Geology, alteration and lithogeochemistry of the Paleoproterozoic Korpela VMS occurrence in Eastern Finland

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Abstract
Korpela is a Cu-Zn-Au VMS occurrence hosted by bimodal, sub-alkaline, volcanic and volcaniclastic rocks. It is part of a Svecofennian supracrustal sequence 1.93–1.91 Ga in age. In this study, lithogeochemical evidence is used to assess the VMS-prospectivity in the Korpela area to serve regional-scale exploration and provide detailed information on chemostratigraphy and hydrothermal alteration within the Korpela succession. Korpela is understood to have been formed in an evolved arc rift, possibly in a continental back-arc environment. The felsic rocks of the sequence are FII-FIIIa, HFSE-enriched (A-type) rhyolites overlain and, locally cross-cut, by mafic rocks with MORB/BABB signatures and felsic synvolcanic porphyry dykes. In the vicinity of Korpela, tonalitic subvolcanic intrusions intrude the supracrustal rocks which share textures common with local shallow VMS-related intrusion complexes. The Korpela area comprises a volcanic succession where primary volcanic textures are completely destroyed by multiple deformation, metamorphism and alteration. Using detailed volcanic chemostratigraphy established from downhole geochemical profiles, 12 chemostratigraphic units and 21 chemical rock types could be identified ranging from basalt to rhyolite. Several metamorphic mineral assemblages were identified which were further classified into six alteration types, i.e. Mg-Fe-S, K-Al-Fe (± S), K-Al-Mg-Fe-S, K, Si-K-Ca (± S) and Ca (± Na), using a combination of mineralogy and geochemistry. The chemostratigraphy and alteration studies help in understanding the volcanic stratigraphy and in recognising a potential VMS-related alteration.

Keywords VMS deposits · Lithogeochemistry · Chemostratigraphy · Hydrothermal alteration · Paleoproterozoic · Finland

Introduction
Volcanogenic massive sulphide deposits (VMSs) are a globally important source of base metals (Pb, Cu and Zn) and other metals (Ag, Au, Cd, Se, Sn, Bi, Ge, Ga and In) (e.g. Franklin et al. 2005; Galley et al. 2007). The exploration and mining history for VMS deposits in Finland is long, dating back to the eighteenth century, when mining began at the Orijärvi deposit, southern Finland (Haapala and Papunen 2015). Economically, the most significant VMS camp in Finland is the Vihanti-Pyhäsalmi belt in the NW part of the Raahe-Ladoga Shear Zone (RLSZ; Fig. 1), a collage of distinct shear zones, where seven deposits with a reported mineral resource and more than ten occurrences have been discovered (e.g. Mäki et al. 2015). About 100 Mt of ore has been mined from the Vihanti-Pyhäsalmi belt since 1954 (Mäki et al. 2015). Despite several near surface discoveries, the RLSZ can nevertheless be considered underexplored at depth. This is particularly true for the SE part of the RLSZ which forms the focus of this study. In the 1950s and 1960s, the exploration focus was in the Virtasalmi suite leading to one mine, Virtasalmi (Cu) (Fig. 1) which was active during the period 1966–1984 (Puustinen 2003). The Viholanniemi area, east of Virtasalmi (Fig. 1c), has witnessed a relatively small amount of exploration. The initial work conducted by the Geological Survey of Finland (GTK) in the northern part of the Viholanniemi suite led to the discovery of the Viholanniemi Zn-Cu-Pb-Ag-Au deposit in 1985 (Makkonen 1991). In the early 1990s, Outokumpu Oy explored the southern part of the area, but exploration activities soon ceased due to poor results (Puustjärvi 1992).
Jäppilä-Virtasalmi block

Maavesi suite
- Granodiorite
  - Boundary of the Maavesi suite

Virtasalmi suite
- Mafic and intermediate volcanic rocks

Viholanniemi suite
- Felsic and intermediate volcanic rocks

Proterozoic
- Granodiorite, granite, monzonite (Central Finland Granulite Complex)
- Paragneiss and greycvacke (Metasedimentary rocks)
- Diorites
- Mafic rocks
- Quartzites

Archean
- Granodiorite
- Migmatitic tonalite
- Mafic rocks
- Thrust fault zone
- Major faults
- Minor faults
- RLSZ

Study area
In the early stages of exploration, it is critical to identify the VMS-prospective belts from the less prospective ones and locate the most favourable lithological units within the volcanic successions (e.g. Hodges and Manojlovic 1993; Galley et al. 1993; Paulick et al. 2001). This requires an understanding of volcanic and chemical stratigraphy and hydrothermal alteration in order to target cost-effectively to the proximity of ore. It has been recognised that there are several critical characteristics in volcanic rocks, especially on felsic suites, that help to identify potentially VMS-prospective systems (e.g. Lesher et al. 1986; Lentz 1998; Barrett and MacLean 1999; Piercey et al. 2001; Piercey 2011). The rift-related and high-temperature magmatism signatures commonly found in FII, FIII and FIV felsic volcanic rocks can be used as belt-scale geochemical indicators for VMS-prospective rhyolites. This widely used classification discriminates between four types of rhyolite: FI, FII, FIII, FIV (e.g. Lentz 1998; Hart et al. 2004; Piercey 2011). Recognition of HFSE-enriched (A-type) rhyolites, overlain by MORB/BABB affinities and felsic synvolcanic porphyry dykes, indicate a VMS-potential rift-related environment (e.g. Lentz 1998; Piercey 2011). Other commonly recognised features related to VMS deposits globally are the associated large subvolcanic intrusive complexes that typically occur in proximity to the deposits (e.g. Galley 1996, 2003; Campbell et al. 1981; Large et al. 1996; Hannington et al. 2005; Piercey et al. 2008; Piercey 2011; Bailes et al. 2016).

In glaciated terrains, as in the Viholanniemi area, the paucity of outcrop means that the details of geology and volcanic stratigraphy rely almost exclusively on drill hole information though information from geophysical surveys and till geochemistry is also used. All the Paleoprotrozoic VMS deposits in Finland and elsewhere have been affected by deformation and regional metamorphism, resulting in recrystallisation of the original alteration minerals to variable metamorphic assemblages (e.g. Roberts et al. 2004; Latvalahti 1979; Mäki et al. 2015; Barrett et al. 2005; Caté 2016; Kampmann et al. 2017; Hollis et al. 2018). This often leads to complex classification of metamorphic mineral assemblages and difficulties in discriminating between lithological units. The use of immobile element geochemistry is a widely recognised tool in the reliable protolith study of igneous rocks, in determining of magmatic affinities and the quantitative estimates of mass, volume and mineralogical changes in hydrothermally altered and metamorphosed sequences (e.g. MacLean and Barrett 1993; Barrett and MacLean 1994; Hannington et al. 2003; Barrett et al. 2005; Mercier-Langevin et al. 2007). Hence, lithogeochemical methods have allowed for the validation of geologic interpretation with proper protolith and chemostratigraphic identification regardless of metamorphism and alteration. Lithogeochemistry has also proven to provide reliable signatures of identifying rift environments and the presence of high-temperature magmatism which are critical factors in VMS Mineral Systems and are used for identifying prospective and barren areas for hosting VMS mineralisation (e.g. Lentz 1998; Hart et al. 2004; Gaboury and Pearson 2008; Piercey 2010, 2011).

Author’s opinion is that these methods have not been utilised widely enough in brownfield or greenfield VMS exploration in Finland. Lithogeochemistry, especially the use of chemostratigraphy and mobile-element geochemistry, has mainly been applied in the Vihanti-Pyhäsalmi belt, in Central Finland (Mäki 1986; Roberts et al. 2003; Roberts et al. 2004; Imaña et al. 2013; Mäki et al. 2015). The study of mobile element ratios and concentrations related to the proximal zone of the Pyhäsalmi deposit (Mäki 1986) served as a successful exploration tool resulting in the discovery of Mullikkoräme VMS deposit in 1987, within the Vihanti-Pyhäsalmi belt (Mäki 1986; Mäki et al. 2015).

Korpela, a recently discovered Cu-Zn-Au VMS occurrence in the Viholanniemi area (Figs. 1 and 2, and ESM Fig. 1), is associated with intense alteration and overprinted by regional metamorphism and deformation. Immobile-element lithogeochemical methods have been used in this study to verify protoliths and establish chemostratigraphic relations derived from downhole geochemical profiles and petrographic observations. Hydrothermal alteration is studied to classify different alteration types which can be further modelled in 3D using mobile-element geochemistry to recognise their geochemical footprints (Hokka 2020). Many of the more recent lithogeochemical studies applied to metamorphosed hydrothermal ore systems have either been undertaken in relation to an active mine or brownfield exploration targets where large amounts of data is available (e.g. Schletter et al. 2003; Roberts et al. 2003; Barrett et al. 2005; Imaña et al. 2005; Mercier-Langevin et al. 2007; Schletter 2007; Mäki et al. 2015; Mills et al. 2016; Caté 2016; Chmielowski et al. 2016; Kampmann et al. 2017; Hollis et al. 2018). Although here the target is in a greenfield area, the same methods are applied, with the following objectives: (1) describe the main geological, mineralogical and geochemical features of the target and hosting volcanic succession. (2) Provide lithogeochemical
Regional geology

The Fennoscandian shield consists of Proterozoic and Archean units. The Archean rocks dominate in the eastern and northern part whereas Proterozoic rocks cover much of the rest of the shield (Koistinen et al. 2001). The latter comprise ca. 1.9-Ga orogenic terrains of southern and western Finland including volcanic-sedimentary and migmatitic gneiss belts and granitoid complexes (Fig. 1a). The VMS deposits of central Finland are hosted by multiply deformed bimodal volcanic rocks within the NW-trending crustal-scale suture zone referred to as the Raaheladoga Zone (e.g. Korsman et al. 1997, Koistinen 1981; Ekdahl 1993; Mäki et al. 2015) or the Raaheladoga Shear Zone (RLSZ; e.g. Mikkola et al. 2018a) (Fig. 1a, b). The RLSZ hosts a set of Paleoproterozoic arc complexes accreted together and against the Archean craton (Korsman et al. 1997). This collisional setting forms the part of the Finnish Svecofennian domain, and is bounded by the Archean basement with overlying Paleoproterozoic (Karelian) sequences in the east and the Central Finland Granitoid Complex (CFGC) in the west (Fig. 1a). The Svecofennian magmatic rocks in this area form two distinct age groups: an older 1.93–1.91 Ga and a younger
interlayers (Fig. 1b). The regional deformation is characterised by nappe-style, northerly verging overthrusts and recumbent, isoclinal folds formed during D1-D2 responsible for the development of the main S2 foliation. The D3 deformation was mainly active after the peak metamorphism at 1.83–1.81 Ga, overprinting all the metamorphic zones formed during the D2 (Korsmann et al. 1988). The D3 deformation structures are cut by ca. 1.8 Ga post-tectonic granites (Vaaasjoki and Sakko 1988) and partly folded by D4 deformation (Kilpeläinen 1988). The development of NE-trending crustal-scale transtensional shear zones and faults during D3-D4 resulted in the juxtaposition of crustal blocks with discordant metamorphic zones (Korsman et al. 1984; Hölltä 1988).

The Jäppilä-Virtasalmi block (Fig. 1c) is part of the southeastern extension of the older, 1.93–1.91 Ga, primitive arc complex of rocks of the Northern Ostrobothnia supergroup forming three major suites (Fig. 2a): the Maavesi, Virtasalmi and Viholanniem suite (Kousa et al. 2018). A major part of the Jäppilä-Virtasalmi block consists of schists and gneisses which are turbiditic in origin and are intruded by gabbro, granite, granodiorite and tonalite of the Maavesi suite. The Virtasalmi suite is mostly dominated by submarine sub-alkaline, subma­rine, bimodal volcanic-sedimentary formations surrounded by mica gneisses and mica schists (Fig. 2a). The Viholanniem suite includes rhyolitic quartz feldspar porphyries, intermediate pyroclastic rocks and lavas with mafic inter­flows or intercalations, and minor carbonate rock interlayers (Korsman 1973; Zhang 2000; Kousa 2009). The southern part of the Viholanniem area comprises more mafic-dominated sequences, locally pillowed lavas that are classified into the Virtasalmi suite (Kousa et al. 2018; Zhang 2000). In stratigraphically upward progression, the mafic volcanic rocks overlie the felsic sequences. The regional metamorphism was studied by Korsman et al. (1984, 1988) which resulted in the classification of progressive metamorphic zones towards the SE from Viholanniem. Two episodes of regional metamorphism have been recognised in the Viholanniem region: a prograde lower and middle amphibolite facies episode associated with the main deformation event D2 (Korsman et al. 1984, 1988).

**Synvolcanic intrusions of the Viholanniem suite**

The Saunakangas intrusion is a multiphase tonalitic granitoid forming the main lithodeme of the Maavesi suite, covering an area of 50–60 km² (ESM Fig. 1). It has a pinkish-white colour and textures from porphyritic to granoblastic and locally it is strongly foliated and sheared. Miarolitic cavities are locally abundant and occasionally filled with epidote and quartz. Typically, plagioclase (albite) is altered to saussurite and sericite and includes epidote (Fig. 3a). Locally, near the intrusion boundary, it contains abundant xenoliths of mafic volcanic rocks (Fig. 3b). Approximately 1 km north of Korpela, the tonalite is transected by fine-grained aplitic dykes (Fig. 3c). The typical alteration feature in the Saunakangas intrusion is epidotisation which form patches of over 80 mm in diameter (Fig. 3a). The pinkish colour is caused by K-feldspar and sericite alteration that is mainly concentrated near the shear zones (Fig. 3d). In the vicinity of volcanic rocks, the intrusion contains minor amounts of finely disseminated magnetite which can also be detected in magnetic surveys as positive anomalies (unpublished GTK data). The U-Pb zircon age from two granodiorite-tonalite samples (ESM Fig. 1) yielded ages of 1908 ± 2 Ma and 1912 ± 3 Ma (Kousa et al. 2018). This is closely coeval to the age of Viholanniem rhyolite, 1914 ± 3 Ma (Kousa et al. 2018) indicating the synvolcanic nature of the intrusion. The Saunakangas intrusion shares features such as epidote- and quartz-filled cavities, with the Kokkokangas granodiorite of the Pyhäsalmy area which is also interpreted as a subvolcanic intrusion associated with the Pyhäsalmy VMS deposit (Ohtoma 2014).

Quartz-feldspar porphyry dykes intrude the volcanic and volcanlastic rocks at Korpela (Fig. 3d, f). The dykes are mainly concordant to semi concordant and range in thickness from 0.5 to 5 m. The porphyries can be subdivided into two subgroups: felsic quartz-eye and dacite types. The felsic quartz-eye porphyries are typically reddish, homogeneous and massive. The K-feldspar, plagioclase and quartz phenocrysts range from 2 to 4 mm in size; they are mainly subhedral and occur in a fine-grained form in groundmass (Fig. 3f). The dyke contacts are typically sharp and lobate suggesting that they were intruded into an unconsolidated volcaniclastic strata. The dacitic porphyries have a more mafic groundmass and distinct reddish phenocrysts of 2–4 mm in size that have partly altered to muscovite (Fig. 3g). Some chloride and carbonate are also present. The porphyries have been affected by varying degrees of synvolcanic intrusion–related K-feldspar, sericite and saussurite hydrothermal alteration (Fig. 3d, g).

**Local geology at Korpela**

The Korpela occurrence, within the Korpela succession, is located in the central portion of the Viholanniem suite and
constrained by several NE- and NW-trending, small-scale ductile shear zones. Based on geophysical potential field datasets (GTK unpublished data), the shear zone has a NW-trending wedge-like geometry. This is interpreted as a high-strain corridor forming a dextral shear zone and hosting the main Korpela hydrothermal alteration domain that is over 1.5 km long (Fig. 2b).

The Korpela succession can be subdivided into five major units: andesite, felsic quartz-phyric rhyolite with minor carbonate interlayers, intermediate to felsic volcaniclastic rock, basaltic sill and synvolcanic intrusives. Andesite sills and flows are interbedded with the felsic volcanic and volcaniclastic units. Basaltic sills or dykes and synvolcanic intrusives overlie but also locally intrude into the Korpela volcanic succession. The synvolcanic quartz-feldspar porphyry dykes (the quartz-eye

Fig. 3 Outcrop and drill core photographs of the subvolcanic intrusion and synvolcanic felsic dykes at Viholanniemi and Korpela. a Mafic cavities and epidote alteration in the Saunakangas tonalite at Vuoriniemi (sample 5, Fig. 2). b Xenoliths of mafic volcanic rocks in the Saunakangas tonalite at Vuoriniemi (sample 5, Fig. 2). The length of the pen is 16.5 cm. c A fine-grained aplite dyke cuts through the Saunakangas tonalite phase at Vuoriniemi (sample 5, Fig. 2). d Locally granitised, high-K-feldspar, rock at the contact zone of andesite flows and the Saunakangas tonalite. e Light coloured, fine-grained quartz-feldspar porphyry (‘quartz-eye porphyry’) dykes with an intense red colour. These have a chemical composition similar to the granitic rocks close to the Saunakangas tonalite. g Dacitic feldspar-quartz porphyry (dacite porphyry) dyke at Korpela. This rock is at the contact with quartz-feldspar porphyry. Ep epidote
porphyries) are homogeneous, massive rocks with sharp contacts with the surrounding volcanic and volcaniclastic rocks. They are similar to the quartz-phryic to aphyric rhyolites that form the spatially large, coherent, felsic volcanic package west of Korpela (Figs. 2a, b and 3e). Volcaniclastic rocks are mainly composed of pyroclastic volcanic fragments that are generated from explosive volcanic activity. These rocks include pyroclastic breccia (see Fig. 5g), lapilli tuff and tuffite. Locally, autoclastic textures can be seen with jigsaw-fit texture indicative of in situ (carapace) breccia. The volcaniclastic fragments are felsic to intermediate in composition, mainly monomict, poorly sorted and clast- to matrix-supported. Strong deformation and penetrative S2 foliation have partly destroyed the primary textures, and fragments and clasts are now elongated along the stretching lineation. West of the Korpela succession, narrow interlayers of carbonate rocks were observed during drilling in the felsic volcanic units. A polymictic clast-supported volcaniclastic conglomerate with felsic, intermediate and mafic

**Fig. 4**  
**a** Andesitic volcanic fragments within the felsic volcanic unit (Outcrop observation: 6888056 N; 539915 E). The hammer handle is 80 cm long.  
**b** Transposed folding of mafic lava in rhyolite unit (Outcrop observation: 6887993 N; 540003 E).  
**c** Deformation fabrics in pervasively sericite altered rock with andalusite porphyroblasts in drill core (DH24, 218.20 m). Andalusite porphyroblasts are oriented parallel to the main foliation.  
**d** Crenulation observed in drill core (DH10, 83.70 m).  
**e** Pervasively altered and deformed andalusite-sericite schist (DH17, 128.30 m). And andalusite, C crenulation, F foliation, Ser sericite
volcanic pebbles and rare mica schist and granitoid pebbles are predominant in the east of Korpela (Fig. 2b) (Kousa 2009).

A large part of the rocks located in the Korpela area have been affected by intense alteration and all the rocks are affected by polyphase (D₁-D₄) deformation and metamorphism resulting in the near-complete destruction of the primary volcanic textures. Thus, it is difficult to identify the primary volcanic textures. At Korpela, the rocks are deformed by isoclinal F₂₃ folds relating to the regional D₂₃ stage (Kilpeläinen 1988). The D₂ is characterised by intense ductile deformation which can be observed by complex fold interference patterns in outcrops where F₂ folds are refolded by F₃ folds (Fig. 4a, b). The deformation during D₄ is brittle-ductile with pegmatites and sulphide-bearing quartz veins favouring...
The Viholanniemi Zn-Cu-Pb-Ag-Au deposit (Figs. 1c and 2a)

Viholanniemi Zn-Cu-Pb-Ag-Au deposit foliation. Local crenulation of S3 dips 60–80 degrees. Zone have a strong foliation and stretching lineation with local pattern in the Korpela succession. Volcanic rocks in the shear repetition of the main rock units support the folded and faulted stage brittle faults cut the lithological units into separate tec-tonic subdomains. The chemotrajectory and alteration mapping together with interpreted lithological contacts and the repetition of the main rock units support the folded and faulted pattern in the Korpela succession. Volcanic rocks in the shear zone have a strong foliation and stretching lineation with local crenulation. The strong penetrative NW-trending S2 foliation and associated mineral and stretching lineation L2 affects most of the silicate minerals. The main axial plane foliation of S2 dips 60–80 degrees towards the SW. According to regional observations by Kilpeläinen (1988), the D3–4 deformation is usually shown as zonal crenulation (S3–4) deforming of S2 foliation. Local crenulation of S3–4 has preferentially been developed in thin bands of sericite which also can be clearly observed in the Korpela drill core (Fig. 4c–e).

Viholanniemi Zn-Cu-Pb-Ag-Au deposit

The Viholanniemi Zn-Cu-Pb-Ag-Au deposit (Figs. 1c and 2a) has been reported as a historic, non-compliant, inferred resource of 250,000 t at 2.1% Zn, 0.2% Cu, 0.64% Pb, 65 ppm Ag and 0.9 ppm Au (Västil 2012). The Viholanniemi deposit has not been mined and it can be classified as a small, early-stage, exploration target. It is situated within the northern part of the Viholanniemi suite (Makkonen 1991; Zhang 2000). It was discovered by GTK in 1985 by combining information from glacial erratic boulder tracing, till geochemistry and airborne and ground geophysical surveys. The sulphides are predominantly hosted by quartz-carbonate±(± tremolite) gangue which forms conformable veins and, locally, as stockwork of veinlets in felsic to intermediate volcanioclastic and felsic quartz porphyry rocks. The average thickness of individual veins is approximately 1–5 cm (Makkonen 1991; Zhang 2000). The ore minerals are sphalerite, galena, chalcopyrite, pyrite and pyrrhotite. Gold and silver are present as various alloys. Gold is mainly in electrum as fine-grained interstitial grains between silicates and carbonates (Makkonen 1991). The Viholanniemi ore body is associated with a distinct, pyrite-sericite dominant, alteration assemblage with local epidotisation. According to Zhang (2000), the sericite-quartz altered rocks show a minor Na2O depletion.

The mineralised zone is approximately 600 m long comprising two separate lenses with an average thickness of 1.1 m. Makkonen (1991) interprets the mineralised lenses to be structurally controlled by the F3 folding that may represent small folds in limbs of a larger asymmetrical fold structure. The primary axial plane of the F3 folds trends northwest-southeast and the fold axis plunges to the southeast (Kilpeläinen 1988; Makkonen 1991). The Viholanniemi occurrence is also affected by the late D4 stage brittle deformation that cuts the lithological units by faults into separate parts (Makkonen 1991).

Mineralisation

In 2013, GTK discovered a mineralised biotite-chlorite-garnet-anthophyllite boulder with 0.9 wt% Cu next to a gravel road at Korpela (Figs. 2b and 5a and ESM Fig. 2c). This resulted in follow-up work including a till geochemical survey, ground geophysical surveys, geological mapping and a total of 3300 m of diamond drilling (Hokka et al. 2014) (Fig. 2).

The style of sulphide mineralisation varies from semi-massive to stringer zones and dissemination (Fig. 5g–i). Drill core samples show a clear base and precious metals enrichment which makes it an attractive exploration target where an economically viable massive sulphide deposit is yet to be discovered. The main sulphide minerals are pyrite, pyrrhotite with minor chalcopyrite and sphalerite. Magnetite and ilmenite represent the oxide minerals. Semi-massive sulphides are typically pyrite with minor pyrrhotite. Sulphides predominate in interstices and open spaces or replace unstable gangue minerals. Locally sulphides, mainly pyrite, have partly or fully replaced lapilli tuff fragments. The sulphide stringers consist primarily of pyrite and minor chalcopyrite and are either interstitial between clasts of volcanioclastic rocks or oriented parallel to the lineation (Fig. 5g, i). Locally, pyrite veinlets are tightly folded and transposed following the crenulation but also as infill of fractures cutting the main foliation (ESM Fig. 2a (2), ESM 2b (1,2)). Native gold has only been observed under the microscope. The amounts of sulphides display a positive correlation with the alteration intensity. The sulphide-bearing fractures subparallel to S2 together with an
increase in sulphide grain size indicate the remobilisation of sulphides during metamorphism.

**Alteration**

Alteration of variable intensity defines steeply dipping pipe-like bodies in the Korpela volcanic succession. The alteration at Korpela is mainly characterised by metamorphosed aluminous, sericitic, chloritic and albite alteration. Based on the current drilling, discordant and laterally restricted intense alteration forms a N to NW-trending domain that has a strike length of at least 1.5 km (Fig. 2b). The altered zone is located predominantly within the volcaniclastic facies rocks, bounded by the porphyritic rhyolite unit to the east (Fig. 2b). The mineral assemblages produced by the hydrothermal alteration are overprinted by metamorphic mineral assemblages that were formed during the D$_2$ progressive stage which peaked at middle amphibolite facies (Kilpeläinen 1988). Alteration is mainly characterised by sericitic, aluminous and chloritic alteration consisting of the following diagnostic minerals in varying amounts: quartz, muscovite, biotite, sericite, andalusite, chlorite, garnet, chlorite, carbonate, staurolite, sillimanite, cordierite, accessory rutile and tourmaline (Figs. 5a–f and 6a–f). Certain aluminous minerals, such as andalusite, occurring as large porphyroblasts ($\leq$ 5 cm) along the main foliation, are re-oriented parallel to, or overgrow, the main S$_2$ foliation (Fig. 5k). It is generally not possible to see through the metamorphic overprint but occasionally volcanic textures are visible in the weakly altered parts. The alteration at Korpela is classified according to mineral assemblages and chemical alteration types based on observations of key mineral abundance, textures and chemical whole-rock assay data. A total of six chemical alteration types can be defined: Mg-Fe-S, K-Al-Mg-Fe-S, K, Si-K-Ca-(± S) and Ca-(± Na) (Fig. 5a–f), as described in detail below.
Methods

The study is part of GTK’s Regional Ore Potential Mapping Project and was conducted intermittently during the period 2013–2016 and comprised field observations, surface and drill core sampling, petrography and whole-rock geochemistry. For this study, a total of 230 drill core samples from 18 diamond drill holes (3313 m drilled) were collected to reconstruct a representative dataset for the main volcanic units of the Korpela succession (Fig. 2). In addition, five outcrop grab samples were collected from different intrusive phases of the Saunakangas intrusion (Fig. 2a). Prior to sampling, geological mapping and core logging were executed and systematically documented in respect to mineralogy, textures, structures, contacts and alteration intensity. The typical length of an individual half core drill sample taken was 40 cm. The core diameter was 41.7 mm. The sampling interval was based on geological logging observations ensuring that the representative proportion of both least-altered rocks and main alteration assemblages were included.

All the samples were analysed during the period 2013–2016 by Labtium Oy, Rovaniemi, Finland. Samples were dried at 70 °C and the standard scheme of crushing consisted of direct one-stage fine crushing using a special type jaw crushers and precision riffle splitting. The pulverizing (to nominal > 90% < 100 μm) was done using a low-chrome bowl with quartzite cleaning done after every sample. Analyses were done using the wavelength dispersive X-ray fluorescence technique (WD-XRF) from pressed powder pellets. Carbon was analysed from all samples by Leco. The REE

![Immobilized-element ratio plots for the Korpela target.](image)

Fig. 7 Immobilized-element ratio plots for the Korpela target. Each rock type forms its own co-genetic group which are highlighted by the ellipsoids. The dashed lines represent fractionation trends and crosses are samples that represent the precursor rock type of each group. a Zr/TiO₂ vs Al₂O₃/TiO₂ plot of the chemical groups showing a continuous trend from basalt to rhyolite. Some groups show more scatter which may be caused by the sedimentary enrichment of feldspars in clastic rocks or reflect mixed provenance (e.g. dacite and rhyodacite). b Zr/Al₂O₃ vs Zr/TiO₂ plot. c Zr/Al₂O₃ vs Al₂O₃/TiO₂ plot. d Zr/Y vs Zr/TiO₂. e Al₂O₃-Zr (compatible-incompatible) bivariate plot showing a slightly negative fractionation trend with polynomial fit ($y = -3E-05 \times x^2 + 0.004x + 16.777$, $R^2 = 0.673$). f TiO₂ vs. Zr (compatible-incompatible) plot showing a negative polynomial fractionation trend ($y = -7E-06 \times x^2 + 0.0011x + 1.0598$, $R^2 = 0.97$) typical for co-genetic calc-alkaline volcanic suite.
and refractory trace elements were assayed by inductively plasma mass spectrometry (ICP-MS) following lithium borate fusion and acid digestion. REE assays were mainly done on the grab samples from the Saunakangas intrusion. Internal quality control (QC) procedures included blanks, replicates and standards which were used to control the quality of whole-rock XRF and ICP-MS analyses.

Due to the pervasive alteration at Korpela, the only reliable method of determining the precursor volcanic rock type is to use the immobile element method. The results of chemical classification for Korpela rock samples are described in ESM Tables 1 and 2. First, the element mobility was tested using data from altered and unaltered samples against the potentially immobile high-field-strength elements (HFSE) from each visibly uniform volcanic unit. The test for immobility was conducted for Al, Ti, Zr, Nb and Y to see highly correlated linear trends for a single-precursor system (Barrett and MacLean 1991; McLean and Barrett 1993). These elements are potentially immobile with sufficient abundance (i.e. concentrations not too close to the detection limits of the assays) to ensure accurate chemical analyses. All the rock units included samples from variably altered and unaltered rock. The Zr-TiO\textsubscript{2} ratio was chosen as the most reliable immobile element monitor because it was found that it provided the best magmatic fractionation curve as defined from least-altered samples of each of the chemical rock types (Fig. 7). Samples were then grouped according to chemical rock types based on different co-genetic linear trends and immobile-element ratios. The groups were validated with other immobile-element plots to see if any overlap occurred (Fig. 7). Samples that did not fit into any of the immobile-element plots tested were treated as outliers. Samples were then further subdivided into magmatic affinity groups based on their Zr/Y ratios. For each chemical rock type, a least-altered sample was selected as an approximation of the precursor composition to determine the primary fractionation trend. The precursor samples were selected on the

![Fig. 8](image-url) Downhole visual log against chemostratigraphic units and their chemical features in DH17. Hydrothermal alteration has obliterated the primary textural and mineralogical characteristics of the volcanic rocks which can be deciphered using immobile element geochemistry. The sulphide-rich parts can be seen as elevated S and Fe contents. The mineralised zones can be observed from rhyolite to andesite and no key stratigraphic horizon has yet been distinguished. The alteration types and style of mineralisation are described in Fig. 5.
basis of (1) having no visible secondary minerals, (2) an absence of visible sulphide minerals (< 1 wt% S) and (3) following a normal major element composition. The least-altered samples were then checked in order to define reasonable fractionation trends and best-fit curves for different immobile elements against Zr. More details of the procedure and a fuller discussion of the results of the mass balance calculations is provided in Hokka (2020).

Results

Immobile-element geochemistry

Immobile element geochemistry was used to reconstruct the volcanic stratigraphy for the intensely altered, metamorphosed and deformed rocks. A total of 12 main chemostratigraphic units and 21 chemical rock types, ranging from basalt to rhyolite, were defined based on different co-genetic linear trends and Al₂O₃/TiO₂, Zr/Al₂O₃, Zr/TiO₂, Zr/Y and Zr/Nb ratios (Fig. 7a–d, ESM Table 2). The least-altered precursor samples presented in ESM Table 3 were used to define the primary magmatic fractionation trends (Fig. 7e, f) from which the mass balance could be determined for the altered rocks (Hokka 2020). The least-altered samples form a well-defined fractionation line that was fitted using a second-order polynomial curve in Zr/TiO₂ immobile element plot. The polynomial fractionation curve shows Ti depletion and Zr enrichment when moving from basalt to rhyolite composition (Fig. 7f).

The effects of net mass changes can be seen by deviation of samples from the fractionation trend in the Zr/Al₂O₃ and Zr/TiO₂ plots (Fig. 7e, f). Therefore, the rock types were validated by immobile element ratios in scatter plots to remove the effect of hydrothermal alteration (Fig. 7). The groups were further subdivided based on their magmatic affinity given by the values of the Zr/Y ratio (Fig. 10b; ESM Table 2) and the Zr/Y vs Zr/TiO₂ scatter plot (Fig. 7d). This yielded a total of 12 chemostratigraphic units and 21 chemical rock types (ESM Table 2).

The volcanic rocks range from basalt to rhyolite, comprising eight chemostratigraphic groups and 17 chemical rock types (ESM Table 1). Rhyolites are the dominant chemostratigraphic unit forming three distinct subgroups which are further
subdivided into 6 different chemical rhyolite rock types all having a calc-alkaline affinity (Fig. 10b). The textures of felsic rocks vary from clearly porphyritic to volcaniclastic and aphyric. The rhyolite A is described as having coherent volcanic textures whereas rhyolite B and C are clearly volcaniclastic rocks. The rhyolites B and C are indistinguishable without lithochemical data. Rhyodacites and dacites are predominantly volcaniclastic and have both calc-alkaline and transitional magmatic affinities. Andesites have been grouped in two (A and B) and further subdivided into five subgroups based on their magmatic affinity. Andesites A and B can be distinguished by the Zr/Al$_2$O$_3$ and Zr/TiO$_2$ immobile ratios and based on their spatial distribution. In
The alteration at Korpela is classified according to mineral assemblages and chemical alteration types (Figs. 8, 11a and 12). A total of six chemical alteration types can be defined after alteration mineralogy and their chemical identifiers: Mg-Fe-S, K-Al-Fe-(± S), K-Al-Mg-Fe-S, K, Si-K-Ca-(± S) and Ca-(± Na) (ESM Table 4). The alteration types form zonation around the sulphide-rich parts and extend horizontally for at least 1 km (Fig. 11b). The footwall alteration at Korpela is mostly intense and pervasive resulting in total or near total destruction of the primary textures.

Mg-Fe-S alteration

The Mg-Fe-S alteration is defined by biotite-anthophyllite-garnet, biotite-chlorite-garnet-anthophyllite, biotite-sericite-chlorite-anthophyllite and carbonate-biotite-tremolite-anthophyllite-chlorite mineral assemblages (Figs 5a and 6b). The anthophyllite and garnet occur as porphyroblasts along the main foliation (ESM Fig. 2c). Besides orthoamphiboles, the Mg-Fe-S rocks contain accessory chlorite, tremolite, cummingtonite and carbonate. There is no muscovite or aluminosilicates present within this alteration type. The Mg-Fe-S alteration is associated with andesite A, which is predominantly located in the northern part of the Korpela succession (Fig. 2b). The alteration type contains mainly chalcopyrite-pyrite stringers. In chemostratigraphic ternary diagrams, the Mg-Fe-S altered samples plot towards the cordierite, garnet and propylitic mineral nodes following the chloritic alteration trend (Fig. 12).

K-Al-Fe-(± S) alteration

The K-Al-Fe-(± S) alteration is a muscovite-sericite-bearing rock with abundant biotite and aluminosilicates (andalusite ± staurolite) (Fig. 5b). The diagnostic feature of K-Al-Fe-(± S) alteration is the lath-shaped porphyroblasts of biotite that both overgrow and cut across the foliation. This alteration type is defined by sericite-biotite-garnet-andalusite, muscovite-biotite-andalusite-garnet-staurolite and quartz-biotite-sericite-andalusite-talc mineral assemblages. Only minor feldspar and ferromagnesian minerals are present. The alteration type contains minor pyrite-pyrrhotite stringers. This alteration type occurs from the chlorite and dacite to andesite. In chemostratigraphic ternary diagrams, the K-Al-Fe-(± S) altered samples plot towards the kyanite and sillimanite mineral nodes (Al-rich end).
which portray the argillic to advanced argillic alteration trend (Fig. 12).

**K-Al-Mg-Fe-S alteration**

The K-Al-Mg-Fe-S alteration is characterised by muscovite with medium- to coarse-grained aluminosilicates along with staurolite and garnet (5–30 vol%). Locally, andalusite porphyroblasts form very large grains (> 5 cm) towards the boundary of the alteration zone. This is observed in DH24 (ESM Fig. 5a). Aluminous nodules are also locally present (ESM Fig. 5b). The ferromagnesian minerals (Mg-Fe amphiboles, chlorite, cordierite) are more abundant (1–5 vol%) compared to the K-Al-Fe-(± S) alteration type. Feldspar is generally minor to absent. The K-Al-Mg-Fe-S alteration type is defined by sericite-quartz-andalusite-cordierite (Fig. 6a), sericite-andalusite-cordierite, magnetite-biotite-quartz-andalusite, sericite-cordierite-quartz, biotite-garnet-cordierite-staurolite and chlorite-staurolite assemblages. The alteration assemblage contains accessory sillimanite, rutile and tourmaline. The alteration type is also more sulphide-rich than K-Al-Fe-(± S) alteration, having abundant pyrite-pyrrhotite stringers and disseminated to semi-massive magnetite which are oriented parallel to the lineation (S2). The alteration is characterised as strong to pervasive in nature. It characterises rock types from rhyolite to andesite composition and is commonly spatially associated with the K-Al-Fe-(± S) alteration. In chemostratigraphic ternary diagrams, the K-Al-Mg-Fe-S altered samples form two subgroups: andesite host and dacite to rhyodacite host. The andesitic rocks display a slight Al enrichment, whereas the dacitic to rhyodacitic rocks are mainly concentrated at the Al-rich end (A, A’) (Fig. 12).

**K alteration**

The K alteration type consist of muscovite- and sericite-bearing rocks (> 20 vol%). The alteration type is distinguishable by its white appearance (Fig. 5c). Abundant quartz and sericite (± biotite) is also present. This alteration type is only locally present and common between or adjacent to aluminous alteration assemblages. The K-altered zones are barren or contain only minor sulphides.

**Si-K-Ca-(± S) alteration**

The Si-K-Ca-(± S) alteration type is defined as pervasively silica-altered rock with > 50 vol% quartz to less-altered quartz-, sericite (±muscovite) and carbonate-rich rocks. This

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**Alteration Mapping**

![Fig. 11](image)

Fig. 11 a Drill hole section 6887400 N, 540500 E showing the alteration types derived from the metamorphic mineral assemblages of altered volcanic rocks. The sulphide-rich (Py + Po) stringers, shown as red markings along the drill hole traces, are mainly concentrated in the domain of K-Al-Mg-Fe-S alteration. b Simplified geological map with spatial distribution of the different alteration types. The sericite-biotite-aluminosilicate-pyrite alteration assemblage (K-Al-Fe-(± S), K-Al-Mg-Fe-S) dominates in the SW and biotite-anthophyllite-garnet-(± chlorite) alteration assemblage (Mg-Fe-S) in the NE part. The carbonate + albite assemblage (Ca-(± Na) is interpreted to represent moderate to weak hanging wall
includes at least the following assemblages: quartz-sericite-pyrite, quartz-magnetite-fuchsite-pyrite and quartz-carbonate. The Si-K-Ca-(± S) alteration type (Fig. 5e) is associated with an andesite to rhyolite precursor and present as local zones, adjacent to aluminous K-Al-Mg-Fe-S and K-Al-Fe-(± S) and Ca-(± Na) alteration types.

Ca-(± Na) alteration

The Ca-(± Na) alteration type includes the Ca assemblages defined by carbonate, quartz-carbonate-muscovite but also a ‘chaotic’ carbonate assemblage including the carbonate-phlogopite-quartz-chlorite-pyrite assemblage (Fig. 6c). These assemblages are spatially distinguishable. Albization is also included in the Ca-(± Na) alteration type, which is characterized by carbonate, and displays as a moderate to strong pink-white coloured coating.

Discussion

Identifying prospective belts hosting VMS deposits and being able to further delineate the targets by studying the volcanic stratigraphy and alteration is proven to be effective. Generally in greenfield exploration, lithochemistry of bimodal volcanic assemblages is used to target rift successions and delineating the potential VMS districts (Gibson et al. 2007; Piercey 2007, 2011). Several critical characteristics exist in regard to volcanic rocks, especially on felsic suites, that help to differentiate potentially VMS-prospective and VMS-barren systems (e.g. Lesher et al. 1986; Lentz 1998; Barrett and MacLean 1999; Piercey et al. 2001; Piercey 2011). Petrochemical evidence has proven that felsic volcanic rocks with elevated HFSE and REE contents and FIII to FII rhyolite composition are commonly associated with VMS deposits in post-Archean evolved environments (Lesher et al. 1986; Hart et al. 2004; Piercey 2011).

Fig. 12 Chemographic diagrams showing the alteration trends for K-Al-Fe-(± S), K-Al-Mg-Fe-S and Mg-Fe-S alteration types at Korpela. The data are recalculated to molecular ratios (i.e. chemical assay results are recalculated by dividing the weight percentage of each oxide by the molecular weight of that oxide). The chemographic diagrams modified after Bonnet and Corriveau (2007); Corriveau and Spry (2014). The altered felsic and intermediate volcanic rocks show two trends: (1) the aluminium-enriched volcanic rocks of K-Al-Fe-(± S), K-Al-Mg-Fe-S alteration types following the advanced argillic alteration trend, and (2) the Mg-Fe-S alteration type described as chloritic alteration. The areas of least-altered volcanic rocks are shown as a grey circle. A’CF: A’ = Al2O3 + Fe2O3 – (K2O + Na2O), C = CaO, F = FeO + MnO + MgO. A’KF: A’ = Al2O3 + Fe2O3 – (K2O + Na2O + CaO), K = K2O, F = FeO + MnO + MgO. AFM: A = Al2O3 – K2O; F = FeO, M = MgO. Act actinolite; Alm almandine (garnet); An anorthite; Ath anthophyllite; Bi biotite; Cal calcite; Chl chlorite; Crd, cordierite; Di diopside; Ep epidote; Grs grossular (garnet); Grt garnet; Hbl hornblende; Hd hedenbergite; Kfs K-feldspar; Ky kyanite; Ms muscovite; Opx orthopyroxene; Prp pyrope (garnet); Sil sillimanite; Tr tremolite
Chemostatigraphy and hydrothermal alteration at Korpela

In this study, immobile-element lithogeochemistry was used to discriminate between the different lithological units obliterated by deformation, metamorphism and hydrothermal alteration. The main lithological groups, determined by immobile elements, range from rhyolite via rhyodacite, dacite and andesite to basalt. The least-altered samples form a well-defined fractionation line indicating a comagmatic volcanic group (Fig. 7). Thus, the continuum of compositions and having overlapping samples means that the discrimination becomes locally subjective and samples at the chemical boundaries could represent either of the two rock types. There is also some scatter to be seen in the intermediate volcaniclastic rock units which might indicate mixed provenance or feldspar enrichment (Fig. 7). In Gifkins et al. (2005), the uncertainty related to inhomogeneous volcaniclastic rocks when determining immobile element ratios were described as possible compositional variations due to mechanical sorting of compositionally different clasts during eruption and transport, or mixing of debris from different volcanic or external sources in mass flows. The lithogeochemical approach using detailed chemical classification allowed us to detect new features of the overall stratigraphy, especially from the strongly altered parts of the sequence (areas of ‘intense alteration’ of Figs. 8 and 9) and where immobile element ratio-based techniques allowed us to classify the precursor rocks even in totally altered rocks.

In VMS and other hydrothermal environments, the metamorphic mineral assemblages can be characterised and correlated with the bulk geochemical compositions and used to identify the premetamorphic alteration zones; this can be used in vectoring towards the potential ore (e.g. Dusel-Bacon, 2012; Galley et al. 1993; Corriveau and Spry 2014; Caté 2016; Dubé et al. 2007a). The presence or absence of distinctive coarse-grained minerals reflects not only VMS-style hydrothermal alteration and P–T conditions during metamorphism, but also the thermal gradient during metamorphism (Dusel-Bacon, 2012). Hydrothermal alteration at Korpela is classified into six alteration types. The most extensive alteration is the outer margin of the altered hanging-wall zone defined by weak sericite ± carbonate and locally pervasive albite alteration (Ca-(± Na)) (Fig. 11a). The footwall alteration is defined by aluminous and sericitic alteration types dominated by sericite-biotite ± andalusite ± garnet ± sericite ± staurolite ± talc (K-Al-Fe-(± S)), sericite ± quartz ± andalusite ± cordierite ± staurolite ± garnet ± chlorite (K-Al-Mg-Fe-S) and muscovite-sericite (K) mineral assemblages in mainly felsic to intermediate coherent and volcaniclastic rocks. A less abundant and more restrictive alteration is biotite-anthophylite-chlorite ± garnet ± sericite ± tremolite ± carbonate (Mg-Fe-S) in coherent basaltic andesite (andesite A) sills and quartz ± sericite ± carbonate ± magnetite assemblage (Si-K-Ca-(± S)). According to Corriveau and Spry (2014), the amphibolite facies analogues to chlorite-rich footwall (inner) alteration zones of VMS deposits are commonly characterised by cordierite, orthoamphibole, Al₂SiO₅ polymorphs (andalusite, kyanite, sillimanite), garnet or staurolite, quartz and plagioclase. In the outer alteration zone or close to high-T alteration pipes, aluminous minerals including Al₂SiO₅ polymorphs, garnet, chloritoid and staurolite are diagnostic (Dusel-Bacon 2012; Corriveau and Spry 2014). The alumnil enrichment is interpreted to reflect the leaching of alkalis under high fluid/rock ratios (Dusel-Bacon 2012). The alteration mapping shows a clear zonation of the main alteration types at Korpela which can be interpreted to present chlorite and aluminous alteration assemblages (Fig. 11).

The typical chlorite-rich footwall alteration zones, and their metamorphosed counterparts of cordierite + anthophyllite assemblages (Gifkins et al. 2005; Dusel-Bacon 2012; Caté 2016), can be interpreted to be present at Korpela by the Mg-Fe-S and K-Al-Mg-Fe-S alteration types. The Al-rich alteration type is not found to be hosted by any particular precursor rock type. This is evident in DH17, where the alteration is dominantly of K-Al-Mg-Fe-S type having the precursor of andesite B1 to rhyolite A1 (Fig. 8). This is also evident in the chemographic diagrams (Fig. 12). Barrett et al. (2005) demonstrated also at the Kristineberg deposit in Skellefte district in Sweden that very different metamorphic mineral assemblages (andalusite-quartz-muscovite and cordierite-chlorite-talc) may be produced from the same felsic precursor rock type. At Lalor Lake (Manitoba, Canada), the high-temperature chlorite-dominated mineralized zones are located in footwall Mg-Fe alteration halo, whereas massive sulphides are constrained by the proximal K or Mg-Ca alteration zones (Caté 2016). The apparently large size of the alteration domain (> 1 km) at Korpela is likely related to the occurrence of multiple mineralised intervals at different stratigraphic positions and may reflect the longevity of the hydrothermal system. The favourable ore-hosting unit or bracketing units are interpreted, based on the presence of sulphide stringers and strong hydrothermal alteration, to be in andesite A1-A2 and B1, dacite A1, rhyodacite A1-A2 and rhyolite A1-B1. The predominant alteration mineral assemblages at Korpela are sericite-biotite ± quartz ± andalusite ± garnet ± staurolite ± talc (K-Al-Fe-(± S)) and sericite-andalusite-cordierite ± garnet ± staurolite ± chlorite (K-Al-Mg-Fe-S) and muscovite-sericite (K), which suggest lower temperature and acidic conditions. The presence of aluminosilicates is a diagnostic feature of the metamorphosed equivalent of advanced argillic alteration assemblages where rocks are leached by acidic hydrothermal solutions at high fluid/rock conditions (e.g. Barrett et al. 2005; Dubé et al. 2007b; Corriveau and Spry 2014). No signs of boiling or acid aluminium-rich alteration being genetically connected to shallow-water conditions can be shown at Korpela because of metamorphism and deformation.
The alteration domain at Korpela is not continuous but more likely form several, discontinuous, parts. This is considered to be due to the overprinting strong deformation and late faulting. Although alteration types are recognised in several drill holes, the connectivity of particular alteration zones in horizontal and vertical dimensions is uncertain due to the sparse drill holes and lack of outcrop exposures. However, alteration mapping based on the current drilling data enables us to distinguish zonation between the different alteration types (Fig. 11). The hanging-wall sequence is clearly represented by the Ca-(± Na) alteration having a distinct albite alteration and carbonate veininess. It is commonly observed that alteration spatially correlates with deformation zones. It is commonly the case that the aluminium-rich alteration zones are intensely sheared to sub-parallelism with the high-strain zones and turned into schist, due to the ductile nature of Al-rich phyllosilicates (Dubé et al. 2007a). Although the intensely altered rocks predominate in the Korpela area, weakly and moderately altered rocks are locally present. This enables us to identify the primary rock types and their textures which are a prerequisite for the mass balance calculations in a mineralising system (MacLean and Barrett 1993; Barrett and MacLean 1994).

**Comparison between Viholanniemi, Pyhäsalmi and global VMS systems**

The Viholanniemi suite belongs to the same, older Svecofennian magmatic, sequence (> 1.91 Ga) as the Vihanti-Pyhäsalmi belt in the RLSZ. Korpela and Pyhäsalmi both comprise deformed and metamorphosed bimodal-felsic, sub-alkaline, volcanic rocks occurring close to subvolcanic felsic intrusions.

Nevertheless, Korpela differs from the Pyhäsalmi area in having evidence of HFSE-enriched (A-type) rhyolites of calc-alkaline affinity and overlain and cross-cut by mafic rocks with MORB/BABB signatures. At Pyhäsalmi, the volcanic rocks are of transitional magmatic affinity, and the basalts and basaltic andesites are tholeiitic and have Island Arc Basalts (IAB) signatures (Rasilainen et al. 2003; Mäki et al. 2015). Similar conclusions were drawn by Roberts et al. (2003, 2004) from the Ruostesuo Zn-Cu and Kangasjärvi Zn-Cu deposits, located at the southern extension of the Vihanti-Pyhäsalmi belt. The altered rocks at the vicinity of the ore deposits in the Pyhäsalmi region (Kangasjärvi, Ruostesuo and Mullikkoräme) are mainly surrounded by sericite-cordierite and garnet-cordierite-anthophyllite assemblages without any evidence of aluminous alteration (Roberts et al. 2003, 2004; Mäki et al. 2015). At Pyhäsalmi, the original proximal part of the hanging-wall sequence, tholeiitic mafic volcanic rock, was removed by fault displacement and is not in contact with the mineralised stratigraphy (Mäki et al. 2015).

The Viholanniemi Zn-Cu-Pb-Ag-Au deposit host lithology is very similar to that of Korpela including felsic and intermediate volcanic rocks interlayered with volcaniclastic units of variable compositions. The Viholanniemi deposit is associated with a pyrite-quartz-sericite (= epidot) assemblage with quartz-carbonate veins. Nevertheless, this sericite-quartz zone shows only minor Na₂O depletion compared to similar sercite-quartz altered rocks at Korpela. This may suggest that the alteration intensity increases towards the Korpela succession, from the sericite-quartz zone to the sericite zone, leading to the more thorough breakdown of plagioclase and, therefore, stronger Na₂O depletion. Makkonen (1991) suggested that the mineralised carbonate-quartz veins at Viholanniemi could represent a stringer zone of the deeper parts of a VMS hydrothermal system. The quartz-sulphide or, less commonly, quartz-tourmaline veins have been documented in some Au-VMS deposits in metamorphosed submarine volcanic settings (Dubé et al. 2007a). However, the Viholanniemi deposit does not exactly fulfill the requirements of gold-rich VMS deposit classification of Poulsen and Hannington (1995) having a lower concentration of gold compared to combined base metals (Zn + Cu + Pb wt%). The main differences between Viholanniemi and Korpela are, for example, the differences in the sulphide content and hydrothermal alteration. Further studies are therefore required in order to discern their genetic relation.

Clearly, a straightforward correlation cannot be made between the Viholanniemi suite and the Vihanti-Pyhäsalmi belt. In this study, petrochemical evidence suggests that the Korpela succession has a different tectonic setting within the primitive arc complex rocks in the RLSZ. Korpela rocks are predominantly transitional to calc-alkaline volcanic or volcaniclastic rocks with the presence of pervasive aluminous and sericitic alteration. The petrochemical assemblages at Korpela resemble that of the bimodal-felsic VMS type (e.g. Galley et al. 2007; Gibson et al. 2007) having the rhyolites of FII-FIIIa chemical signatures (Fig. 10c) which are interpreted to have formed via partial melting of either continental or oceanic crust resulting from basaltic underplating during rifting (Lesher et al. 1986; Barrett and MacLean 1999; Hart et al. 2004; Piercye 2011). In addition, the rhyolites have strongly elevated HFSE contents (e.g. Zr at 350–550 ppm; Fig. 10f), similar to rocks commonly associated with a continental rift or continental back-arc rift setting (Piercye 2007). Lawrie (1992) suggested an oceanic or back-arc setting for the Virtasalmi area with the hesitation of not having any evidence for earlier felsic calc-alkaline arc complex rocks. In fact, the felsic, calc-alkaline dominated, volcanic rocks that Lawrie (1992) did not identify may be located in the Viholanniemi suite. Zhang (2000) presents that the volcanics in the northern
part of the Viholannniemi area indicate an incipient arc rift setting having detected MORB and BABB mafic rocks with high contents of compatible elements (TiO$_2$) and subduction and within-plate volcanism-related multi-element distribution patterns. Mafic volcanic rocks belonging to the Virtasalmi suite typically have pillow structures and pyroclastic textures (Kousa et al. 2018) suggesting a submarine volcanic environment (Lawrie 1992, Zhang 2000). Other geological evidence to support the rift setting (Vivallo and Claesson 1987) at Korpela are the presence of felsic to mafic dykes and tholeiitic basalt-dominated lavas in the southern part of Viholannniemi suite. Felsic and mafic dykes are important because they provide evidence of rift corridors: the dykes are supposed to have exploitation of the same deep-seated pathways that circulated hydrothermal circulation (e.g. Gibson et al. 1999; Galley 1996, 2003; Campbell et al. 1981). Observations of the in situ fragmentation of the volcaniclastic rocks provide evidence for rocks associated with subaqueous felsic domes and cryptodomes (McPhie et al. 1993). Despite the fact that no massive sulphide deposit is yet to be found at Korpela, the textural features from sulphide stringer zones provide evidence for replacement processes (e.g. Doyle and Allen 2003; Piercey 2015). These textural features are (1) the occurrence of sulphides as interstices and open spaces or replacement of gangue minerals, (2) volcaniclastic rocks and coherent lavas as intermediate host rocks and (3) a strong pipe-like alteration domain and a weaker hanging-wall alteration zone. These observations are preliminary and further studies are needed to confirm the sub-seafloor replacement-style massive sulphide environment.

The proposed tectonic setting of volcanism is mainly based on petrochemical assemblages with supportive geological evidence from drill core which means that a tectonic setting cannot be drawn to a final conclusion in this study. Generally, intra-continental back-arc environments are highly prospective for VMS deposits, especially for gold-rich VMS (Galley et al. 2007; Dubé et al. 2007a; Caté 2016). The VMS deposits in these types of settings occur in, mainly submarine, mafic bimodal to felsic bimodal and bimodal siliciclastic orogenic and greenstone belts from Archean to Phanerozoic in age (Dubé et al. 2007a; Galley et al. 2007). Deposits are commonly located adjacent to major crustal-scale faults and large subvolcanic intrusions (Dubé et al. 2007a). Examples of bimodal-felsic VMS districts are the Paleoproterozoic Skellefte and Bergslagen Districts in Sweden (e.g. Allen et al. 1996a; Allen et al. 1996b; Galley et al. 2007; Gibson et al. 2007), the Palaeozoic Finlayson Lake District (e.g. Peters et al. 2007) and the Orдовician Bathurst Camp in Canada (van Staal et al. 2003). Gold-rich VMS deposits are typically found in calc-alkaline centres and locally characterised by aluminous alteration interpreted as metamorphosed advanced argillic alteration zones indicative of high-sulphidation conditions and formed in shallow-water submarine equivalents to subreal epithermal deposits (e.g. Sillitoe et al. 1996; Hanington et al. 1999). Similar evolved arc settings have also been suggested for SW Finland, at the Haveri Cu-Au (Tampere schist belt) and liljiärvä Cu-Au-Zn (Orijärvi formation) (Eilu 2012). The bimodal Orijärvi formation and overlying Kisko formation (ca. 1.90–1.88 Ga) within Uusimaa belt, SW Finland, are predominantly of calc-alkaline to tholeiitic affinity, and resemble semi-continuous rift-related setting from primitive extension to evolved arc-type environment (Latvalahti 1979; Mäkelä 1989; Väisänen and Mänttäri 2002). Orijärvi formation hosts several auriferous VMS deposits and occurrences (Mäkelä 1989). Dubé et al. (2007b) concludes that aluminous schists with anomalous Au and/or Zn values in an intermediate to felsic, transitional to calc-alkaline volcanic or volcaniclastic rocks represent excellent exploration targets.

### Subvolcanic intrusions and synvolcanic dykes

Subvolcanic intrusions in the rift or caldera systems have commonly been interpreted as supplying heat to drive the convective hydrothermal systems through synvolcanic deep-seated fault structures (Campbell et al. 1981; Galley 2003; Galley et al. 2007). The Saunakangas intrusion fits into Galley’s (2003) prospective VMS-related subvolcanic intrusion size range of 10–60 km$^2$. The presence of foliation, miarolitic cavities, epidote alteration patches, transecting of aplitic felsic dykes and xenoliths of mafic rocks in the Saunakangas intrusion (Fig. 3a–c) are all common features of VMS-associated subvolcanic intrusions (Galley 2003; Hanington et al. 2005). Most of the Saunakangas tonalite samples, collected from different intrusive phases, show slightly different chondrite-normalised REE patterns compared to VMS-related subvolcanic intrusions elsewhere (ESM Fig. 4a, b) (Galley 2003; Ohtoma 2014). The exception to this is the tonalite sample 5, located at the porphyritic tonalite phase close (< 200 m) to the Viholannniemi volcanic rocks (Fig. 2a and ESM Fig. 1). The extent of this particular intrusive phase is hard to estimate due to lack of outcrops (Fig. 2). Sample 5 shows very similar REE signatures to the immediate felsic and intermediate rocks from Viholannniemi (ESM Fig. 4c). The similar chondrite-normalised REE pattern indicates compositional matching to the associated volcanic succession which is described elsewhere as a typical feature for shallow subvolcanic intrusion complexes (Piercey 2011).

### Conclusions

The Korpela Cu-Zn-Au occurrence is situated in the central part of the Viholannniemi suite, in the Jäppilä-Virtasalmi block, which forms the southeastern end point of older (ca. 1920–1930 Ma) Svecofennian rocks. Korpela is within a structural
block of a bimodal, sub-alkaline, volcanic succession. It is characterized by HFSE-enriched (A-type) rhyolites of calc-alkaline affinity, rhyolites of FII-FIIa signatures and overlain and cross-cut by mafic rocks with MORB signatures. The lithochemical signatures of the least-altered rocks are indicative of extensional and high-temperature felsic volcanic rocks which are critical for VMS Mineral Systems. The proximal presence of a subvolcanic tonalitic intrusion, lithological assemblages and trace element characteristics of felsic and mafic rocks suggest that Korpela, within the Viholanniemni suite, represents a bimodal, felsic dominated, mature arc rift of possible continental back-arc environment.

Based on detailed immobile-element methods, 12 chemostratigraphic units and 21 chemical rock types can be identified, ranging from basalt to rhyolite, at Korpela. The least-altered volcanic rocks define a common magmatic fractionation trend indicating a largely comagmatic volcanic group. The least-altered volcanic rocks define a common magmatic fractionation trend indicating a largely comagmatic volcanic group with dominantly calc-alkaline affinity. Chemostratigraphy of the hosting succession, even where completely converted to least-altered volcanic rocks define a common magmatic frac-
tionation trend indicating a largely comagmatic volcanic group with dominantly calc-alkaline affinity. Chemostratigraphy of
the hosting succession, even where completely converted to secondary metamorphic mineral assemblages, provides an important tool for stratigraphic correlation with alteration types and the sulphide-rich zone. The sulphides occur as stringers oriented parallel to the S2 foliation and are locally tightly folded and transposed following the crenulation. The sulphide-bearing fractures subparallel to S2 are an expression of remobilisation and present mainly as Cu sulphide stringers within the Mg-Fe-S alteration type and Fe sulphide stringers within the K-Al-Mg-Fe-S alteration. The iron sulphides occur, predominantly, in dacite A1 and rhyolite B1, whereas the Cu sulphides are concentrated mainly with andesite A1. Volcanic rocks were affected by different degrees of silicification, aluminium, sericitisation and chloritisation alteration at Korpela. During amphibibole facies metamorphism at the regional D2 deformation stage, the hydrothermal mineralogy was transformed to mineral assemblages characterised by varying amounts of quartz, muscovite, biotite, sericite, andalusite chlorite, garnet, chlorite, carbonate, staurolite, sillimanite, cordierite and accessory rutile, sillimanite and tourmaline. Six chemical alteration types were recognized at Korpela: Mg-Fe-S, K-Al-Fe-(± S), K-Al-Mg-Fe-S, K, Si-K-Ca-(± S) and Ca-(± Na). The alteration types are spatially distinguished zones that are interpreted to reflect VMS-style hydrothermal alteration. The Mg-Fe-S alteration type is indicative of Mg-metasomatism. The K-Al-Mg-Fe-S and K-Al-Fe-(± S) types are characterised by strong aluminous alteration (Al-rich phase) which is interpreted to portray advanced argillic alteration. The hanging-wall alteration is described by a sodium and carbonate alteration assemblage.

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