Svecofennian orogen at 1.92-1.79 Ga.

The Palaeoproterozoic rocks in the Lapland-Kola orogen include small amounts of juvenile, 1.96-1.91 Ga in age, island arc-type rocks and large volumes of felsic granulites. The main rocks in the central Svecofennian province are igneous, predominantly 1.89-1.87 Ga in age, in the Central Finland granitoid complex (CFGC). The Småland area of the Svecofennian province includes subduction-related juvenile volcanic and plutonic rocks formed between 1.83 and 1.82 which were metamorphosed. Rocks of the Gothian (1.64-1.52 Ga) and Telemarkian events (1.52-1.48 Ga) (G & T in Figure 2) are present in the Sveconorwegian orogenic belt in the SW part of Fennoscandia. The 1.34-1.14 Ga period includes bimodal magmatism associated with sedimentation. The Sveconorwegian orogeny (1.14-0.97 Ga) involved accretion of terranes followed by post-collisional magmatism between 0.96 and 0.90 Ga. The opening of the Iapetus Ocean started ca. 600 Ma ago, and the final continent-continent collision occurred during the Scandian orogeny (430-390 Ma), followed by an orogenic collapse. The Upper Allochthon in the Caledonian orogenic belt (Fig. 1) is characterised by Phanerozoic rocks (500–430 Ma) derived from the Iapetus Ocean, including ophiolites and island-arc complexes (LAHTINEN, 2012).

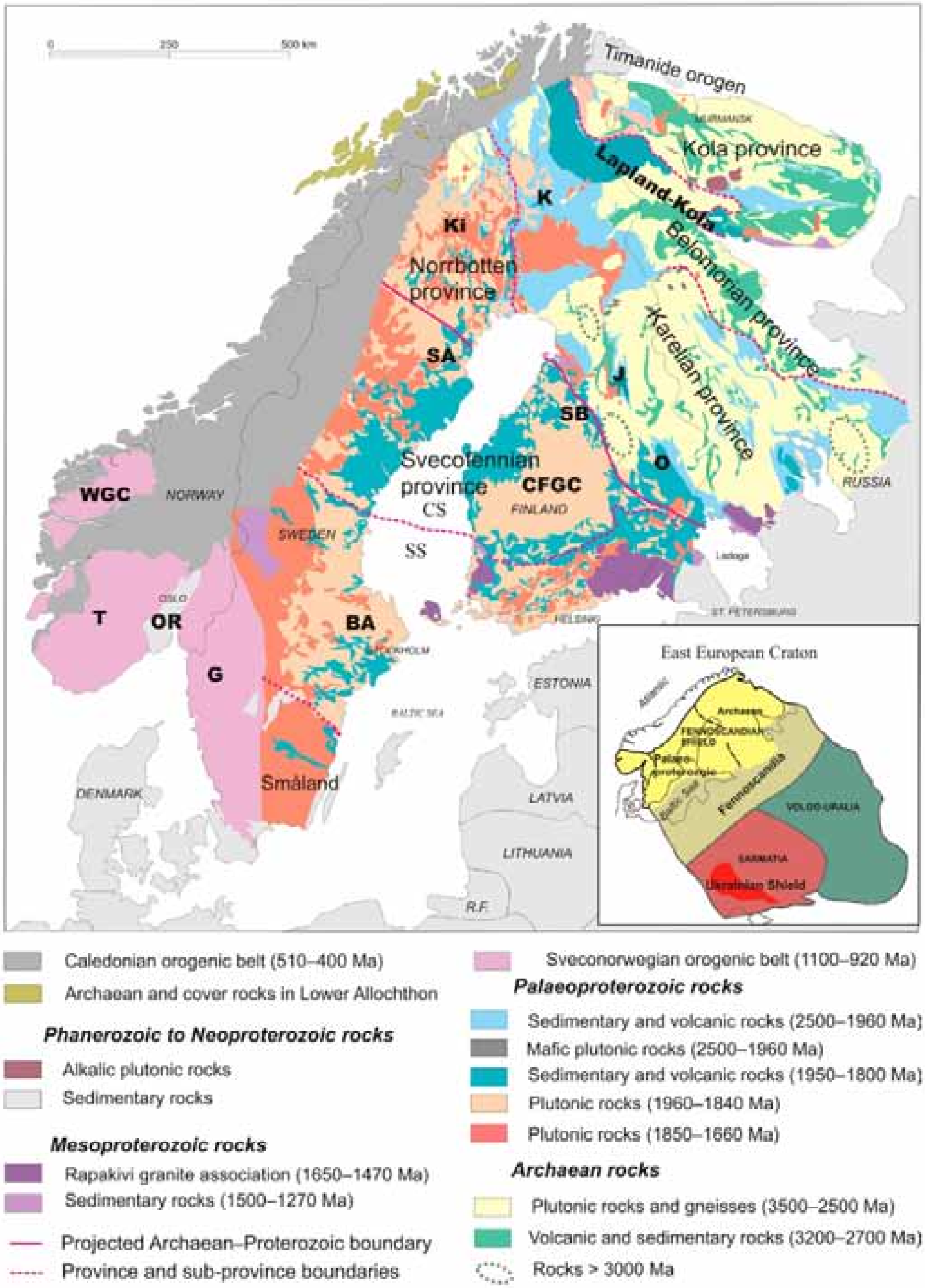

Figure 2: Fennoscandia and its location within the East European Craton. Geological map after (LAHTINEN, 2012) based on KOISTINEN et al. (2001). CS – Central Svecofennia; SS – Southern Svecofennia. Areas and localities: BA – Bergslagen area; G – Gothian terranes; J – Jormua; K – Kittilä; Ki – Kiruna; O – Outokumpu; OR – Oslo rift; SA – Skellefte Area; SB – Savo Belt; T – Telemarkian terranes; WGC – Western Gneiss Complex.

The dominant age of economically important deposits in the Fennoscandian Shield is roughly 1.8 Ga. This age can be detected in numerous mineralisations and can be correlated to the Svecocarelian orogeny. However, for mafic-ultramafic igneous rocks hosted deposits ages around 2.4 Ga are characteristic (e.g. for the Kemi intrusion 2.44 Ga (ILJINA AND HANSKI, 2005); cf. end of Archaean cratonization at ca. 2.5 Ga (FAUPL, 2003)). Apart from the Archaean and Palaeoproterozoic orogenies the Meso- and Neoproterozoic ones do not contribute to the formation of major deposits in North Finland/Sweden (e.g. BERGMAN et al., 2008).

Although the majority of economic deposits can be found in the Palaeoproterozoic parts of the Fennoscandian Shield, there are also significant but mostly uneconomic Ni-PGE, Mo, BIF and orogenic gold deposits in the Archaean parts (BERGMAN et al., 2008).

The metallogeny of northern Finland and northern Sweden is very diverse and ranges from mafic to ultramafic intrusions hosting Cr, Fe, V, Ti, Ni, Cu and PGE´s, VMS deposits (Cu-Zn), epigenetic Cu-Au and gold-only deposits, as well as apatite iron deposits, skarn-like iron deposits, stratiform/stratabound sulphide deposits and also IOCG style deposits (iron oxide-copper-gold).

Day 1 – Geology in the south of Rovaniemi, Finland

Stop 1 66.12045°N 25.98728°E

The first stop of the excursion is a former Au prospect and trial mine of Gold Fields Arctic Platinum Oy, Konttijärvi. Here the footwall contact of the 2.4 Ga old Konttijärvi intrusion is located. The observed units above the basement are the marginal series, mineralized gabbro, pyroxenite, peridotite and the diorite of the main intrusion. The marginal series consists of an intrusion breccia and shows upward diminishing geochemical influence of the basement. In the peridotites, autolites are observed, i.e. rocks that look like conglomerates with magnetite seams around the peridotitic "clasts" – probably early crystallisates from the roof of the chamber (Figure 3). The whole complex is metamorphosed to the lower amphibolite facies.

Figure 3: Peridotitic "clasts"which can be derived from the roof of the magma chamber.

Stop 2 65.59502°N 26.48201°E

Next stop is the central part of the Pudasjärvi Granulite belt which mainly comprises of 2.972 Ga old charnockites and enderbites. The outcrop consists of mafic two-pyroxene granulites which show a negative Nb/Ta anomaly. This normally indicates that these rocks were derived from subduction of igneous rocks, but in this area no eclogites are known, so the genesis remains enigmatic.

Stop 3 65.49847°N 26.57576°E

The third stop is a highlight of the excursion, presenting some of the oldest rocks of Europe at the TTG belt at Siuruantie. This trondhjemite outcrop is special, because most of the other trondhjemite outcrops around yield 2.8 Ga ages, but this has a zircon age of 3.5 Ga. All trondhjemites exhibit a metamorphic overprint at 2.5 Ga. Trondhjemite contains accessory garnet, some K-feldspar rich pegmatites and mafic enclaves of orthopyroxenite. The outcrops are crosscut by quartz veins containing contain blue high-temperature quartz grains.

Stop 4 65.69116°N 25.94080°E

The Archean (2.7 Ga) Oijärvi greenstone belt exposes a typical succession of Fe-tholeiites, basalts, low-Mg komatiites, micaschists and greywackes. In sericite schists, up to 8 g/t Au can be found. The outcrop visited shows the upper border of the magmatic succession: well preserved pillows which were only metamorphosed in the lower greenschist facies (Figure 4).

Figure 4: Pillow basalt of the Archean Oijärvi greenstone belt.

Excursion Day 2 - Kemi Chromite mine, Finland (65.786449°N 24.712836°E)

Geology

The Kemi mine operates in a mineralised mafic-ultramafic layered intrusion within the Portimo metallogenic district (PGR, Cr, Ni) that is divided into the Tornio, Kemi, Penikat and Portimo layered intrusions. The mineralisations are associated with the 2.44 Ga old rifting stage (PERTTUNEN & VAASJOKI 2001). The Svecokarelian orogeny (1.9-1.8 Ga) led to a lower-amphibolite facies metamorphism. Today there is a general dip of the rocks and the ore layer of 70° to the NW. The chromitite layer, known for 4 km long along strike, is cut into several ore bodies by numerous faults. Based on the gangue minerals, four mineralogical ore types can be classified as a talc-carbonate, serpentinite, tremolite and a chlorite based ore. The tremolite-based ore is best for processing, in contrast the serpentinite-based

Figure 5: The view into the former open pit mine of Kemi.

ore is a bigger challenge. The average thickness of the chromite layer is 40 m and varies between 12 and 110 m. The hanging wall contact is straight and on the other hand the footwall contact is like a slump structure and seems to be brecciated. The intrusion comprises an ultramafic lower part and a gabbroic upper part, both resting on a late Archean granitoid footwall. The average Cr_2O_3 content of the ore is about 26 % at a 22 % Cr_2O_3 cut-off grade and an average Cr/Fe ratio of 1.6. The annual production is about 300,000 t of upgraded lumpy ore (36.5 % Cr_2O_3), respectively 750,000 t of fine concentrates (44.5 % Cr_2O_3). The extension of the ore to depth is unknown. Seismic measurements indicate a depth of several kilometres. Mining is economic because of the convenient location and the advanced processing and ferrochrome production technology at the nearby Tornio smelter.

Stop 1

After the general introduction, a viewing platform of the open pit was visited. The open pit is about 200 m deep (Figure 5). Above the basement composed of Archean granitoids in the footwall the layered intrusion is exposed, including some dark diabase dykes. Entrance into the underground mine is by a small bus. In the maintenance area at level 500 m some controller and lecture rooms, maintenance areas and a geological lab with drill core storages are situated. The cores show that pyrite occurs in the hanging wall of the chromite layer and green chromian garnet (uvarovite) was formed during metamorphism.

Figure 6: An outcrop near the mining area shows the intrusion in the footwall and the Svecokarelian volcanic rocks in the hanging wall. Between those, a conglomerate layer (detailed view) of about 40 cm thickness occurs.

Stop 2

Near the Kemi chromite mine, a small outcrop exposes the upper contact of the Kemi layered intrusion. Figure 6 shows the sequence with 2.4 Ga old gabbro in the footwall and the younger Svecokarelian volcanite (1.9-1.8 Ga) in the hanging wall. Between those, a conglomerate layer of about 40 cm thickness with Archean granite pebbles occurs. The pebbles reach diameters of about 20 cm.

Day 3 - Aitik copper mine, Gällivare, Sweden (67.07903° N 20.94743°E)

Mine & Geology

Aitik is Sweden's biggest copper mine (industrial area: 7000 ha) and constitutes Europe's largest open pit with a dimension of 1.1 x 3.0 km and a current depth of 450 m. Aitik means "storehouse" in the language of the Sami, the native people of Lapland and was discovered in 1932. Boliden AG started production in 1968 and mined 36 Mt ore and 29 Mt waste rocks in 2016. To date, 744 Mt of ore and 741 Mt of waste rock have been mined. At Aitik´s estimated peak in 2020, 45Mt/a ore shall be produced. Production is assumed to continue for the next 27 years. The resources of the deposit amount to 1.8 billion tons; the reserves are around 1.2 billion tons of ore. The main metals found in Aitik are copper, gold and silver, whereas 1t

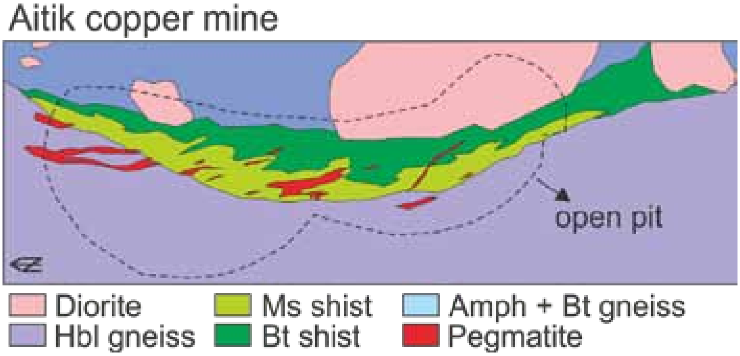

Figure 7: Geology of the Aitik mine (presentation by Boliden AG).

of ore yields approximately 2 kg Cu, 2 g of Au and 0.1g of Ag. The recovery rate is relatively high, with nearly 90% for Cu, 65% for Au and 50% for Ag. Additionally to the big pit, a smaller, second open pit Salmijärvi in the south is also mined. The exploration for a third pit, called Likavaara is still ongoing.

The Aitik deposit lies within the Norrbotten Craton and has an approximate age of 1.88 Ga. It is situated in the Kiruna-Ladoga shear zone (Figure 7). Rocks within the mine area are divided into three different parts: 1) the hanging wall, made up of strongly banded hornblende gneisses; 2) the main ore body, which consists of three strongly deformed and altered units: muscovite schist, biotite schist and biotite gneiss and 3) the footwall complex, consisting of porphyric diorite. The mineralisation is interpreted as a metamorphosed Porphyry Copper deposit (hydrothermally altered host rock) overprinted by later IOCG-style mineralisation, based on the character of the high salinity ore fluids, the alteration and mineralisation styles. The mineralisation consists of veinlets as well as disseminated chalcopyrite, pyrite, pyrrhotite and magnetite in the hydrothermally altered, metamorphosed and strongly deformed host rocks. Accessory minerals include bornite, chalcocite, malachite, molybdenite, sphalerite, galena, arsenopyrite, scheelite and uraninite. The main ore zone roughly dips towards the west (45°) and plunges to the north, with ore grades decreasing with depth. The lower contact is approximately where biotite gneisses change into regional biotite-amphibole gneiss. Pegmatite dykes penetrate all units. They have an apparent age of 1.8 Ga and show insignificant amount of REE, molybdenite and tourmaline mineralisation. The intrusion of the pegmatites is interpreted to be contemporary to the IOCG overprint of the ore body.

Figure 8: View from the southern margin of the open pit. On the northern flank the intrusion of rose coloured pegmatites is clearly visible. A part of the processing plant can be seen on the eastern side of the pit.

Stop 1

Our first stops are the overview platforms on the eastern and southern margins of the open pit. The full extents of the mine as well as the most prominent features of the geology were clearly visible (Figure 8).

Stop 2

At the deepest level of the open pit, active mining exposes well mineralized rock with some high-grade Cu ore. After blasting, the ore is loaded with excavators (bucket size 80 t) on haul trucks, which load up to 300 t and transport the rock to an in-pit crusher (Figure 9).

Figure 9: Loading of a haul truck wish freshly blasted ore.

Due to their hardness, the pegmatites are the least favourable rocks for the crushers. From the in-pit crusher the ore boulders, with a maximum size of 40 cm, are transported to the processing plant via 7 km of conveyer belts. In the processing plant the ore is milled and the sulphides are separated from the waste rock by flotation. The resulting copper concentrate is transported via railroads to the smelters. The waste rock is either used for road construction in the vicinity or within the mining area or dumped on heaps.

Stop 3

The final stop was the core shed near the processing plant. In sum over 10.000 m have been drilled for exploration. Three cores were presented, which are from the north end of the open pit. They were horizontally drilled from NW to SE. In this section the muscovite schist and hornblende-gneiss, hosting the chalcopyrite/pyrite mineralisation, as well as fine grained magnetite and molybdenite are exhibited. Geochemical analysis displays sections with enhanced amounts (<12 ppm) of gold. The intense deformation, due to two metamorphic events, as well as the pervasive alteration (epidote, chlorite, garnet, feldspars, muscovite and biotite) of the host rock is shown. Furthermore the distinct border between the mineralised zone and the footwall is visible. Pegmatite veins are in contrast to the surrounding rock, hosting idiomorphic, black tourmaline crystals.

Day 4 - Kiruna iron ore mine, Sweden (67.84236°N 20.19281°E)

Mine & Geology

The mine is operating the Kiirunavaara deposit, which is a Kiruna type apatite iron oxide deposit. The mining operation started as open pit in 1900, since 1962 only underground mining has been done. The magnetite ore body is about 4 km long and 80 m wide and strikes north-south, dipping steeply to the east. Proven depth of the body is about 1800 m. The main haulage level is at 1365 m depth and has an installed capacity of 35 million tons per year. With level 1365, 614 million tons of reserves were developed, with an estimated lifetime of approximately 20 years. The used mining method is sublevel caving. The output rate is about 90% with an extraction rate of 115%. The cut-off grade is 45% Fe. The production in 2016 was 24.0 million tons of pellets and 2.9 million tons of fines and special products.

The geochemical composition of Kiruna-type apatite iron ore is different from other iron ore formations. It is rich in phosphorous (0.05-5%), vanadium (300-3000ppm), depleted in sulphur, copper (<100ppm) and gold (<10ppb). The ore is characterised by a considerable variation in the style of mineralisation, host rock lithology, alteration, P-content and associated minor components. Three groups of deposits are distinguished: 1) breccia-type 2) stratiform-stratabound massive type 3) intermediate type (MARTINSSON et al., 1994; BERGMAN et al., 2001). The breccia-style apatite iron ore is hosted by intermediate to mafic volcanic rocks, in a stratigraphically low or middle position of the Kiirunavaara rocks, or within the underlying Porphyrite Group, which is mainly andesitic in composition and commonly porphyritic with phenocrysts. A minor component is amphibole. Accessory components are pyrite, chalcopyrite and titanite. Alteration of the host rocks is mainly expressed by the presence of albite, actinolite and scapolite. The breccia type has a low P-content (0.05-0.3%), an average iron content of only 30% and contains magnetite as the only iron oxide (MARTINSSON et al., 2016). The stratiform-stratabound type comprises tabular lenses at stratigraphically high positions within the Kiirunavaara Group. Hematite is the major iron oxide, but varying amounts of magnetite and apatite are common (P-content varies from 1 to 5%). The hematite is formed from primary magnetite. The gangue minerals are mainly apatite, quartz and carbonate. The host rocks are commonly altered, with typical products like sericite, chlorite, biotite, tourmaline and carbonate. The hanging wall may also be strongly silicified and altered, including K-spar alteration. Examples of this ore type are the Per Geijer deposits (i.e. Nukutus, Henry, Lappmalmen and Rektorn). The intermediate-style apatite iron ore shares features with both of the main groups of apatite iron ores. This type is mainly stratabound in character but also comprises ore breccias. Magnetite is the dominant iron oxide. Minor compo-

Figure 10: View into the sink holes above the Kiruna orebody

nents are amphibole and titanite. They are high in Fe-content (55-68%) and the average P-content is rather low but can vary considerably, and amounts from 0,02 to >5% are possible. The host rock is often altered, with formation of amphibole, albite, biotite and locally scapolite. Examples are the Kiirunavaara, Luossavaara, Malmberget and Gruvberget deposits (MARTINSSON et al., 2016).

Stop 1

After detailed presentations on mine geology and processing, busses were taken on the main ramp down to level 1365 m where most of the operation equipment and the production control centre are installed. . There all safety systems are monitored and production processes are recorded. The tour continued into the maintenance hall, where wheel loaders, barring machines etc. are located and checked. Furthermore the control room of the drilling machines was visited. Three operators are responsible for eight drilling machines, which drill fans with eight boreholes with a length of 54 m.

Stop 2

Next stop was the mining area at level 993 m, block 9, where the typical development of the stopes from the hanging wall to the foot wall was visible. A drilling machine was visited on level 935, and at level 878 a draw point with the blasted fans was shown.

Stop 3

From a viewpoint at the highest point in the mine area the impressive sink holes ("Pingen") which result from the sublevel caving method are visible (Figure 10). Magnetite veins are exposed in porphyrite overlying trachyte and trachyandesite.

Stop 4

In the main control centre, the loading and unloading of the underground trains, the crushers at the chutes and skips in the shaft are remotely controlled.

Day 5 - Geology of the Kiruna District, Sweden

The Kiruna district is located in the Svecofennides (PARÁK, 1975 a) in the north of the Norrbotten craton. The basement exposed in the northern part of the Kiruna area comprises Archean granites and gneisses (FORSELL, 1987). In the west of Kiruna the basement is overlain by the Kiruna Greenstone Group. These rocks derived from effusive basalts or andesites, and preserved pillow structures within spilites can be found (PARÁK, 1975 a). The Greenstone Group is covered by the Kurravaara conglomerate with up to 600 m thickness and fragments of overlying keratophyre. The keratophyre section is a sequence of extrusive felsic porphyry flows known as the Kiruna porphyries. Within the Porphyry group it is indicated that mafic rock types (basalt and porphyry) are oldest, followed by intermediate alkaline rock types (syenite and syenite porphyry) and acid volcanics and metarhyo-

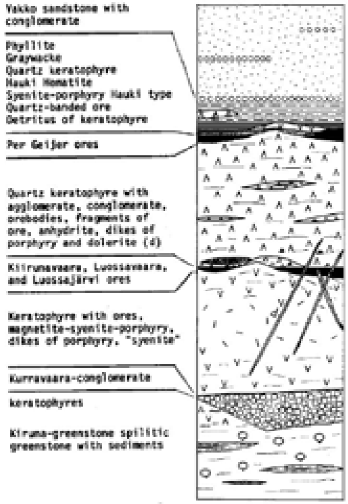

Figure 11: Stratigraphic scheme of the Precambrian volcanic complex of the Kiruna district, northern Sweden after (PARÁK, 1975 a)

lites (quartz-bearing porphyry) in highest position (WITSCHARD, 1984) (Figure 11).

The apatite-iron deposits of Kiirunavaara and Luossavaara are placed in a compositional break in the Kiruna porphyries, between the syenite porphyries of the footwall and quartz-bearing porphyries of the hanging wall (VOLLMER et al., 1984). The Luossavaara orebody is about 1.2 km long and 23 m wide; drilling indicated that the mineralisation pinches out with depth (JENSEN et al., 2012). The ore composition is mainly magnetite with apatite, actinolite, albite and scapolite as gangue constituents (GEIJER & ÖDMAN, 1974; HALLBERG, 2012). GEIJER (1910) assumed that the ores were products of magmatic differentiation and proposed an intrusive origin for all the iron ores. The “ore breccias” (smaller and larger fragments of porphyry in a “matrix” of iron ore, see Figure 12 b) within the contact zone of the mineralisation and the Kiruna porphyries were considered to exemplify the intrusive character of the ore. However, PARÁK (1975 b) interpreted the iron ores as products of volcanic exhalative-sedimentary processes. Further to the north the so-called Per Geijer ore deposits of Rektorn, Nukutus, Lappmalmen and Henry occur, which differ from the larger deposits in size, iron oxide mineralogy, gangue mineralogy (apatite, quartz and carbonates) and alteration style. These apatite-banded orebodies are found higher in the stratigraphy of the Kiruna porphyry (HALLBERG, 2012). The Hauki and Henry deposits comprise predominantly hematite and in the Rektorn, Nukutus and Lappmalmen deposits both hematite and magnetite are found (FRIETSCH, 1973).

The Lower Hauki Formation consists of iron ore bearing quartz-sericite altered metavolcanic and metasedimentary rocks. This formation has been considered to form the youngest part of the Kiruna porphyries and mostly rests directly on the Per Geijer ores with an extension from the town of Kiruna westward to Kurravaara and an eastward dip of 50-70° (PARÁK, 1975 a). The overlying Hauki Conglomerate and greywacke form the basal part of the Upper Hauki Quartzite Group (after FORSELL, 1987) or the Vakko series (after PARÁK,1975 a).

In respect to the tectonic evolution, the unconformity between the orebodies of Kiirunavaara and Luossavaara and their footwall porphyries indicates that folding and denudation preceded the deposition of the apatite iron-ores, whereas this tectonic episode may be connected with the emplacement of plutonic rocks. Intense deformation is demonstrated by isoclinal folding of the greenstones and porphyries (FORSELL, 1987).

Stop 1 - Luossavaara 67.87513°N 20.22167°E

The top of Luossavaara offers an overview of the whole Kiruna area with the main

Figure 12: a) View at the mined iron ore of Luossavaara with the active mine of Kiirunavaara in the background; b) "ore breccia" with components of the syenitic footwall within a "matrix" of magnetite at the Kiirunavaara deposit.

deposit of Kiirunavaara about 4 km to the south (Figure 12, a), Lake Luossajärvi in the southwest, and the smaller Per Geijer deposits of Rektorn, Nukutus, Lappmalmen and Henry in the northern and eastern area. To the SW-W, small epigenetic copper deposits hosted by the Greenstone Group rocks such as the Viscaria copper mine can be spotted.

The tour continues from the top of Luossavaara to the abandoned mining area, where the altered trachyandesitic footwall is exposed (67°87'67.19"N, 20°22'53.52"E). Also oxidized copper minerals, such as malachite and azurite are present. After crossing the approximately 23 m thick mineralisation towards east the rhyolite-rhyodacite of the hanging wall with a possible flow structure (ignimbrite) is exposed.

Stop 2 - Henry 67.89613°N 20.24438°E

A car drive 5 km in northern direction resumes the tour to the old mine dumps of the Per Geijer-type ore deposit of Henry. The rocks consist mainly of hematite with minor apatite. 100 m further to the east the rocks comprise mainly apatite (Henry-Apatitite) and also a paragenesis of magnetite and hematite is exposed. After FRIETSCH (1973) the magnetite-bearing ores tend to be placed close to the quartz-bearing porphyry of the footwall, whereas the hematite-bearing ores can be observed in the proximity of the metasomatically altered Lower Hauki Series.

Stop 3 - Nukutus 67.89691°N 20.25811°E

The deposit of Nukutus 700 m to the east of Henry consists of magnetite and hematite. In the SW close to the lake a massive ore block with flow structures and cross-bedding (Figure 13, a) shows the apatite-banded character of the orebody.

Stop 4 - Hauki 67.89249°N 20.26962°E

Approximately 750 m to the SE the higher stratigraphic level comprises the youngest rocks of the Kiruna area are exposed in an abandoned quarry, which consists mainly of Hauki quartzite and conglomerate. These rocks were formerly mi-

Figure 13: a) Apatite-banded Per Geijer ore of the Nukutus deposit; b) Mn-dendrites on cleavage planes of the Hauki quartzite, which overlies the Per Geijer ores; c) contact of the Hauki quartzite and the overlying Hauki conglomerate with components of the Kiruna porphyries.

ned by LKAB as an additive for the pellet production. Further Mn-dendrites can be observed on the cleavage planes of the Hauki quartzite (Figure 13, b).

Stop 5 - Hauki Conglomerate 67.85885°N 20.26227°E

The last stop shows the stratigraphic contact between the Hauki Quartzite and the overlying Hauki Conglomerate of the Upper Hauki Group (Figure 13, c). The conglomerate predominantly contains clasts of porphyrites and tuffites of the underlying Kiruna porphyries and might show an inverse gradation. PARÁK (1975 a) also mentions components of iron ore. Fabric data show a moderate dip of the quartzite and conglomerate to the east.

Day 6 - IOCG and orogenic gold deposits of the Central Lapland Greenstone Belt

Geology

The Central Lapland Greenstone Belt (CLGB) is mainly built up of Paleoproterozoic (mafic) volcanics and sediments. The succession starts with felsic and intermediate volcanic rocks which can be assigned to an initial rifting stage some 2.44 Ga ago. Basalts and quartzites follow. Notably the latter host gold mineralisation. Finally the youngest units of the CLGB are conglomerates and quartzites which were formed approximately 1.89 Ga ago.

Stop 1 - Hannukainen 67.55650°N 23.99364°E

This site is situated on the Karelian craton close to the boundary with the Norrbotten craton on the western edge of the CLGB. It has lately become economically interesting (acquired by Northland Deposits in 2005) due to the five thrust-related tabular/lenticular massive magnetite bodies which are hosted by a clinopyroxenite-rich “skarn” and dip to the SW. The grade of metamorphism is amphibolite facies.

Besides the main interest in iron there are also considerable amounts of copper and gold. Contents of 0.17 % (up to 0.8-1%) of copper and sometimes gold contents above 0.5 ppm seem to be a promising by-product in the future. In the past, 4.5 Mt of ore have been mined by Outokumpu. Drilled reserves are 200 Mt with an average content of 32.2 % Fe and 0.17% Cu. Apart from magnetite also pyrrhotite and locally molybdenite, but also monazite and uraninite (in traces) can be found. The total REE content can reach more than 1000 ppm.

The monzonite and diorite which were overprinted by the “skarn”-forming hydrothermal event were dated to 1.86 Ga (zircon dating), whereas the mineralisation itself formed at 1.81 Ga (according to metasomatic titanite) and 1.80 Ga (metasomatic zircon) respectively. Therefore it can be postulated that the metasomatic event is ca. 60 Ma younger than the host rocks. Apparently the sulphides are younger than the magnetite (NIIRANEN et al, 2007).

The mineralisation occurs in three different types: First of all the massive type, second the brecciated type and finally the disseminated style where magnetite and chalcopyrite are hosted in albitized basalt accompanied by biotite and cummingtonite.

For the first event highly saline fluids are assumed by investigation of fluid inclusions. They are responsible for the albitisation of the “skarn” and can be characterized by high sodium contents (32-56 wt. % NaCl equivalent) and a fluid temperature of over 450°C. These parameters might point to a magmatic origin. This event presumably caused the economically interesting mineralisation.

Different to the fluids of the first event the fluids of the second show lower temperature and 7-22 wt. % NaCl equivalent. They are responsible for the sulphide formation, Au and Ag tellurides, and younger magnetites (NIIRANEN et al, 2007).

Stop 2 - Saattopora 67.79274°N 24.40512°E

This deposit is bound to the south dipping (45°) Sirkka thrust zone and hosts gold in quartz/carbonate (mainly ferro-dolomite) veins in phyllite, mafic tuffs and komati-

Figure 14: Typical N-S striking gold-bearing quartz-veins in albitized phyllites of the Saattopora orogenic gold deposit.

ites. It represents a typical orogenic gold deposit formed from H_2O-CO_2 fluids (9% NaCl eq.) at 300-350°C. In Figure 14 these vertical, N-S striking, extensional veins can be seen in phyllite which is in general completely albitized.

Initially Outokumpu Oyj was prospecting for copper and zinc in this area and only later became aware of the gold concentrations which are essentially accumulated in two bodies (mined in pits A and B). All of the gold is present as native gold.

In general three different events need to be distinguished for the gold mineralisation. Starting with the oldest at 1.91 Ga the gold deposit of Kittilä is the biggest and most prominent example of this event. It is followed by a mineralizing event around 1.86 Ga and finally one at 1.80 Ga. The latter event is responsible for the mineralisation in Saattopora.

In pit B a presumably explosion-related clastic sediment can be seen (Figure 15) which consists of a quartz, carbonate and sulphide matrix and is mineralogically the

Figure 15: Clastic sediment which might have formed by explosion. Due to the nearby fault and the adjacent "unaffected" mafic volcanite in the south a connection to the indicated fault (red) seems likely. In the inset "a" two different kinds of clasts can be distinguished – white (quartz) and grey (albitized phyllite).

same as the mineralized zone. Regarding the clasts, pale albitized phyllites, white quartz (including gold) and mafic volcanic rocks can be observed. So far 6.3 t of gold and 5200 t copper have been mined.

Near the mining area a crenulated greenstone outcrop of the CLGB reflects the locally important metamorphic event at 1.83-1.80 Ga.

Stop 3 - Hirvilavanmaa 67.74918°N 25.18504°E

The mineralisation of the Hirvilavanmaa area, discovered by GTK in 1986, is also related to the Sirkka thrust zone and was operated in three deposits with a total of 100.000 t of ore being mined. It is classified as an orogenic gold deposit and differs from the former mineralisation by its host rocks - gold can be found in komatiites and tholeiitic basalts, but not in phyllite. Apart from the uneconomic pyrite and chalcopyrite, also chromite, Ni minerals and various tellurides can be found. Additionally, an early talc alteration needs to be mentioned. As in the Saattopora area the mineralisation is accompanied by a quartz/carbonate alteration.

Genetically the fluid inclusions which show 15 wt.% NaCl equivalent may point to an influence of evaporites to the formation. Until now 320 kg gold has been extracted at a content of 2.9 g of gold per ton.

Stop 4 - Sorretiakumpu 67.74787°N 25.17246°E

Finally an interesting outcrop of massive fuchsite/carbonate rock was visited (Figure 16). It formed metasomatically by alteration of a 2.05 Ga old komatiite which supplied the necessary chromium for the formation of fuchsite. Elevated concentrations of gold and high nickel concentrations are noteworthy.

Figure 16: The massive fuchsite rock outcrop of Sorretiakumpu which derives from the interaction of potassium- and calcium-rich fluids with komatiites.

Day 7 – Kittilä Gold Mine, Finland (67.89887°N 25.38848°E)

The Kittilä gold deposit is situated in the Central Lapland Greenstone Belt (CLGB), consisting of a Paleoproterozoic volcanic and sedimentary cover (2.5-1.97 Ga) overlying the Archaean granite gneiss basement (3.1-2.6 Ga) (HANSKI AND HUHMA, 2005). The main deposit is situated along the Suurikuusikko Trend shear zone (Figure 17). The individual ore bodies occur along the Kiistala Shear Zone, an approximately 25 km long strike-slip shear zone active in the later stages of the orogenic development of the CLGB. The orogenic Suurikuusikko gold deposit is one of the largest known gold resources in northern Europe (PATISON et al., 2007).

Metavolcanics as well as BIFs and black schists are the major lithologies hosting the Kittilä deposit. Those rocks are sometimes heavily altered by carbonate, chlorite and albite alteration. Furthermore they are sheared and brecciated. Pinch and swell structures can also be found. The refractory gold is mainly bound to arsenopyrite (75 %), sometimes to pyrite (21 %), and only 4 % of the gold present is free gold. The proven reserves of the Kittilä deposit are 4.5 million ounces (30 Mt at 4.64 g/t Au); another approximately 2 million ounces are indicated.

Production has started in 2010 and the mine is expected to be in operation until 2034. In 2012 the open pit mining (in the two pits „Suuri“ and „Roura“) ceased and the entire production was moved to the subsurface. In 2016, 202,508 ounces of gold were produced, and a total of 1.6 million tons of ore extracted.

After the flotation the ore enters a CCD circuit followed by CIL leaching electrolysis and smelting. The end product produced in Kittilä contains about 70 to 80 % Au. Neither the silver nor the arsenic present in the ore is used.

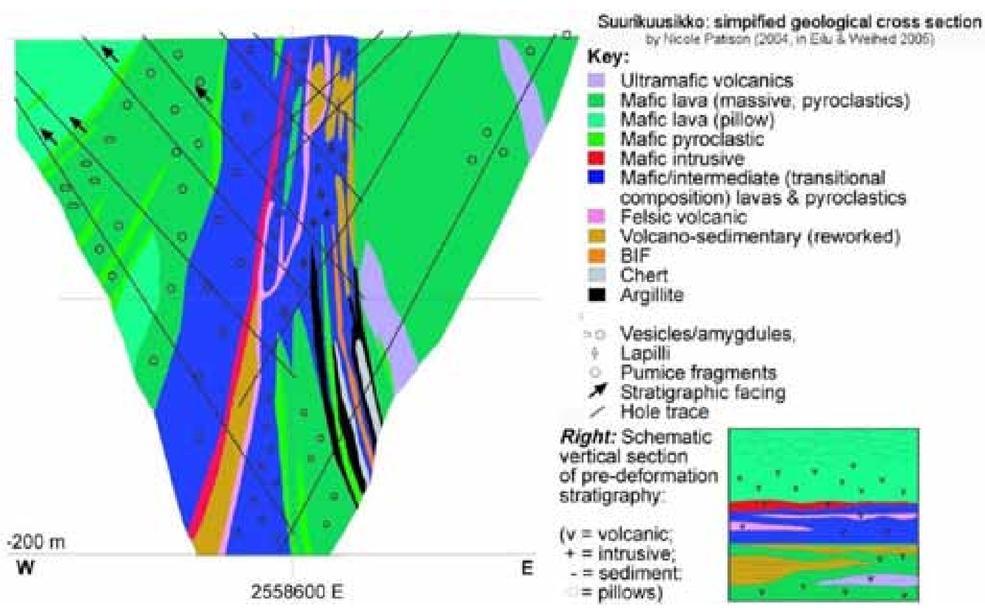

Figure 17: Simplified geological cross section of the Suurikuusikko Trend (EILU & WEIHED, 2005).

About 20 km north of the current production area lies another deposit, "Kuotko". This deposit of another mineralization type (the gold is linked to quartz-veins) is currently in exploration.

Stop 1

After the presentation a lookout over „Suuri" - the larger open pit – was visited. The almost vertical N-S-striking graphitic shear zone is clearly visible (Figure 18). This shear zone can be followed all through the Lapland Greenstone Belt (at least 100 km).

On average it is about 100 to 200 m wide; the ore zone itself is 10s of meters wide. Due to the pinch and swell structures the width of the shear zone varies. On the western side of the shear zone mafic pillow lava is located, separated from the shear zone by a sharp contact. The rocks on the eastern side are mafic lavas too; these rocks are by far more altered. For that reason the contact is not that sharp.

Figure 18: Overview of the open pit in Kittilä. The N-S-striking shear zone is clearly visible.

Stop 2

South of the „Suuri" open pit is one of the few outcrops in the area – a prospect area called "South Pit" which had been cleaned of till. The arsenopyrite needles (max. 2 mm long) as well as the pyrite are clearly visible, just like the graphitic fault zone. Nevertheless the mineralisation is always situated in the volcanics; it only appears close to the graphite – the dissemination of the gold is therefore linked to the graphite. If both pyrite and arsenopyrite are present the likeliness of gold mineralisation is usually high. The black and white schists are quite hard due to the alteration (silicification). Particularly impressive are various visible shear structures like pinch and-swell structures. Finally, the core shed was visited.

Excursion day 8 - Pahtavaara gold mine, Finland (67.63037°N 26.41519°E)

History

The Pahtavaara deposit was discovered by GTK in 1985 during geochemical sampling and basement rock mapping activities. Between 1995 and 2000, Terra Mining Oy operated the Pahtavaara mine using the open pit method. In 2003, Scan Mining Oy acquired the Pahtavaara gold mine, extracting ore from the open pit from 2003 to 2007. In 2008, The Lappland Goldminers Oy took over the mining license from Scan Mining and the production was moved from open pit (Figure 19, a) to underground. The operation lasted for six years until 2014. In September 2016, Rupert Resources Finland took over the Pahtavaara project following the bankruptcy of Lappland Goldminers Oy. Currently, Rupert Resources conducts infill drilling and resource modelling of the deposits because geological model was not available from the previous owners. Based on LAPPLAND GOLDMINERS (2014), total measured resource of Pahtavaara gold mine is 0.618 Mt at 1.97 g/t Au based on cut-off-grade of 0.5 g/t.

Geology

The Pahtavaara deposit is hosted by a thick sequence of meta-komatiites, volcaniclastic sediments, pyroclastic rocks and komatiite-related mafic metavolcanic rocks (KORKIAKOSKI, 1992). The host rocks have been metamorphosed into upper-greenschist facies conditions (EILU et al., 2007). Meta-komatiite is dominated by tremolite, actinolite, chlorite and biotite (Figure 19, b-d). The metamorphic mineral assemblages include tremolite, actinolite, biotite, chlorite and carbonate (mainly dolomite – siderite) (Figure 19, b-d).

The Pahtavaara deposit consists of five ore bodies: (1) Karoliina (2) Wilhemiina, (3) North Flank West Harpoon, (4) North Flank East, and (5) Samurai. Mineralisation extends along a linear structure that trends east-west, generally 5 – 10 m wide and dipping at about 70 – 80 degrees. This deposit comprises several lens-shaped (Figure 19, e), irregular, sub-vertical bodies, which occur along the shear zones at the contact between the komatiitic lavas and the volcaniclastic sediments.

Gold is characterized by free gold hosted in a contact between quartz-carbonate (dolomite-siderite) veins, barite and altered meta-komatiite. Gold in Pahtavaara has high purity (low silver content). Locally (e.g. Karoliina ore body), gold is associated with massive sulphides that consist of pyrite, chalcopyrite and minor pentlandite (Figure 19, d and f). In the biotite schist gold is closely associated with magnetite and talc-carbonate veins, in which it is fine-grained and occurs together with pyrite (KORKIAKOSKI & KILPELÄ, 1997). Magnetite may reach up to 5 – 10% in the biotite schist or biotite-talc breccia. Alteration related to gold mineralisation is characterised by the formation of biotite, amphibole, carbonate, magnetite and albite.

Exploration

During 2016 –2017, Rupert Resources conducted geochemical, geophysical and

Figure 19: (A) Main pit area of Pahtavaara gold mine. (B) Actinolite in massive quartz-carbonate veins. Sulphides are identified as pyrite and chalcopyrite. Rock is collected from a stockpile in the crushing plant of Pahtavaara gold mine. (C) Unmineralised metakomatiite consists of talc – chlorite – tremolite in Karoliina ore body. (D) Lithological contact between metakomatiite (left, green color) with massive sulphides (right, yellow color) at Karoliina ore body. (E) Pinch and swell structures of quartz-carbonate veins in the Karoliina ore body. (F) Drill hole photograph of altered massive sulphides. Copper minerals are altered into malachite.

drilling work in order to delineate the extension of ore bodies. These methods included ionic leach of soil and chip samples, geochemical multi-element analysis of till and heavy minerals, induced polarization (IP) geophysics and a diamond drilling campaign. In July 2017, Rupert Resources has completed 25 km of IP, 47,710 m of drilling and 27,000 samples assayed. In the Karoliina ore body, drill hole intersects yielded 25 g/t Au over 6 meter and 11.7 g/t Au over 4.8 meter (RUPERT RESOURCES, 2017). Base metal mineralisation in Pahtavaara has been identified using test pit and infill drilling methods. This is the next target for exploration in the future.

Mining

Thirty km of 5m x 5m underground tunnels have been opened since mining started in 2008. The lowest level is -220 m and is approximately 460 m below the surface. The surface level is around +250 m and the bottom of the pit is at +165 m. The ore is mined by open stoping method with heights varying between 15-25 m.

Processing

The excavated ore is transported from the mine to the crushing facilities at the mineral processing plant next to the mine office. After crushing, the ore is ground up to 1.5 mm grain size using a semi-autogenous (SAG) mill with a capacity of 1,500 tpd. The ore is concentrated at the Pahtavaara plant using hydrocyclone, shaking table, Humphrey spirals and flash flotation. Based on the technical experience from previous owners, approximately 60-75% of gold can be recovered from the ores.

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