Bulletin of the Geological Society of Finland, Vol. 97, 2025, pp 143–171 https://doi.org/10.17741/bgsf/97.2.003

Revisiting the Pyhäsalmi volcanic complex, western Finland: new insights from volcanic-facies mapping

Janne Hokka* and Ville Järvinen

Geological Survey of Finland, P.O. Box 96, FI-02151 Espoo, Finland

VERTAISARVIOITU
KOLLEGIALT GRANSKAD
PEER-REVIEWED
www.tsv.fi/tunnus

Abstract

The Pyhäsalmi Volcanogenic Massive Sulfide (VMS) deposit, hosted by volcanic rocks of the 1.93–1.91 Ga Vihanti–Pyhäsalmi–Rautalampi belt, is the largest base metal sulfide deposit in Finland (75.7 Mt at 0.9 wt.% Cu, 1.9 wt.% Zn, 0.4 g/t Au, and 14.1 g/t Ag, production 1962–2022). Although significant geological research and mineral exploration projects have been conducted since the 1950s, a comprehensive reconstruction of the volcanic setting and the linkages between volcanism and ore-forming processes has been missing. Based on outcrop mapping and relogging of old drill core in the Pyhäsalmi area, we identify 18 volcanic, sedimentary, and intrusive lithofacies with distinctive lithological and structural characteristics. The study area is dominated by rhyolitic lavas and/or domes, mafic lavas and intrusions, and a volcanogenic sedimentary facies composed of interbedded mudstone and sandstone turbidites. Volcanic facies associations suggest that the eruptive style of felsic volcanism was submarine and non-explosive, forming coherent rhyolitic flows and dome complexes with quench-fragmented hyaloclastic dome margins. Minor resedimented autoclastic volcanic breccias are also found. Volcaniclastic rocks were emplaced as turbiditic mass transport deposits in a submarine slope environment, and are intercalated with hemipelagic sediments, indicating a deep water below-wave-base depositional environment. The Pyhäsalmi ore formation is linked to the permeable autobrecciated facies of rhyolite domes/lavas which are found in contact with sedimentary facies. In contrast, the adjacent Mullikkoräme deposit (1.15 Mt) may represent a less-permeable dome/lava setting with no associated sedimentary facies. Volcanic facies associations (e.g., peperites and hyaloclastites) suggest shallow intrusive (cryptodome) to extrusive felsic volcanism in both the Pyhäsalmi and Mullikkoräme successions, followed by (extension-related) extrusive and locally weakly pyroclastic mafic magmatism on the seafloor. The study highlights new belt-scale exploration potential in areas of similar volcanic and sedimentary lithofacies associations and allow more detailed comparison with other base metal sulfide deposits and occurrences within Vihanti–Pyhäsalmi–Rautalampi belt.

Keywords: Vihanti–Pyhäsalmi–Rautalampi belt, Paleoproterozoic, Fennoscandian Shield, Facies analysis, Volcanism, VMS

*Corresponding author (email: janne.hokka@gtk.fi)

Editorial handling: Shenghong Yang (email: shenghong.yang@oulu.fi)

1. Introduction

The Paleoproterozoic 1.93–1.91 Ga Vihanti–Pyhäsalmi–Rautalampi belt (Kohonen et al. 2021), located in the Raahe–Laadoga zone (RLZ; Fig. 1), has been explored for more than 70 years and has the highest exploration potential for undiscovered volcanogenic massive sulfide (VMS) deposits in Finland (Rasilainen et al. 2014; Mäki et al. 2015). The Pyhäsalmi Zn–Cu–S–Au–Ag mine (Fig. 1) is the largest base metal deposit in Finland with a total production of 63 Mt between 1962–2022 (520 000 t Cu, 1 320 000 t Zn, 32 000 000 t S, 10 t Au, and 500 t Ag) (Pyhäsalmi mine website 2025). To date, together with the Vihanti Zn–Pb–Ag deposit with a total production of 37.2 Mt between 1952–1992, it represents the only "world-class" VMS deposit discovered in the RLZ. About 8 km NE of the Pyhäsalmi mine is the small Mullikkoräme VMS deposit (Fig. 1) (1.15 Mt of 6.1% Zn, 0.9% Pb, 0.3% Cu, 45 ppm Ag, and 1 ppm Au; Mäki et al. 2015).

The Pyhäsalmi area has been studied since the discovery of the VMS deposit in 1958, with pertinent information scattered in numerous articles (Helovuori 1979; Huhtala 1979; Mäki 1986; Ekdahl 1993; Lahtinen 1994; Laine et al. 2015; Kousa et al. 1994; Mäki & Puustjärvi 2003; Mäki et al. 2015; Islam et al. 2025), several industry and survey reports (Marttila 1993; Puustjärvi 1994, 1999; Kousa et al. 1997; Huhma et al. 2021), and MSc theses (Imaña 2003; Ohtamaa 2014; Kähkönen 2017; Hettula 2019, Kontkanen 2024). Despite the vast amount of geological data collected in the Vihanti–Pyhäsalmi–Rautalampi belt, it has not yielded significant new discoveries, raising questions about the maturity of the search space and the effectiveness of the current exploration models. For example, the Pyhäsalmi and Mullikkoräme deposits are hosted in rocks of similar lithology and overlapping U–Pb ages (Puustjärvi 1994; Mäki & Puustjärvi 2003; Huhma et al. 2021) but are classified in separate stratigraphic units: Pyhäsalmi in the Pyhäsalmi group and Mullikkoräme in the overlying Vihanti group (Mäki et al. 2015; DigiKP 2022).

Recent studies in Pyhäsalmi have been focused on the deep ore body and its immediate wall rocks which exhibit strong folding and shearing (Miettinen 2011; Mäki et al. 2015; Hettula 2019). No comprehensive description of volcanic and sedimentary facies, reconstruction of facies architecture, or the linkage between volcanism and ore-forming processes has been presented. Since the last major belt-scale articles (Mäki & Puustjärvi 2003; Laine et al. 2015; Mäki et al. 2015), there has been an increased application of volcanic facies analysis for mapping of ancient volcanic terrains, leading to an improved understanding of the relationship between volcanism and ore-forming processes in several VMS belts (e.g., Allen et al. 2002, 2024; Rosa et al. 2008; Montelius et al. 2007; Ross et al. 2020, Simán et al. 2025). Volcanic facies analysis involves systematic mapping of outcrop or drill core with a focus on descriptive collection of lithological (e.g., composition, texture) and lithofacies characteristics (e.g., primary volcanic and depositional structures) (Fig. 2) (McPhie et al. 1993). The descriptive observations are then compiled and interpreted, first as facies associations and then as a whole, in order to infer the depositional setting and volcanic environment of the system. The scale can vary from a single outcrop to belt-scale. As part of a larger research framework, volcanic facies analysis forms a solid foundation for belt-scale assessment of metamorphic volcanic terranes and, thus, improved genetic and exploration models (Fig. 2) (e.g., Allen et al. 1996, 2024; Soriano & Marti 1999; Rosa et al. 2008; Hokka & Lahtinen 2025; Simán et al. 2025).

Here, we present new results of volcanic facies analysis based on camp-scale bedrock mapping and relogging of representative drill cores within the Pyhäsalmi–Mullikkoräme study area (Fig. 1), also known as the Pyhäsalmi volcanic complex (Mäki & Puustjärvi 2003). Our aims for this work were to 1) define and constrain the volcanic facies associations present, 2) understand the eruptive, emplacement, and depositional settings of the rocks, and 3) based on the results, present a conceptual model of the volcanic facies architecture of the Pyhäsalmi–

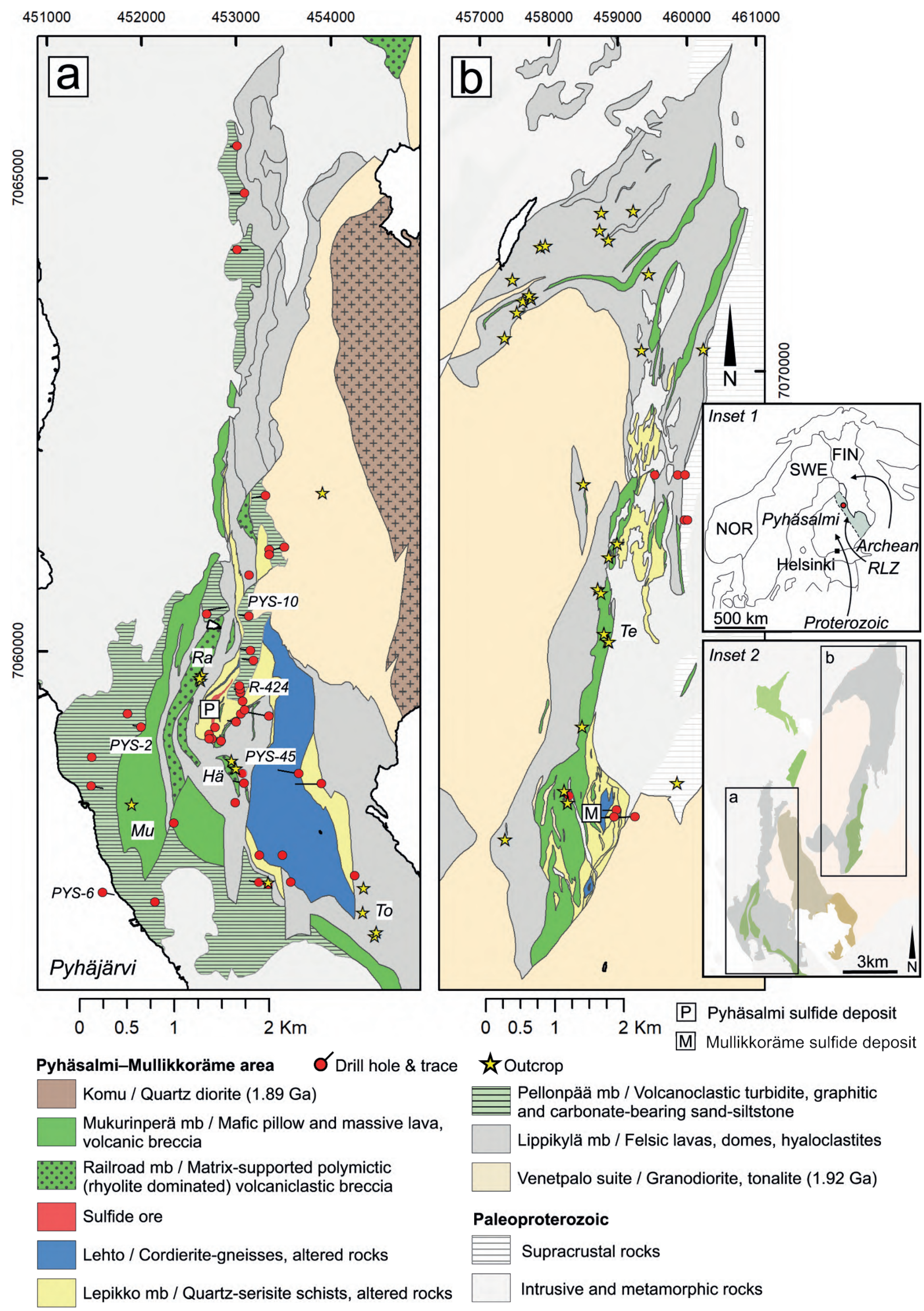

Figure 1. Bedrock/member/facies map of a) Pyhäsalmi and b) Mullikkoräme areas. Inset 1 shows the location of the Pyhäsalmi VMS deposit in the Raahe–Laadoga zone (RLZ). Inset 2 shows locations of maps a) and b) on a generalized geological map. Outcrop observations marked with stars and relogged drill holes with red circles (surface-projected drill core traces marked with black lines). Outcrop locations used in text (abbreviated): Härkälä (Hä), Mukurinperä (Mu), Topiskonräme (To), Railroad cut (Ra), Tetrinmäki (Te). Map modified from the bedrock map of the Geological Survey of Finland (Bedrock of Finland – DigiKP, 2021) with stratigraphic members from Mäki & Puustjärvi (2003).

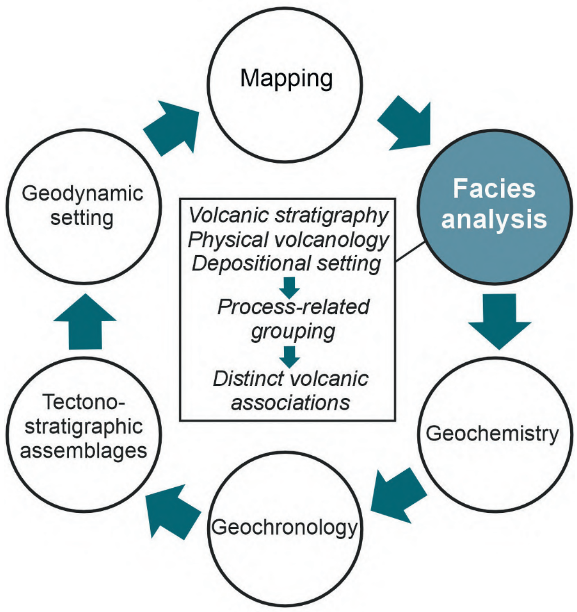

Figure 2. Workflow for comprehensive belt-scale mineral system analysis in greenstone belts. Modifed after Syme (2007).

Mullikkoräme area, with implications for VMS exploration.

This work has been conducted as part of the STRAMIN-project (2024–2026) of the Geological Survey of Finland (GTK). The project aims to better characterize the various volcanic sequences within the RLZ regarding their age, whole-rock and isotope geochemistry, volcanic stratigraphy and tectonic settings, with comparisons between mineralized and unmineralized areas. These topics will be discussed in future papers – in this paper, we introduce a case study for the application of volcanic facies analysis, and hope to highlight the importance of understanding the physical volcanology of an area to establish a solid base for planning and interpretation of future results (Fig. 2).

2. Geological background

The study area is located in the 1.93–1.91 Ga Vihanti–Pyhäsalmi–Rautalampi belt in Central Finland (Fig. 1). The belt is part of the Raahe–Laadoga zone (RLZ), a major NW–SE trending cryptic suture zone between the Archean Karelia craton to the NE and the Paleoproterozoic accretionary-collisional orogen of the Svecofennian domain (1.93–1.79 Ga) towards the SW (Lahtinen et al. 2005; Bogdanova et al. 2015). The belt formed as a 1.93–1.91 Ga juvenile oceanic arc, now accreted to the Archean craton, and constitutes the oldest part of the (Paleoproterozoic) Svecofennian domain in Finland (Lahtinen 1994; Korsman et al. 1997; Huhma et al. 2021). The belt is made up of metamorphic arc volcanic and intrusive rocks and deep marine sediments, now found as dismembered ribbons within crustal scale tectonic blocks delineated by the intersecting shear zones of the RLZ (Mäki & Puustjärvi 2003; Mäki et al. 2015).

Bedrock of the study area comprises bimodal volcanic rocks surrounded by migmatitic mica gneisses and plutonic rocks (Fig. 1). The area hosts the Pyhäsalmi and Mullikkoräme base metal sulfide VMS deposits (and few other occurrences) interpreted to have formed in an island arc setting (Mäki 1986; Gaál & Gorbatschev 1987; Ekdahl 1993; Lahtinen 1994; Kousa et al. 1994; Roberts et al. 2004; Eilu et al. 2013). Stratigraphically, the Pyhäsalmi deposit is included in the Ruotanen formation of the Pyhäsalmi group, whereas the Mullikkoräme deposit is included in the Mullikkoräme formation of the Vihanti group (Mäki et al. 2015). The two formations have been interpreted either as lateral counterparts (Mäki & Puustjärvi 2003), or, alternatively, with the Mullikkoräme formation immediately overlying the Ruotanen formation (Mäki et al. 2015). Both formations comprise felsic and mafic intrusive rocks, lavas, and pyroclastic deposits, of calc-alkaline to tholeiitic affinity (Kousa et al. 1994; Mäki & Puustjärvi 2003; Mäki et al. 2015). In the Ruotanen formation, felsic volcanic rocks (the Lippikylä member) are overlain by mafic volcanic rocks and pillow lavas (the Mukurinperä member), with a similar lithostratigraphic sequence envisaged for the Mullikkoräme formation (Puustjärvi 1994; Mäki & Puustjärvi 2003; Mäki et al. 2015). Volcaniclastic metasediments of the Pellonpää formation overlie the bimodal volcanic rocks

(Mäki & Puustjärvi 2003). The Pyhäsalmi and Mullikkoräme areas are separated by the Venetpalo intrusive suite, a zoned synvolcanic intrusion that occupies the central parts of the study area (Fig. 1) (cf. Helovuori 1979). In the Venetpalo suite, the subvolcanic Kettuperä unit, yielding an age of 1924 ± 3 Ma, has been correlated with the felsic volcanic rocks, and is thus considered the age of the Pyhäsalmi volcanism (Mäki & Puustjärvi 2003; Kousa et al. 2013; Ohtomaa 2014). Ages of felsic volcanic rocks in the Mullikkoräme formation are the same (1921 ± 2 Ma and 1925 ± 4 Ma) (Helovuori 1979; Kousa et al. 2013; Huhma et al. 2021).

The host lithologies of the Pyhäsalmi and Mullikkoräme VMS deposits mainly consist of pyroclastic deposits (rhyolitic lapilli tuffs), rhyolitic and basaltic lava flows and breccias, and dikes or sills of various compositions (Kousa et al. 1997; Puustjärvi 1999; Mäki et al. 2015). The footwall and host rocks of the Pyhäsalmi deposit are composed of altered felsic rhyolites and mafic and andesitic (subvolcanic) intrusions, whereas the hanging wall is a tholeiitic sequence consisting of coherent and brecciated mafic volcanic rocks (Mäki et al. 2015). The Pyhäsalmi deposit has been considered to have formed by massive sulfide accumulation on the seafloor (mound-type), as well as subseafloor replacement within the permeable felsic pyroclastic dominated strata (Imaña 2003; Miettinen 2011; Mäki et al. 2015). The volcanic sequences hosting the sulfide ore deposits have been multiply deformed and metamorphosed during the Svecofennian orogeny at 1.93–1.79 Ga. Deformation phases D1–D4 shaped the ores into their present position relative to the host rocks and surrounding alteration zone (Puustjärvi 1999; Mäki & Puustjärvi 2003; Laine et al. 2015; Mäki et al. 2015; Islam et al. 2025).

3. Volcanic facies analysis

Data was collected between autumn 2024 and spring 2025 and consists of a total of 51 bedrock mapping sites and relogging of 53 diamond drill holes (Fig. 1). A total of seven facies associations, subdivided into 18 lithofacies, were recognized in the Pyhäsalmi–Mullikkoräme area (Table 1). In the following text, references to Table 1 are presented in parentheses (e.g., lithofacies 1.1).

The following descriptive volcanic and sedimentary lithofacies characteristics were systematically documented at each outcrop and drill core (see McPhie et al. 1993): interpreted composition (felsic–mafic), phenocrysts (type, size, amount), grain size, sorting, clast/matrix textures and components (e.g., pumiceous and lithic clasts, crystals), primary igneous textures and depositional structures, tectonic/deformational structures, contact relationships, geometry, and range in the type, style and intensity of alteration. Volcanological nomenclature and grain-size terms are used after McPhie et al. (1993).

In summary, outcrops are dominated by coherent felsic lavas, with coherent and volcaniclastic basalts also present. In drill core, however, the volcanogenic sedimentary facies association is a major constituent in the Pyhäsalmi area but is absent in the Mullikkoräme area. According to visual estimation, the metamorphic grade varies from lower greenschist to upper amphibolite facies.

3.1. Volcanogenic sedimentary facies association

The volcanogenic sedimentary facies association has been observed only in drill core and only in the Pyhäsalmi area (Fig. 1). As shown in Figure 3, the association comprises repeated interlayered sequences of laminated grey siltstones and sandstones (lithofacies 5.2), black graphitic mudstones (lithofacies 5.3), graded turbiditic sandstone-breccias (lithofacies 5.1), and chaotic intervals of intraformational breccias (lithofacies 5.5) composed of intrabasinal clasts derived from the aforementioned facies and slumped and mixed together in various proportions and structures. Unit thicknesses vary significantly, and only a few, or all, of the associated facies may be present in a single

Table 1. Summary of lithofacies identified in the Pyhäsalmi–Mullikkoräme area.

Facies association	Number	Lithofacies	Description	Interpretation
1 Felsic volcanic	1.1	Coherent porphyritic rhyolite	Coherent rhyolite. Porphyritic with eu-subhedral quartz and feldspar phenocrysts (typically 5–10% vol % & 1-3 mm; up to 50 vol% and 2-5 mm). Homogeneous units with thicknesses up to several 100's m.	Lava/dome or shallow intrusion (cryptodome)
	1.2	Coherent aphyric rhyolite	Banded (flow-laminated), coherent, aphyric	Lava/dome or shallow intrusion (cryptodome)
	1.3	Monomictic rhyolite breccia	Clast supported matrix poor monomictic rhyolitic breccia. Irregular to blocky clasts showing in situ fragmentation textures (jigsaw fit clasts) and curviplanar surfaces (in-situ hyaloclastite). Fine-grained brown mica-rich sedimentary matrix (peperitic hyaloclastite).	Hyaloclastite, hyaloclastic peperite; aprons and marginal in situ autoclastic facies of lavas/domes
2 Mafic volcanic	2.1	Coherent basalt	Massive to pillowed with 2- to 6-mm amygdales that vary widely abundance. Variable degree of epidote altered.	Basaltic lavas/sills
	2.2	Coherent pillow basalt	Deformed flattened pillows 10–50 cm (up to 1 m), zoned alteration weak to strong with epi-chl cores, cut by mafic dykes; amygdule rich (Mullikkoräme); minor pale-brown interpillow material/sediment (Mukurinperä)	Subaqueous basaltic lava
	2.3	Monomictic basaltic breccia	Irregular cm-dm monomictic basaltic fragments, clast- to matrix-supported, strongly altered epidotized fine grained (sedimentary?) matrix. Grades into coherent and pillow basaltic facies.	Hyaloclastite and hyaloclastic peperite; margins of basaltic flows and shallow intrusions
	2.4	Monomictic basaltic fluidal-clast breccia	Monomict, poorly to moderately sorted matrix-supported, epidote ± chlorite altered, fluidal spatter clasts dispersed in a matrix of finer, blocky, spatter debris. Clasts (mostly 2-10 cm) angular to sub-angular to tail-shaped with variable degree of vesicularity. Locally, graded indicating local (downslope) resedimentation.	Association of basaltic ejecta, pillow lavas, and feeder dykes; Subaqueous basaltic fire fountain deposit (fissure vent)
3 Dyke/sill	3.1	Rhyolitic to basaltic dikes or sills	Quartz ± feldspar phenocrysts; Plagioclase ± amphibole phenocrysts	Syn-volcanic dikes or sills
4 Synvolcanic resedimented volcaniclastic	4.1	Polymictic clast-rich volcanic breccia	Weakly polymictic felsic clast-dominated, matrix-to clast-supported, locally graded with rhyolitic angular to subangular clasts in intermediate-mafic volcaniclastic matrix.	Rapidly resedimented, syn-eruptive volcaniclastic deposit; flow or talus-breccia on top or at the margin of a coherent lava flow/dome; locally redeposited hyaloclastic breccias
	4.2	Polymictic matrix-supported volcanic breccia	Matrix-supported, very well-sorted with angular to sub-angular mafic rotated-clast (1-15 cm) in fine-grained (1-3 mm) matrix.	Resedimented syn-eruptive volcaniclastic deposit

5	Volcanogenic sedimentary	5.1	Volcanic sandstone-siltstone	Repeated cm-dm thick sequences of coarse (pebbly) sand, often normally graded, followed by distinctly finer grained siltstone beds. Some coarser beds show erosional (scoured) basal contacts. Coarser sandstones are always compositionally homogeneous, made up of pale grey felsic volcanoclastic material. Locally pseudofiamme textured clasts.	Turbiditic deposition of eruption-fed pyroclastic material (source of material not known)
		5.2	Silt-mudstone	Grey to dark silt-mudstones, up to 150 m thick layered/laminated sequences, intercalated with graphitic and carbonaceous mudstones and rare dolomites, and interrupted by coarse turbiditic volcaniclastic sandstones.	Massive to laminated intercalated sand-silt-clay deposits and associated facies suggest deep sea sands
		5.3	Graphitic-sulfidic mudstone	Black graphitic mudstones, dm–tens of m thick massive or laminated sequences. Often contain disseminated/laminated pyrrhotite. Intercalated with sand-mudstone facies.	(Hemi)pelagic sediments, possibly exhalative
		5.4	Carbonaceous mudstone	Typically <1 m-thick, mid-grained and tremolite-rich calc-silicate skarns, intercalated with (graphitic) sand-mudstones. Rare clast-supported calcite-breccia sandstones.	Skarns interpreted as metamorphic products of carbonate-rich submarine sediments
		5.5	Intraformational breccia	Chaotic assemblages of variable sized slumps, clasts and patches of above facies; sand-mudstone clasts/boulders supported in structureless and poorly sorted pebbly sand-mudstone; slumping and soft-sediment deformation structures; fluid escape structures; rip-up clasts	Spectrum of clast composition and sizes, matrix supported, suggest mixing of turbiditic to pelagic volcanogenic sediments during gravitational failure of slopes possibly due to volcano-seismic events
6	Hydrothermal and sulfide-rich	6.1	Hydrothermally altered	Sericite-quartz and cordierite-anthophyllite-sericite alteration variables	Pervasively hydrothermally altered rock unit
		6.2	Massive sulfide	Massive pyrite deposit with accessory pyrrhotite, chalcopyrite and sphalerite	Massive sulfide deposit
7	Sandy sedimentary	7.1	Mica-rich sandstone	Foliated mica-rich flow unit associated with the monomict rhyolite breccia. Thickness several meters.	Sandy turbidite or sandy-silty mass flow

drill hole (Fig. 4). Nevertheless, the main lithofacies characteristics of textural and compositional layering can be observed even with a relatively high-degree metamorphic overprint (Fig. 3n). We correlate this facies association with the Pellonpää member of Mäki & Puustjärvi (2003).

3.1.1. Silt–mudstone lithofacies

The silt–mudstone (lithofacies 5.2) comprises sequences of layered to laminated, massive to graded greenish grey siltstones and fine sandstones with interlayers of black graphitic mudstones (black schists) (Fig. 3e, g, i). The graphitic mudstones (lithofacies 5.3) commonly contain laminated or disseminated pyrrhotite (Fig. 3a). Calc-silicate interlayers (lithofacies 5.4.), now tremolite skarns, and rare dolomite–calcite breccias are also found as layers up to a few meters thick (Fig. 4a, c). The silt–mudstone facies is irregularly interlayered with the turbiditic volcanic sand–siltstone (lithofacies 5.1) as described below. Thick intervals (> 100 m) of homogeneous interlayered siltstone–black schist can be observed in drill holes like PYS-6 (Fig. 4b).

Repeated silt–mudstone couplets suggest deposition by low-density turbidity currents or hemiturbidites in a deep marine environment (Stow & Smilie 2020). Some of the thicker massive sequences may also represent the deep-water massive sand facies, deposited by sandy debris flows or high-density turbidity currents (Stow & Johannson 2000). Fine-grained laminated siltstones and black schists most likely indicate hemipelagic "background" sedimentation (Stow et al. 2001). The laminated pyrrhotite in the black schists may, at least locally, be related to deposition of metalliferous chemical sediments of submarine volcanic-hydrothermal origin ("exhalites") (Laitala 2015). The calcite breccias likely represent redeposited carbonate successions or similar material transported from a shallower water setting (shelf?), but have also been interpreted as carbonate-facies exhalites (Huhtala 1979).

3.1.2. Volcanic sand–siltstone lithofacies

The volcanic sand–siltstone (lithofacies 5.1) shows interlayered cm- to dm-thick upwards-fining sequences composed of coarse volcaniclastic sandstone-(breccia) overlain by finer-grained sand-siltstone layers (Fig. 3g, h, i). The coarser layers are texturally variable. Typically, they are moderately to well sorted with normal-graded beds and erosional to non-erosional basal contacts. The clasts are angular to rounded, 1–10 mm in size, and compositionally homogeneous with fine-grained texture suggesting origin as felsic volcanic debris (Fig. 3f, g, h, m). In contrast, some of the coarser layers are poorly bedded and contain cm- to dm-sized rip-up clasts of sand-, silt- and mudstone (Fig. 3d, f). Silt-filled "veins" cross-cutting bedding may represent water-escape structures (Fig. 3b, i). The finer-grained sand–siltstone layers overlying the coarser layers are compositionally homogeneous, laminated or layered, and normal graded (Fig. 3g, i).

Based on the graded bedding, partial Bouma series, absence of shallow water structures (e.g., ripple marks), and association with the other submarine facies, this lithofacies represents turbidite deposition in a deep-marine below wave-base (>200-m-depth) setting (Stow & Johansson 2000; Stow & Smilie 2020).

3.1.3. Intraformational breccia lithofacies

The intraformational breccia (lithofacies 5.5) is composed of chaotic mixtures of cm–dm-sized clasts (possibly up to boulder-sized?) composed of massive and laminated sand–mudstone, and set in a structureless and clast-poor pebbly silt–mudstone matrix (Fig. 3j, k, l). Laminated clasts show folding (slumping) suggesting soft-sediment deformation. Layer thicknesses vary from few dm to up to 5 m.

The variable clast size and composition, commonly disturbed primary sedimentary structures, occurring in an overall massive/structureless facies, suggests mass transport of intrabasinal submarine slope sediments by sliding, slumping, or debris flow (Shanmugam 2019; Stow & Smilie 2020).

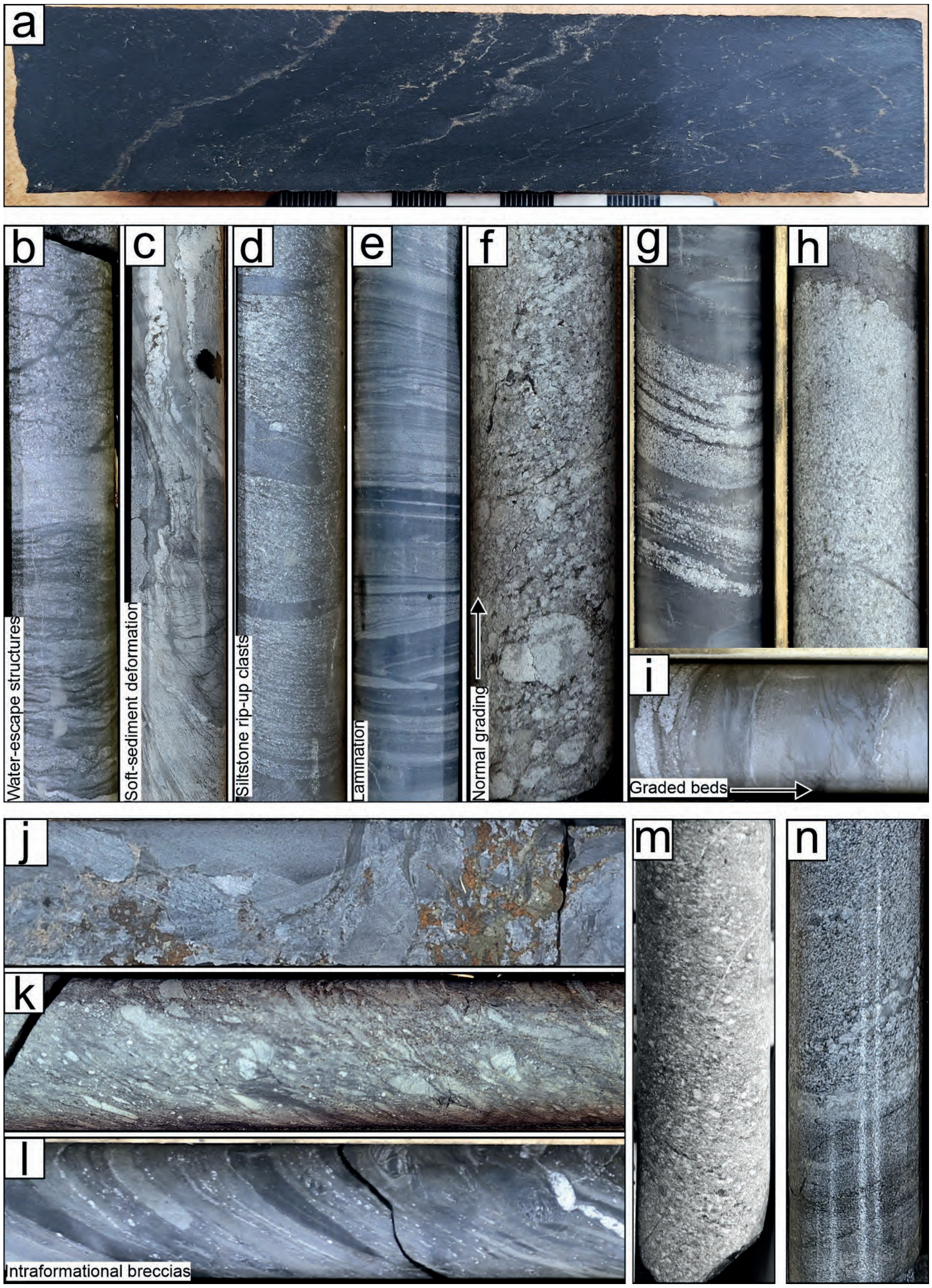

Figure 3. Drill core photographs illustrating the lithofacies of the volcanogenic sedimentary facies association (Table 1). a) finely laminated graphitic pyrrhotite-bearing mudstone (lithofacies 5.3; PYS-3 61.85); b) water escape structures in silt–sandstones (lithofacies 5.1–5.2;PYS-11 155.0); c) faults and folds interpreted as soft-sediment deformation (lithofacies 5.2; PYS-9 58.50); d) siltstone rip-up clasts in sandstone (lithofacies 5.1; PYS-11 149.40); e) laminated siltstone (lithofacies 5.2; PYS-6 294.50); f) normal graded pebbly sandstone (lithofacies 5.1; PYS-3 120.0); g & h) interlayered sand–mudstones (lithofacies 5.1–5.2; PYS-3 120–121); (i) normal graded sand-mudstone layers (lithofacies 5.1–5.2; PYS-3 120.0). j–i) Intraformational breccias (lithofacies 5.5); j) sandstone–sulfide breccia (PYS-3 71.50); k) sandstone breccia (PYO/LII-3 32.55); l) siltstone breccia with pebbly mudstone matrix (PYS-5 47.0). m) Crystal -rich volcaniclastic sandstone (lithofacies 5.1; PYS-4 133.40). n) Relatively high metamorphic grade sand–siltstone with relict primary layering (lithofacies 5.1; PYO/SÄ-5 113.0). Diameter of all samples is about 5 cm.

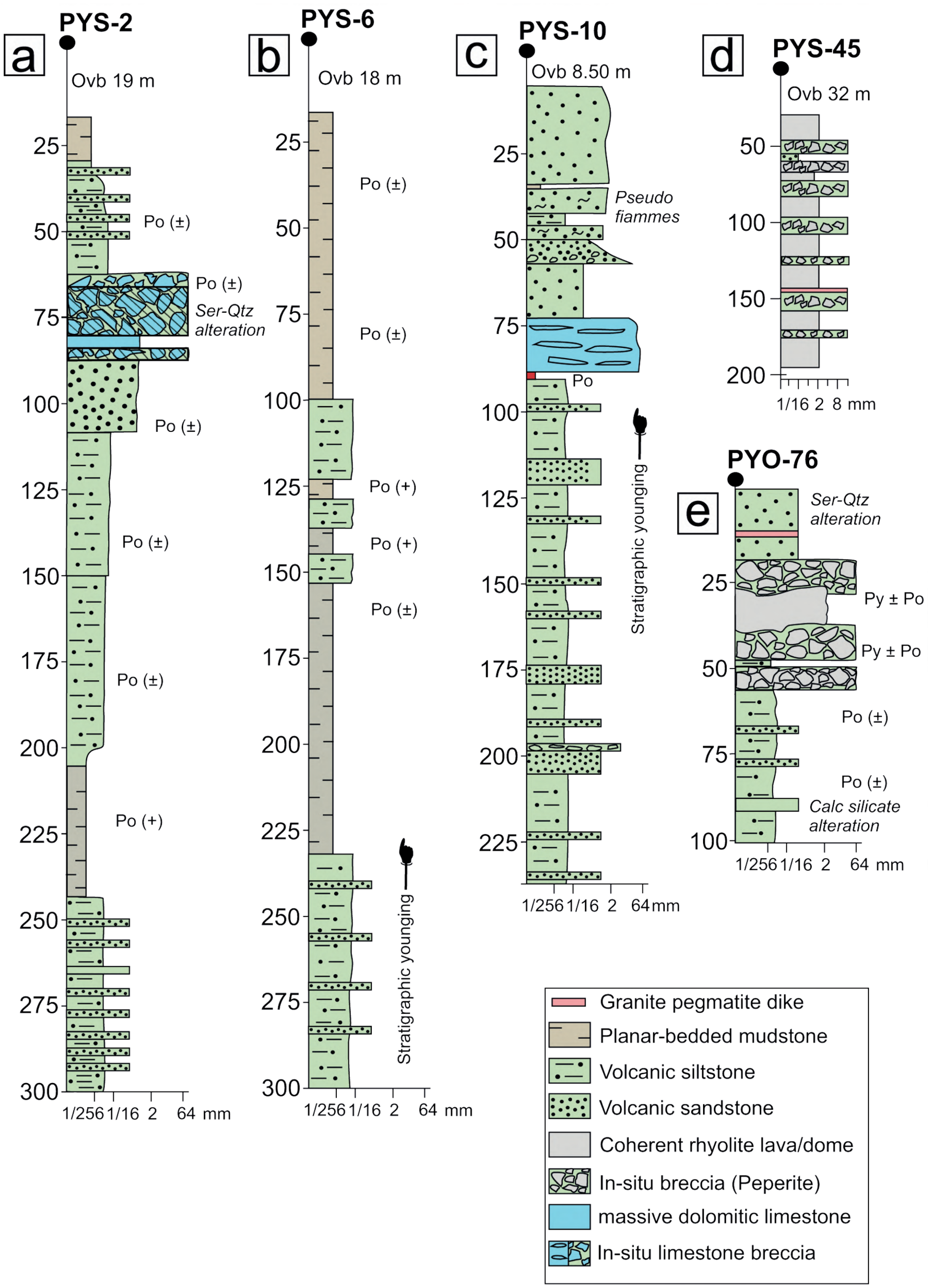

Figure 4. Downhole strip-logs of drill holes PYS-2, -6, -10, -45 (a–d) from Pyhäsalmi (labeled in Fig. 1); and PYO-76 (e) approximately 12 km south of Pyhäsalmi. Direction of stratigraphic younging is based on graded bedding.

3.2. *Felsic volcanic facies association*

3.2.1. Coherent rhyolite lithofacies

The coherent felsic volcanic lithofacies comprises homogeneous rhyolites (lithofacies 1.1–1.2). These are typically evenly porphyritic with 5–20 vol.% of 1–2 mm unbroken eu-subhedral quartz and (typically slightly smaller) feldspar phenocrysts in a fine-grained felsic groundmass (Fig. 5b). A coarser grained facies is also commonly found in sharp contact, with up to 20–50 vol.% of 2–5 mm phenocrysts. Euhedral 0.5–2 mm magnetite porphyroblasts are present in about one-third of the observed outcrops. In the Topiskonräme outcrop (Fig. 1), a clearly flow-banded facies (lithofacies 1.2) is observed (Fig. 5a) (McPhie et al. 1993). The felsic volcanic rocks are deformed with weak to strong foliation, and they are cut by pegmatitic and N–S trending mafic dikes and locally intruded by basaltic lavas. They are also cut by (synvolcanic?) granodiorite and younger granite intrusions.

In outcrop, this lithofacies is characteristically homogeneous and is found in tens to hundred meters sized outcrops with no significant compositional or textural variation observed. The porphyritic textures and lack of compositional and textural variation (i.e. bedding) strongly suggests that the lithofacies represents extrusive or shallow intrusive emplacement of rhyolitic magma (McPhie et al. 1993).

3.3.2. Monomictic rhyolite breccia lithofacies

In outcrop and drill core, the coherent rhyolite grades into monomictic rhyolite breccia (lithofacies 1.3) towards the outer margins of coherent units. This facies comprises monomictic clast-supported matrix-poor rhyolitic volcanic breccias (Fig. 4d; 5c, d; 6). Clasts are irregular to blocky, 3–30 cm in size, and commonly quartz–feldspar porphyritic similar to the coherent lithofacies. The larger clasts show curviplanar margins and *in situ* fragmented (jigsaw fit) textures (Fig. 5c; 6c). Some outcrops are strongly foliated and show flattened elongated clasts. These textures indicate minimal clast transport and are characteristic of non-explosive subaqueous quench fragmentation (McPhie et al. 1993), and these rocks are thus interpreted as hyaloclastites.

As observed in outcrop (Topiskonräme; Fig. 1) and drill holes (PYS-35, -43-, -45, -46; Fig. 4), the monomictic rhyolite breccia (hyaloclastite) is in contact with both the synvolcanic resedimented volcaniclastic and the volcanogenic sedimentary facies associations (4 and 5 in Table 1). The monomictic rhyolite breccia shows variable amounts of brown to dark fine-grained mica-rich matrix (Fig. 5c, d; 6), and the matrix-richer breccias are interpreted as peperitic hyaloclastites. Peperites are volcaniclastic rocks comprising irregular magmatic clasts in a sedimentary or volcaniclastic matrix, and are formed by interaction between lavas or shallow intrusions and wet unconsolidated sediments.

The monomictic rhyolite breccias are interpreted to be related to in situ hyaloclastic and peperitic fragmentation of lava, rather than explosive pyroclastic eruption processes (McPhie et al. 1993). The hyaloclastites are interpreted as in situ lava/dome margins, with some groundmass-richer types (Fig. 5f) possibly representing minor redeposition along dome flanks, whereas the previously mentioned coherent rhyolite facies represents the centers of lava flows and/or (crypto) domes. We correlate the felsic volcanic facies association with the Lippikylä member of Mäki & Puustjärvi (2003).

3.3. *Sandy sedimentary facies association*

The sandy sedimentary facies association consists of a fine-grained, mica-rich, and locally garnet-bearing foliated sandstones to siltstones (lithofacies 7.1). Characteristics of this lithofacies are poorly constrained as we observe it only in contacts and as matrix in the monomict rhyolite breccia (lithofacies 1.3). It is observed in an outcrop (Fig. 5d) and drill holes (PYS-109, -150, -169, -170). This association can be several meters thick but is typically less than

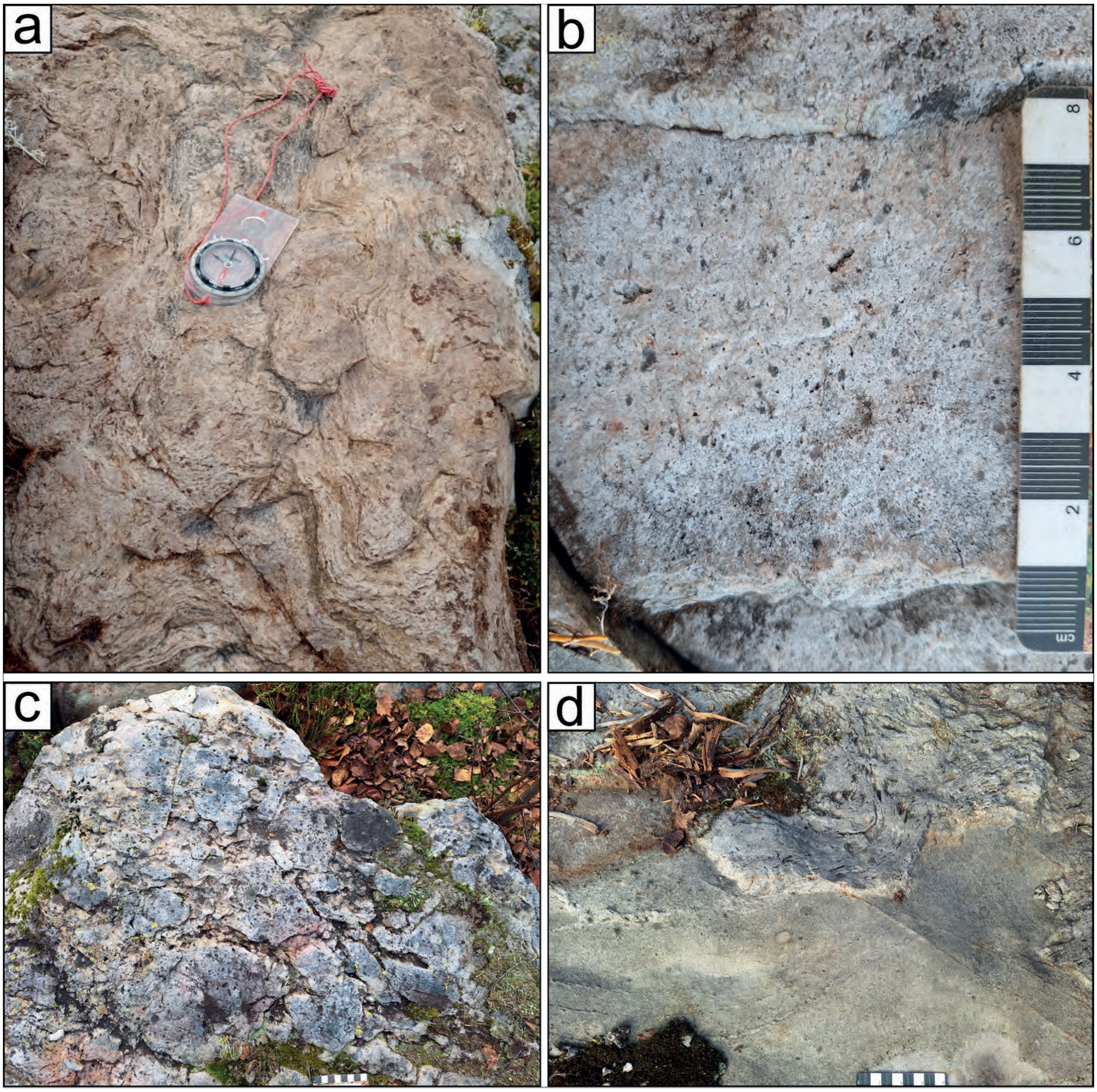

Figure 5. Field photographs of the felsic volcanic facies association (Table 1). a) Flow-banded rhyolite at Topiskonräme (lithofacies 1.2; VJJA-2024-123; 7056982 N, 454466 E). b) Quartz–felspar porphyric rhyolite at Siirinvuori, Lohvanperä (lithofacies 1.1.; VJJA-2024-145; 7071803 N, 457878 E). c) Monomictic clast-supported matrix-poor rhyolitic breccia with jigsaw fit clasts at Topiskonräme (lithofacies 1.3; VJJA-2024-125; 7057032 N, 454478 E). d) Quartz-porphyritic rhyolite (lithofacies 1.1) intruding fine-grained sandy sediment (lithofacies 7.1) at Topiskonräme (VJJA-2025-3; 7056959 N, 454493 E).

a meter. No contact (gradational or otherwise) between the sandy sedimentary (lithofacies 7.1) and the volcanogenic sedimentary facies associations (lithofacies 5.1–5.5) has been observed and their stratigraphic relationship is unclear.

3.4. Mafic volcanic facies association

The mafic volcanic facies association comprises coherent, pillowed, and brecciated basalts. Coherent (massive) and variably amygdaloidal basalts (lithofacies 2.1) are found in several locations. Associated basaltic pillow lavas

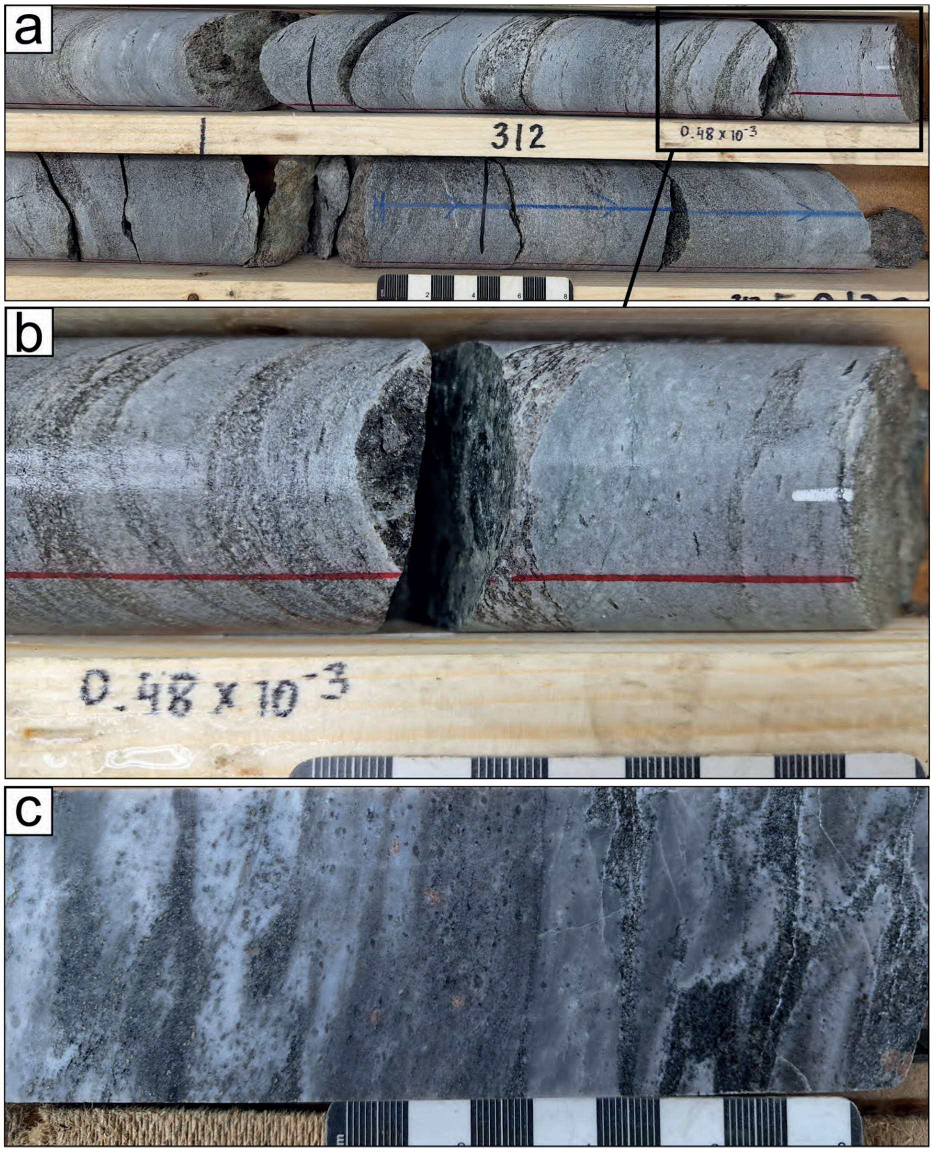

Figure 6. Photographs from drill core in Pyhäsalmi (a, b: LIPDD001 312.10, c: PYS-156 1368.0) showing rhyolite breccia with sedimentary matrix. Rhyolite clasts are monomict with coherent quartz-porphyritic textures and locally show jigsaw-fit structure suggesting origin as (peperitic?) hyaloclastite.

(lithofacies 2.2) are found in outcrops in Mukurinperä, Tetrinmäki, and at the Mullikkoräme deposit (Fig. 1). Pillows are deformed and flattened, typically 20–50 cm (up to 1 m), and sometimes amygdale-rich, with minor or absent inter pillow matrix (Fig. 7f). Rarely, the coherent basalt grades into monomictic basaltic breccia (lithofacies 2.3), which varies from clast- to matrix-supported, with irregularly shaped 5–30 cm basaltic fragments set in a fine-grained, possibly sedimentary matrix that is strongly altered to epidote. Massive coherent basalt and narrower mafic dikes are commonly found cross-cutting or intruding the felsic volcanic rocks. The dikes typically strike north–south.

A 150 x 150 m outcrop area in Tetrinmäki (Fig. 1) exposes a more complex basaltic facies association. It comprises well preserved basaltic pillow lavas overlain by pillow breccias and massive

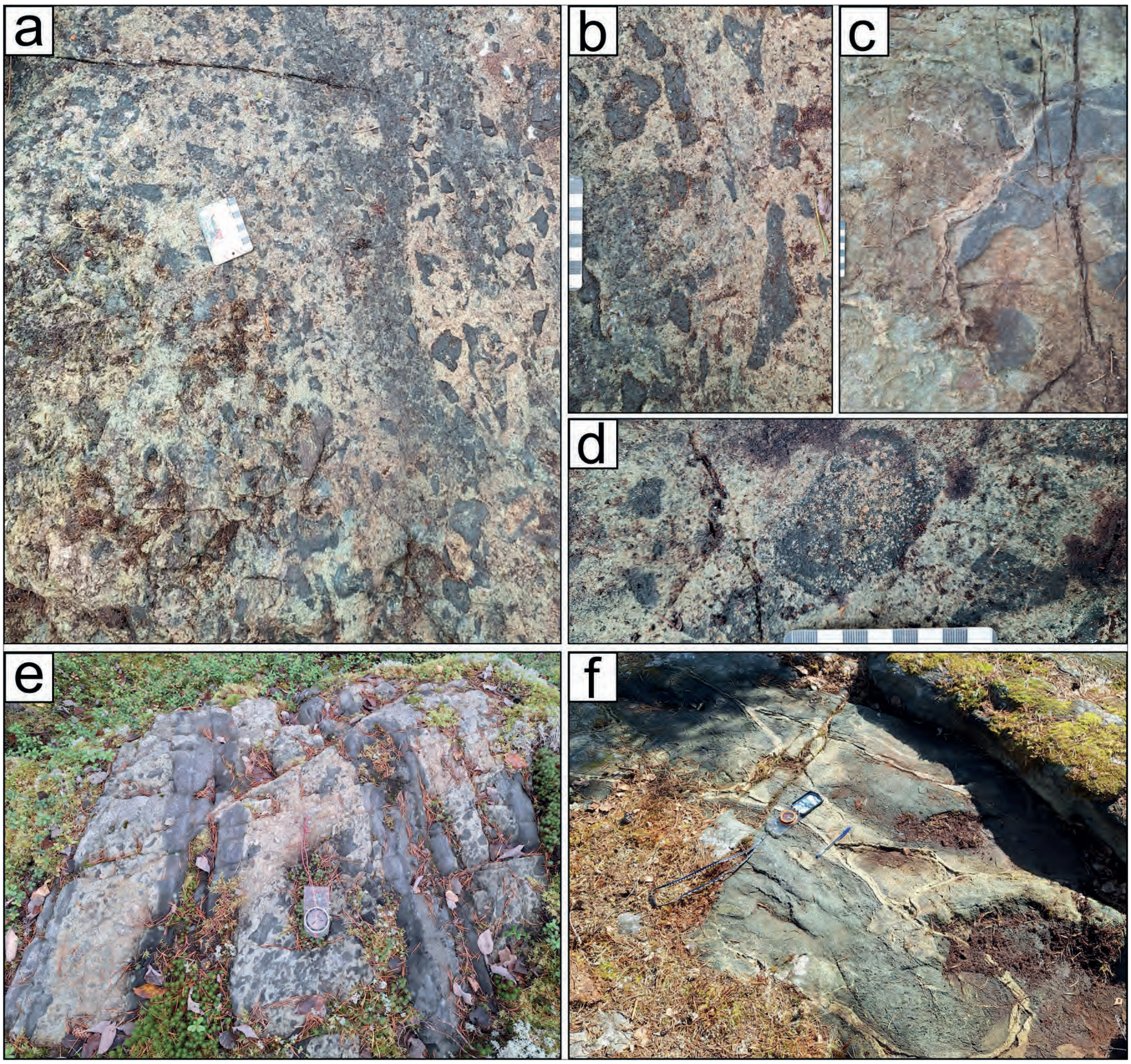

Figure 7. Photographs illustrating selected lithofacies of the mafic volcanic facies association, which make up the basaltic fissure vent complex at Tetrinmäki, Mullikkoräme. a–b) Poorly bedded monomict basaltic breccia (lithofacies 2.4) with strongly altered (epidotized) matrix. c) Strongly epidotized coarse pillow breccia. d) Clasts range from poorly sorted, non-vesicular to highly vesicular types within an epidotized matrix. e) Parallel sheeted mafic dikes cross-cutting basaltic breccia debris (VJJA-2024-161; 7066085 N, 458854 E). e) Coherent basaltic pillow lava facies (lithofacies 2.4), blue pen cap indicates top direction (VJJA-2024-163; 7066199 N, 458802 E).

to thickly bedded basaltic breccias composed of fluidal clasts and curviplanar and blocky juvenile fragments (Fig.7a-d, f). Locally, fluidal-clast breccia is interlayered with pillow breccias and pillow lavas. The basaltic rocks are crosscut by parallel sets of mafic sheeted dikes striking 140–160° (Fig. 7e). The fluidal clast breccia (lithofacies 2.4) is monomict, composed of 5–30 cm fluidal shaped and irregularly amygdaloidal mafic clasts with a distinct tail or drop-shaped form and locally a fine-grained rim, set in a finer epidote–chlorite altered breccia matrix, and variably accompanied by blocky and curviplanar clasts (Fig. 7d). The fluidal clast breccia occupies 30–60 vol.% of the breccia. All clasts are aphyric, and the matrix between them comprises 40–60 vol.%. Strong alteration results in a pseudoclastic texture (at least locally) and hinders detailed determinations of clast-matrix relationships. The mafic breccia is intruded by rare feldspar-porphyritic (andesitic) dikes. The mafic breccias are in sharp intrusive contact to a (late-orogenic) quartz–feldspar porphyritic granite in the east. The western contact is not observed.

The mafic volcanic facies association is interpreted to represent submarine effusive and shallow intrusive emplacement of basaltic magma. Pillow lavas can form in any subaqueous environment regardless of water depth, and they are common in deep marine environments (McPhie et al. 1993; Morgan & Schulz 2012). Monomict basaltic breccias represent hyaloclastic peperites, as previously described. At Tetrinmäki, the basaltic fluidal clasts (Fig. 7b) represent bombs and indicate near-vent deposition from a fountain-type submarine eruption, with basaltic liquid ejected and rapidly quenched in the water column before deposition on the seafloor (Allen et al. 1996; Simpson & McPhie 2000; Cas et al. 2003; Montelius et al. 2009). We correlate the mafic volcanic facies association with the Mukurinperä member of Mäki & Puustjärvi (2003).

3.5. Synvolcanic resedimented volcaniclastic facies association

3.5.1. Polymictic clast-rich volcanic breccia lithofacies

The polymictic clast-rich volcanic breccia (lithofacies 4.1) is poorly bedded and clast- to matrix-supported (Fig. 8a). Clasts are lithic, 1–30 cm, angular to subrounded, and dominantly composed of coherent quartz–feldspar phyric rhyolite (Fig. 8b), with a lesser portion of fine-grained mafic-felsic metavolcanic rocks. The matrix is mica-rich volcaniclastic sandstone (<1–2 mm) with a greenish color suggesting mafic–intermediate composition. The lithofacies is poorly to moderately sorted, and locally shows graded bedding. Observed outcrops are strongly foliated with elongated clasts.

This lithofacies was observed in outcrops and in one drill hole in the Pyhäsalmi area. Approximately 500 meters south of the Pyhäsalmi mine, in the Härkälä outcrop (Fig. 1), the unit is in sharp contact with the coherent rhyolite facies (lithofacies 1.1). Just north of the mine, in the Railroad cut outcrop (Fig. 1), the unit is in contact with the coherent basalt facies (lithofacies 2.1). Based on these outcrops, the thickness of the unit is at least 5–50 m. In drill hole PYS-170 (just south of Härkälä) the unit is intersected for approximately 50 meters (Fig. 8b).

Mixing of felsic and mafic volcanic detritus, together with abundance of angular felsic clasts, suggest rapid and local synvolcanic resedimentation with minor reworking. The quartz–feldspar-phyric rhyolite clasts (blocks) were likely sourced from the underlying felsic lavas/domes and thus indicate a younging direction (see Fig. 10). The felsic clasts were mixed with mafic material sourced from mafic eruptions. Overall, this lithofacies unit is interpreted as a felsic dome-collapse or talus breccia formed by submarine debris flow. We correlate this lithofacies with the Railroad cut member (“Hyppykuppakivi”) of Puustjärvi (1999), located between the felsic (Lippikylä member) and mafic (Mukurinperä member) volcanic facies associations (Mäki & Puustjärvi 2003).

3.5.2. Polymictic matrix-supported volcanic breccia

The polymictic matrix-supported volcanic breccia (lithofacies 4.2) is characteristically matrix-rich and clast-poor (Fig. 8d, e). The matrix is poorly-sorted dark grey volcanic sandstone with abundant 1–5 mm angular-subrounded felsic fragments (mostly plagioclase laths?). Suspended are about 5–10 vol.% of flattened and randomly oriented lithic volcanic clasts, which are angular to subrounded, 1–15 cm in size, and mainly composed of fine-grained mafic volcanic rocks with subordinate felsic aphanitic and porphyritic volcanic rocks. The unit is in sharp contact with the coherent and monomictic rhyolite breccia facies and is cut by mafic and intermediate subvolcanic dikes.

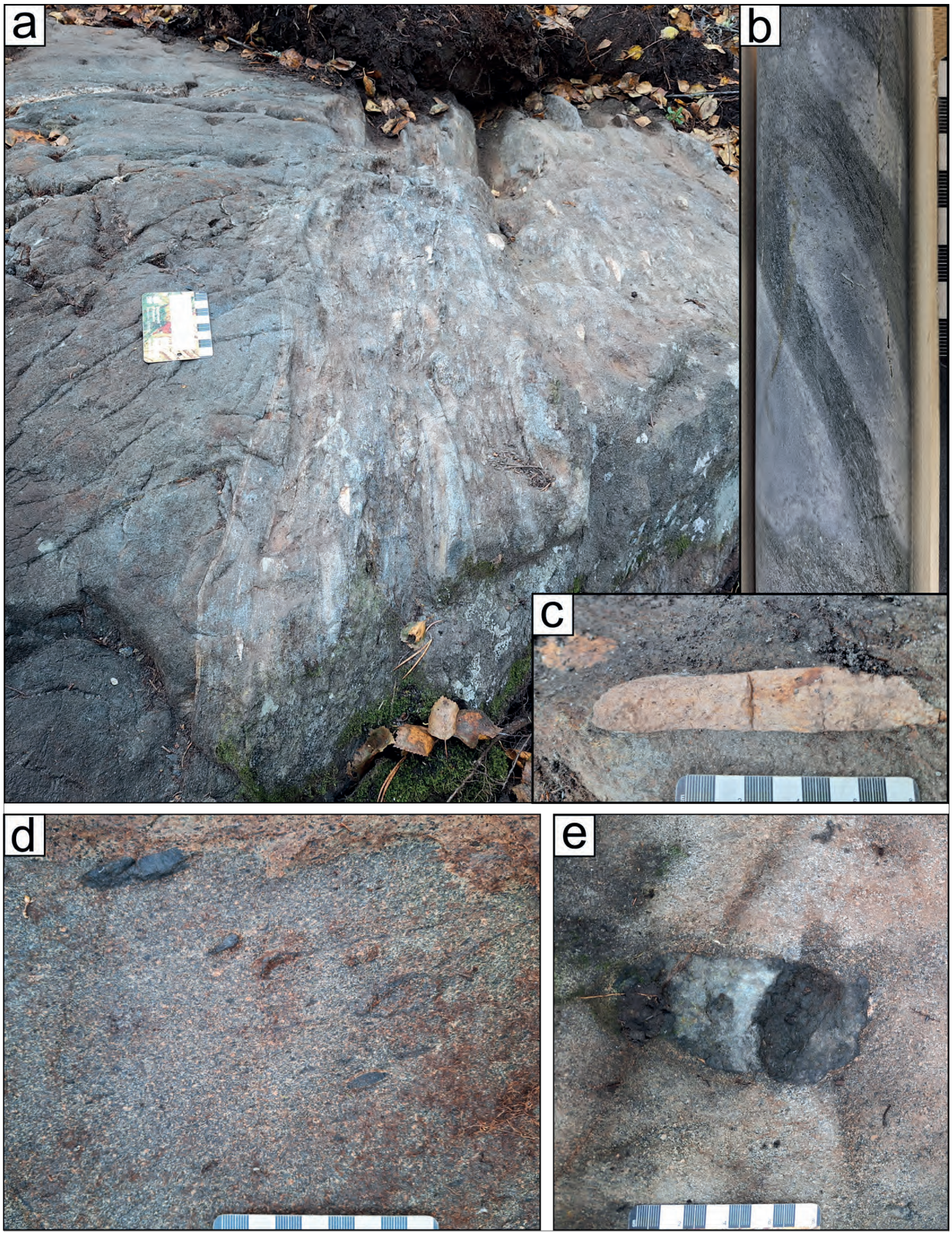

Figure 8. Photographs illustrating lithofacies of the synvolcanic resedimented volcaniclastic facies association (Table 1). a–c) Clast-rich resedimented facies (lithofacies 4.1). a) Matrix- to clast-supported clast-rich polymictic volcanic breccia ("Hyppykuppakivi" in Puustjärvi 1999) cut by a mafic dike, located at Härkälä, Pyhäsalmi (VJJA-2024-117; 7058775 N, 452982 E); b) Angular to subrounded, poorly sorted, quartz-phyric clasts within a mica-rich, partly altered volcaniclastic sandstone (drill hole PYS-170 167.0). c) Characteristic angular clasts of coherent rhyolite in Härkälä outcrop. d) Matrix-supported clast-poor polymictic breccia (lithofacies 4.2), with e) randomly oriented poorly sorted dark (mafic?) clasts (VJJA-2024-138; 7056578 N, 455303 E).

Randomly oriented and polymictic volcanic clasts suspended in a structureless matrix suggest origin by volcaniclastic debris flow (McPhie et al. 1993). The clast compositions indicate a local volcanic source.

3.6. Dike/sill facies association

The dike/sill facies association (lithofacies 3.1) comprises typically <1–2 m-thick dikes cross-cutting supracrustal rocks. Subvolcanic dikes range in composition from rhyolitic (quartz ± feldspar-phyric) to andesitic (plagioclase ± hornblende-phyric) and are strongly porphyritic with 3–10 mm phenocrysts. Mafic dikes are fine–medium-grained to (uralite) porphyritic, and locally show reaction-rims, chilled margins, and marginal breccias in contact with the felsic volcanic rocks; they generally trend north–south. Along the contact zones of the 1.93–1.92 Ga (Helovuori 1979) Venetpalo intrusive suite, granodioritic–tonalitic dikes are found cutting felsic volcanic rocks. Narrow leucogranitic pegmatite dikes are common in the Pyhäsalmi area, and are also rarely found in tens-of-meters large homogeneous outcrops (e.g. Härkälä; Fig. 1). Reddish coarse-grained to porphyritic granitoid dikes are common in the Mullikkoräme area.

3.7. Hydrothermal and sulfide-rich facies association

3.7.1. Hydrothermally altered lithofacies

We divide the hydrothermally altered lithofacies to sericite–quartz and cordierite–anthophyllite–sericite alteration variables (lithofacies 6.1), following the interpretation of Mäki & Puustjärvi (2003). Based on drill core observations from Pyhäsalmi, the rocks in the vicinity of sulfide deposits have been pervasively hydrothermally altered to sericite + quartz ± cordierite ± pyrite ± pyrrhotite assemblages. Primary textures have been obliterated making identification of the protolith difficult (Fig. 9). However, the intensity of hydrothermal alteration varies resulting in a locally patchy appearance. Locally, relicts of primary lithofacies characteristics appear to have been preserved (e.g. layering). Contacts between altered and unaltered rocks are both gradual and sharp.

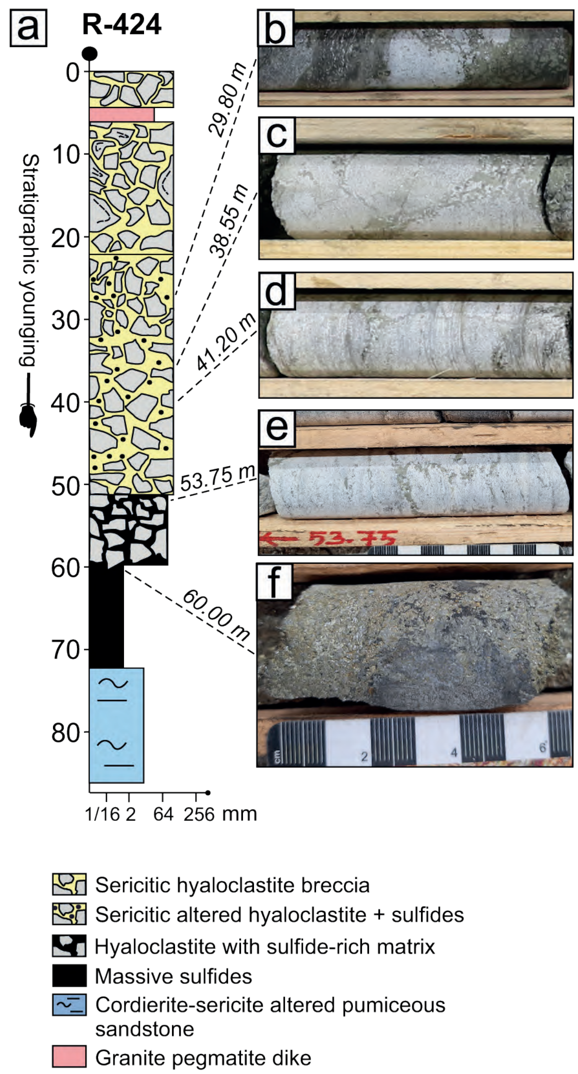

Figure 9. Downhole strip-log of drill hole R-424 showing the association between massive sulfide facies (lithofacies 6.2) and quartz–sericite altered monomicitic rhyolite breccia (lithofacies 1.3).

3.7.2. Massive sulfide facies

The Pyhäsalmi ore is characterized as massive sulfide ore with >70 vol.% sulfides (lithofacies 6.2).

It mainly consists of medium- to coarse-grained massive pyrite ore with accessory pyrrhotite, chalcopyrite and sphalerite. Locally, sphalerite-rich ore with pyrite and subsidiary chalcopyrite ± galena ± pyrrhotite was observed. In the mineralized section of drill core R-424, sulfides gradually infill the matrix of the (quartz–sericite altered) rhyolitic hyaloclastite (lithofacies 1.3; Fig. 9). Within the massive sulfide ore, several angular porphyritic rhyolite clasts (~30–50 mm) are observed (Fig. 9). We interpret these textural features as sulfide infilling and replacement of permeable parts of rhyolitic dome complex margins in a subseafloor environment (see Fig. 10).

4. Discussion

In this study, we have presented an internally consistent observational dataset with a reasonable coverage of the study area (Fig. 1), and a unified interpretation of our findings. The eruptive, transport, and depositional processes interpreted from the lithofacies characteristics of observed units have been presented previously and summarized in Table 1. Based on a compilation of these observations, a conceptual model of the interpreted volcanic facies architecture of the Pyhäsalmi volcanic complex is presented (Fig. 10). However, it must be pointed out that in ancient volcanic terrains often only an incomplete and potentially biased record of the subsurface geology is available, and it might be difficult to draw a complete picture of the paleovolcanic environment (Marti 2022). This is especially true in cases where key volcanic facies, such as the volcanogenic sedimentary facies (lithofacies 5.1–5.5 in Table 1), are only observed in drill core. As a result, there is uncertainty regarding the relative abundance of each lithofacies. Additionally, it remains poorly constrained as to what degree do the facies associations reflect a lithostratigraphic sequence, or do they rather reflect contemporaneous lateral changes in eruptive/depositional environments. Also, due to the overprinting effects of complex deformation, metamorphism and alteration, stratigraphic correlation of the lithofacies would require detailed structural and geochemical interpretation, which is beyond the scope of this study.

Mäki & Puustjärvi (2003) concluded that the Pyhäsalmi sulfide ore is hosted in rhyolites and their altered equivalents. They also suggested that no significant hiatus in volcanism occurred during the formation of the VMS deposit, as no evidence of chemical precipitates, pelagic sediments, or reworked volcaniclastic materials have been found between the rhyolitic and basaltic volcanic sequences (Kousa et al. 1997; Mäki and Puustjärvi 2003). Mäki and Puustjärvi (2003) concluded that the Pyhäsalmi volcanic complex formed as a submarine ensialic rift basin with deposition of felsic lavas or domes first (the Lippikylä member; see Fig. 1), and then mafic lavas (the Mukurinperä member), and later stratigraphically overlying accumulation of volcaniclastic sediments with calcareous skarn and graphitic interbeds (the Pellonpää member). Our findings are consistent with previous results and affirm that the Pyhäsalmi VMS deposit is hosted by coherent rhyolite lavas or domes (Fig. 9 and 11) (Puustjärvi 1999; Mäki & Puustjärvi 2003; Mäki et al. 2015). However, contrary to previous interpretations, our findings suggest that sedimentary rocks (volcaniclastic turbidites and hemipelagic sediments) are far more prevalent in the Pyhäsalmi area than initially thought.

It has been suggested that volcanic activity was preceded and succeeded by clastic sedimentation in the Pyhäsalmi area (Helovuori 1979; Huhtala 1979; Ekdahl 1993). We present the first detailed observations and characterization of this subject (e.g., Fig. 3). The relatively common association of hyaloclastite and peperite facies with coherent rhyolites (Fig. 5 and 6) suggests that the silicic magmas were emplaced within a volcanic-sedimentary basin (Fig. 10). A dark fine-grained mica-rich metasedimentary matrix is observed in the hyaloclastites, but the lithofacies of the matrix cannot be reliably determined (lithofacies 7.1) or correlated with the volcanogenic sedimentary facies (lithofacies 5.1–5.5) – this ambiguity is reflected in Fig. 10. Whether clastic sediments were present during volcanism and hydrothermal alteration is an important question, as these sediments might represent potential host rocks for ore.

The only unambiguous observation of the volcanogenic sedimentary facies (lithofacies 5.1–5.5) being intruded by the felsic volcanic facies is found outside the study area (12 km south in Ollinniemi) in drill core PYO-76 (Fig. 4e), where the coherent rhyolite intrudes the moderately sericite altered volcanogenic sedimentary facies (Fig. 4). Similarly, the observations from the hanging-wall contact of the Pyhäsalmi deposit (Fig. 9) also suggests that the hydrothermal system that produced the Pyhäsalmi sulfide ore affected both the margins of the brecciated felsic domes (hyaloclastites) and the adjacent volcanogenic sedimentary facies (Fig. 10). Intrusion of felsic lava into the volcanogenic sedimentary facies – and the apparent hydrothermal alteration of the contact sediments (Fig. 9c) – indicates that sediments were already present during volcanism. Thus, the VMS ores in the area could hypothetically be partly hosted in sedimentary facies host rocks.

Based on the available evidence, we infer that either the volcanogenic sedimentary facies (lithofacies 5.1–5.5), or a sedimentary succession of roughly similar origin (lithofacies 7.1), was present and being deposited during the emplacement of the felsic volcanism. Therefore, we infer the depositional environment of the felsic volcanism from the lithofacies characteristics (facies models) of the volcanogenic sedimentary facies, as discussed in more detail below.

4.1. Depositional setting

Composite models for submarine slope sedimentation along active volcanic arcs have been presented (Stow et al. 1998; Soriano & Marti 1999). Both models are applicable to an extensional volcanic arc basin setting, as inferred to Pyhäsalmi previously (Lahtinen 1994; Mäki & Puustjärvi 2003). The volcanogenic sedimentary facies association (lithofacies 5.1–5.5; Fig. 3), as described here from the Pyhäsalmi area, shows similar lithofacies and organization as these models. According to the models, the suite of lithofacies in the volcanogenic sedimentary association reflect a range of deep-water (>200 m depth) sedimentary processes, including hemipelagic "background" sedimentation intermixed with slope-related slide, slump, debris flows, and turbidity currents (e.g. Stow and Smilie 2020). Slope instability and failure may have been triggered by volcanic-seismic events (Stow et al. 1998; Soriano & Marti 1999), with *en masse* downslope slumping and debris flows producing the chaotic intraformational breccia facies (Fig. 3). Sedimentation and volcanism may have been contemporaneous, with significant input of volcaniclastic sedimentary material consequently reworked in such slope-related processes. Additionally, both fine and coarse volcaniclastic material (i.e., pumice and ash; Fig. 3g, m) may represent fallout from subaerial explosive eruptions, or off slope turbiditic reworking of such material. Furthermore, volcaniclastics may represent deposits from subaqueous explosive eruption plumes that collapse into turbidity currents (Kano 2003; Cas & Simmons 2018; Druitt et al. 2024). We have found no evidence of primary pyroclastic deposits, but we cannot rule out the possibility of mixed eruption-fed volcaniclastic–turbiditic processes in the formation of the volcanogenic sedimentary facies association (e.g., lithofacies 5.1) (McPhie et al. 1993). The lack of evidence for shallow water depositional structures (Stow et al. 1998) in Pyhäsalmi suggests that the depositional setting was likely a deep (below wave-base) submarine volcano-sedimentary rift basin. We conclude that the volcanogenic sedimentary facies association represents typical turbiditic and hemipelagic "background" sedimentation of a sedimentary basin intruded by felsic dome-like lavas and volcaniclastics (Fig. 10).

While the existence of variably migmatized mica schists of turbiditic origin in the Vihanti–Pyhäsalmi belt has been established (e.g. Mäki

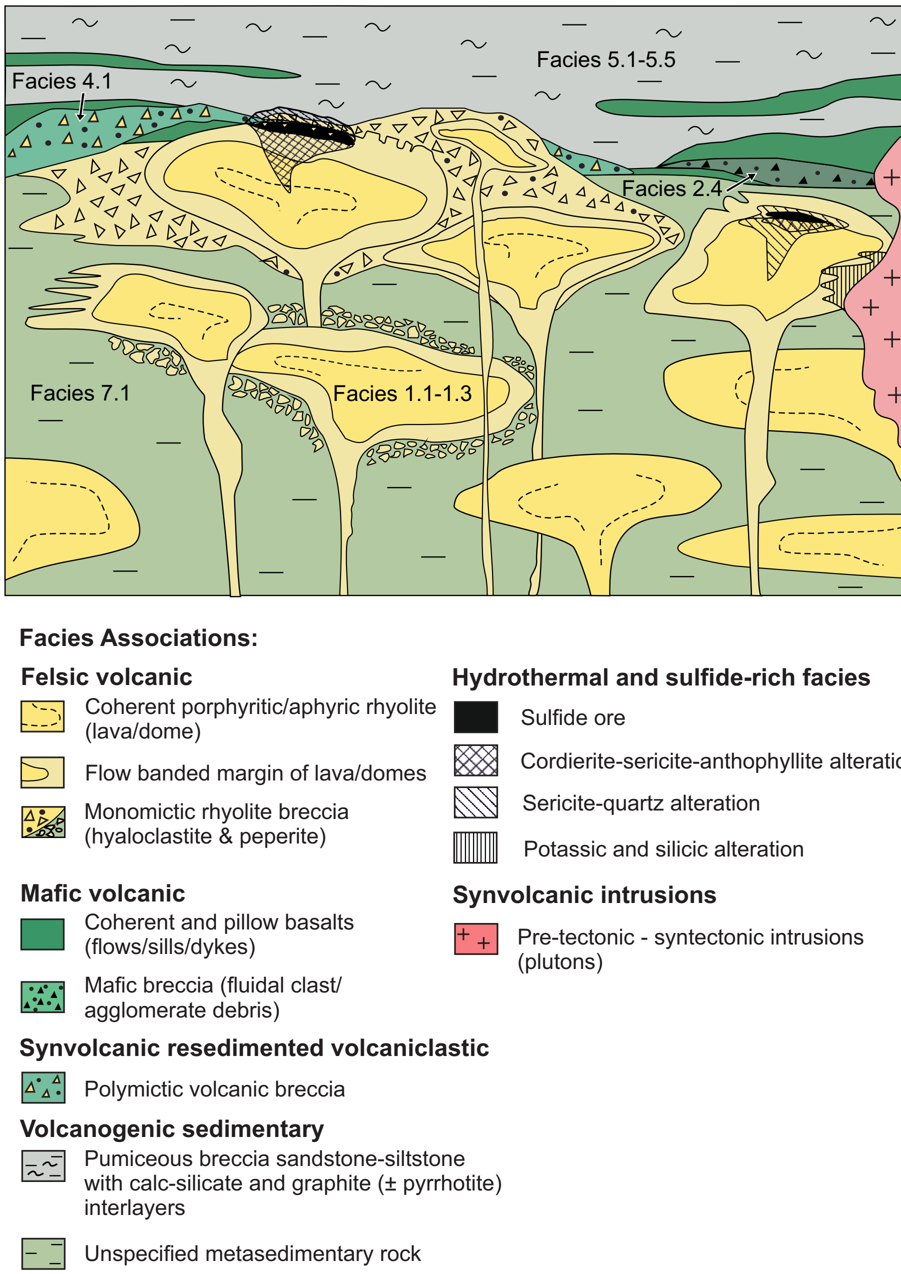

Figure 10. Conceptual model of the volcanic architecture of the Pyhäsalmi–Mullikkoräme study area. Setting of the Pyhäsalmi VMS deposit on the left, Mullikkoräme on the right.

& Puustjärvi 2003), these sedimentary facies associations have not been described before in any detail from the older (1.93–1.91 Ga) so called Lower Svecofennian rocks and, contrary to our interpretation, they have been interpreted as either older or younger relative to the VMS prospective volcanism. Similar basin fill sediments as presented here have been described from the younger (Upper Svecofennian) Ylivieska belt in the RLZ (Strand 2002; see also Västi 1989) and globally, for example, from the Iberian Pyrite Belt (Soriano & Marti 1999).

4.2. Eruptive style of volcanism

The presence of voluminous rhyolitic coherent and autoclastic lithofacies (lithofacies 1.1–1.3), with no unambiguous evidence of primary pyroclastic deposits (see lithofacies 5.1), indicates an effusive eruption style and is interpreted to have formed through submarine effusive or shallow intrusive magmatism. These deposits were emplaced as felsic lavas, domes, cryptodomes or other type of deep-seated intrusions (e.g., laccoliths). The coherent lithofacies represents flows or dome centers, while the hyaloclastic facies indicates brecciated dome margins (Fig. 10) (McPhie et al. 1993). Submarine dome complexes exhibit relatively simple facies associations compared to more complex systems, such as the caldera-related associations of subaqueous pyroclastic flows and their resedimented equivalents. Although dome complexes can be voluminous, they remain relatively confined and localized, with minimal transport from the eruption site to the final point of deposition (McPhie et al. 1993; Allen et al. 1996; Ross & Mercier-Langevin 2014).

Dome complexes are often associated with pyroclastic deposits. Considering that pyroclastic rocks are often difficult to recognize once overprinted by metamorphism, deformation, and alteration, it remains uncertain whether they are genuinely absent in the stratigraphy of the study area or have simply gone unrecognized. We speculate that the absence of such deposits indicates that the felsic (crypto)dome growth was largely sealed without explosion, or may have experienced only subtle, thinly layered, and easily missed phreatic eruptions. The absence of voluminous felsic pyroclastic deposits (e.g., submarine ignimbrites) could also suggest a deep-water setting for the Pyhäsalmi–Mullikkoräme felsic volcanism, as rhyolitic dome-volcanoes are more likely to be explosive when water-magma phreatomagmatic activity occurs under low hydrostatic pressure (i.e. shallow water, < 200 m; Cas et al. 1990; Kano 2003). The confining pressure of the water column at depth of ~3000 m will preclude explosive pyroclastic fragmentation (Cas 1992).

4.3. Basaltic volcanism and extensional setting

The volcaniclastic rocks (lithofacies 4.1–4.2; Fig. 8) are interpreted as resedimented syn-eruptive volcaniclastics representing subaqueous volcaniclastic mass flow deposits. Lithofacies 4.1 (the Härkälä outcrop; Fig. 1) is located between the felsic (Lippikylä) and mafic (Mukurinperä) stratigraphic domains. The unit is composed of coherent felsic blocks, likely sourced from the underlying felsic lavas/domes, and a matrix of intermediate-mafic volcanic debris, likely sourced from syn-depositional initial mafic eruptions (Fig. 10) (this study; Puustjärvi 1999; Mäki & Puustjärvi 2003). The unit possibly formed in an extensional graben-environment, which, with progressive rifting, led to the production of more voluminous mafic lavas at spreading centers which now overlie the felsic volcanic rocks in the study area (Mäki & Puustjärvi 2003). Lithofacies 4.1 may represent an easy to identify stratigraphic marker horizon which could be traced in drill core (Fig. 8a–c.)

At the Tetrinmäki outcrops in Mullikkoräme (Fig. 1), pillow lavas are associated with thick mafic breccias and sheeted dikes (Fig. 7). Elsewhere, such facies associations have been interpreted to have formed from submarine fountain eruptions fed by basaltic fissure vents (Allen et al. 1996; Simpson & McPhie 2001; Cas et al. 2003; Montelius et al. 2009; Cas & Simmons 2018; Hokka & Lahtinen 2025). We also interpret the Tetrinmäki association to represent a basaltic fissure vent complex (Fig. 11). The mafic breccia (lithofacies 2.4) forms a thick unit (> 100 m) of basaltic spatter clast breccia debris mixed with coarser pillow breccias and crosscut by feeder dikes. The eruption of the mafic breccia lithofacies occurred at high discharge rates from fissure vents, whereas pillowed flows formed during periods of low discharge rate (Allen et al. 1996). The sheeted dikes represent conduits that transported magma to the surface, forming fissure vents and pillow flows. At Tetrinmäki, the sheeted dikes presently strike 140–160°. This orientation is likely perpendicular to the orientation of the paleo-rift

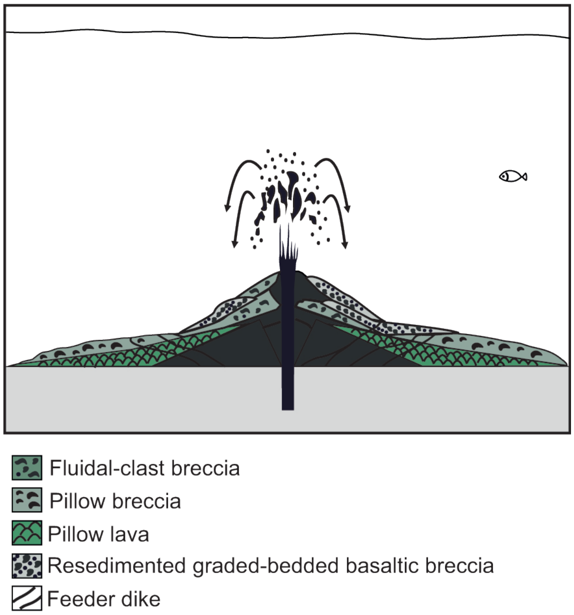

Figure 11. Subaqueous fountain-type (Allen et al. 1996; Simpson & McPhie 2001; Cas et al.2003) fissure vent eruption complex suggested for Tetrinmäki, Mullikkoräme area (see Fig. 1).

axis and may thus indicate the strike of a synvolcanic fault system. Elsewhere in the study area mafic dikes generally strike north-south.

4.4. Submarine dome complexes and VMS deposits

The submarine felsic dome complex setting is important for VMS ore formation for two main reasons. 1) Empirically, we know that felsic dome complexes emplaced in sedimentary basins are one of the most prospective settings for ancient VMS deposits (Allen et al. 2002; Ross & Mercier-Langevin 2014). 2) Conceptually, a bimodal volcanic stratigraphic sequence evolving from submarine effusive felsic volcanism to tholeiitic mafic volcanism indicates an extensional rift-related setting where the main mineral system components for VMS deposit formation are present: shallow heat sources, synvolcanic extensional structures for focusing of hydrothermal fluids, and ambient ocean water for precipitating ore (Franklin et al. 2005).

VMS ore formation often relates to the late-stage evolution of specific rhyolite volcanoes and is followed by a significant change in the mode of volcanism and sedimentation, such as a hiatus in felsic volcanism, increased deposition of mudstones, and fissure eruptions of mantle-derived basalts (Allen et al. 2002). The facies associations presented here suggest that the evolution of the Pyhäsalmi volcanic complex and associated VMS deposit shows similar change in volcanic-sedimentary patterns where the formation of the VMS deposit was likely coeval with the final phases of growth of a rhyolitic volcanic center and the transition to a dynamic deep-sea sedimentary basin with extensional basaltic volcanic activity.

Similar volcano-sedimentary lithofacies associations with felsic dome complex hosted VMS deposits as Pyhäsalmi are described from the Iberian Pyrite Belt in Spain–Portugal (Soriano & Marti 1999; Tornos 2006; Rosa et al. 2010), in the Noranda district, Canada, (Gibson & Galley 2007), and in the Skellefte district, Northern Sweden (Allen et al. 1996). Felsic dome complexes can be related to various geodynamic environments and facies associations (e.g., Pichler 1965; Gibson et al. 1999; Franklin et al., 2005; Morgan & Schulz 2012; Ross & Mercier-Langevin 2014). Geographically, the closest analogy to the Pyhäsalmi volcanic complex is the 1.90–1.88 Ga Skellefte district, although notable differences exist, such as the timing of volcanism (Kousa 1994). The district is dominated by submarine volcanism with abundant rhyolitic (pre-tuff cone) cryptodomes emplaced into turbidites of pyroclastic (tuff cone) origin (Allen et al. 1996; Allen et al. 2002). In the Skellefte district, the sulfide deposits are mainly interpreted as having formed via replacement-style deposition and are associated with the contact between volcanic and sedimentary rocks (e.g., Allen et al. 1996; Montelius 2007; Schlatter 2007). For example, the Rävliden North, Långdal, Långsele, and Renström VMS deposits all contain organic-rich mudstones in the immediate hanging wall (Allen et al. 1996; Weihed et al. 2002; Allen & Svenson 2004; Simán et al. 2025), similar to those we have observed in the Pyhäsalmi deposit.

4.5. Host rocks, hydrothermally altered rocks, type of deposit

The hydrothermal alteration in the vicinity of the Pyhäsalmi mine obscures the primary textures and complicates facies mapping. There are two large hydrothermal alteration zones located on the eastern side of the Pyhäsalmi mine (Fig. 1): 1) the cordierite–anthophyllite–sericite zone, and 2) the sericite–quartz alteration zone, which are part of the Lehto and Lepikko lithodemes, respectively (Puustjärvi 1999; Mäki & Puustjärvi 2003). The Lepikko lithodeme has been correlated to the felsic volcanic rocks of the Lippikylä member (Mäki & Puustjärvi 2003), whereas for the Lehto lithodeme protoliths have been suggested to represent either mafic lavas and pyroclastites (Mäki & Puustjärvi, 2003) or a mafic to intermediate sill-like body (Mäki et al. 2015).

Porosity in host rocks may enhance the processes of hydrothermal circulation and, thus, result in more wide-spread alteration in VMS systems (e.g., Gibson et al. 1999; Doyle & Allen 2004). Our evidence of sulfide-rich hyaloclastic breccia facies and the overlying altered sedimentary facies (Fig. 9) suggest that the hydrothermal system responsible for the formation of the Pyhäsalmi sulfide deposit likely operated along the margins of a brecciated felsic dome (autoclastic facies) and clastic volcanogenic sediments. Further evidence for sub-seafloor replacement, as previously suggested by Imaña (2003) and Miettinen (2011), includes the relicts of coherent felsic rocks within the sulfide ore and the infiltration of metamorphic VMS-related alteration assemblages into the matrix of the volcaniclastic facies (Fig. 9). We propose that the Pyhäsalmi ore is hosted by effusive and subvolcanic intrusive felsic domes, along with associated autoclastic facies (Fig. 10). The large size of the alteration zones in Pyhäsalmi (Fig. 1) could be related to the abundance of both felsic dome breccias (hyaloclastites) and clastic sedimentary rocks (volcaniclastic turbidites). In addition, the hanging wall of the active hydrothermal system may have been insulated by rapid deposition of mass-flows (lithofacies 5.1–5.5), renewed lava flows, or other impermeable lithologies, providing a sealing layer for concentrated fluid flow and better metal precipitation and allowing the system to expand laterally in the porous clastic host rocks for several kilometers (Doyle & Allen 2003; Tornos 2006; Tornos 2015; Imaña et al. 2019; Simán et al. 2025).

Compared to Pyhäsalmi, the Mullikkoräme area features a facies association dominated by rhyolite domes in close contact with mafic volcanic rocks, with no clear evidence to dome margins and adjacent sedimentary facies. Thus, a direct correlation between the deposits cannot be drawn, as the immediate host facies associations differ (Fig. 10). The more abundant carbonate, sphalerite, and galena at Mullikkoräme also suggest lower-temperature mineralizing processes than at Pyhäsalmi (Mäki et al. 2015). These differences may be due to different stratigraphic levels between the deposits. Also, the sedimentary facies may simply not have been preserved in the Mullikkoräme area. In addition, the alteration zones appear to be more limited in the Mullikkoräme deposit compared to Pyhäsalmi (this study; Puustjärvi 1994). In coherent lavas and intrusions, hydrothermal fluid circulation may be more focused into synvolcanic fault and breccia zones (Doyle & Allen 2003). This suggests that the Mullikkoräme sulfide deposit formed within a felsic volcanic sequence with a lower primary permeability, thus limiting hydrothermal fluid circulation (Tornos 2006).

Despite differences in the observed facies associations between the Pyhäsalmi and Mullikkoräme deposits, our results show no evidence of two repeated volcanic cycles overlying each other, as proposed by Mäki et al (2015). Rather, we favor the interpretation of Mäki & Puustjärvi (2003) in that the Pyhäsalmi and Mullikkoräme areas represent stratigraphically lateral formations (Fig. 10).

Subvolcanic intrusions are considered as the primary heat engines responsible for hydrothermal systems and it is well documented that VMS deposits are spatially associated with intrusions of certain composition and size (Galley 2003; Franklin et al. 2005). The Kettuperä gneiss has been interpreted as a subvolcanic intrusion, a synvolcanic cryptodome, related to VMS mineralizations

(Puustjärvi et al., 1999; Mäki et al., 2015). Along contact zones (>15 m thick) of the 1924 Ma Kokkokangas granodiorite (previously Kettuperä of Helovuori (1979), presently Kokkokangas after Puustjärvi (1999)), we find the felsic volcanic rocks to be hydrothermally brecciated and strongly epidote ± albite ± potassium -altered, with stockworks of cross-cutting mafic to felsic dikes. The intrusion may represent a polyphase pluton, but overall it appears homogeneous and coarse grained (deep-seated, no obvious boiling or hydrothermal textures).

4.6. Implications for VMS exploration

Critical lithofacies for exploration targeting are submarine felsic lavas and/or (crypto) domes and their clastic margins at the contacts with the volcanogenic sedimentary facies association (the Pellonpää member). In addition to the felsic volcanic host rocks, the sedimentary facies appears to be synvolcanic and hydrothermally altered, and when associated with felsic volcanic centers, it may provide a potential host for VMS mineralization.

Pyrrhotite-bearing exhalites are associated with the sedimentary facies over a broader area (Laitala 2013) and, although mostly barren themselves, they imply high regional prospectivity. The extensive coverage of similar volcaniclastic turbidites and hemipelagic sediments elsewhere in the Vihanti–Pyhäsalmi–Rautalampi belt, and the potential for buried rhyolitic lavas or (crypto)domes, highlights the need for widening the scope of exploration into less tested areas. Massive sulfides could generally accumulate during quiescent times or settings associated with those hemipelagic sediments trapped between several domes or on the top of domes. In such settings, the deposited sulfides may be then protected from influx of pyroclastics and reworked volcaniclastics. In addition, the mafic pillow lava (and fountain) facies provide a robust paleo-seafloor indicator that can be used to target the underlying submarine felsic lavas and domes.

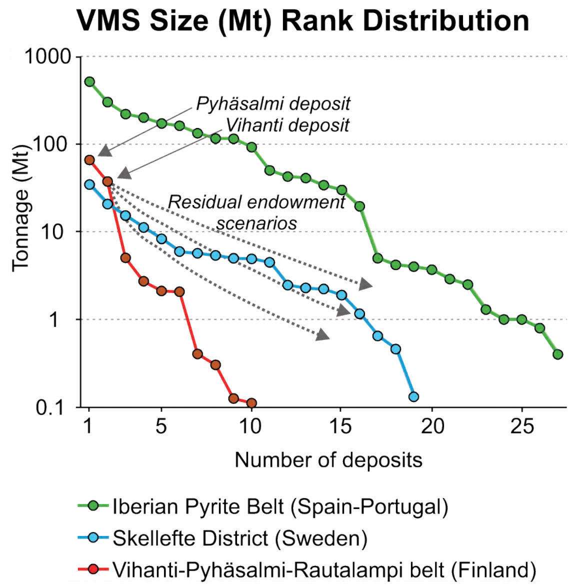

Figure 12. Size-rank distribution of the Vihanti–Pyhäsalmi–Rautalampi belt (red) compared to the mature Skellefte district (blue) and the Iberian Pyrite Belt (green) (Allen et al. 1996; FODD 2012; Rasilainen et al. 2014; Tornos 2016, and references therein). At the belt scale, the tonnage tends to follow a log-normal distribution, resulting in a linear trend in the plot. Dashed lines illustrate the potential for undiscovered deposits in the Vihanti–Pyhäsalmi–Rautalampi belt.

Compared to the Iberian Pyrite Belt and the Skellefte district, the Vihanti–Pyhäsalmi–Rautalampi belt appears underexplored based on a simple statistical comparison of residual metal endowment (Fig. 12). Figure 12 emphasizes the potential for several undiscovered medium-sized (5–20 Mt) deposits, assuming a log-normal tonnage distribution for the sizes of the undiscovered deposits (Fig. 12).

Huhtala (1979) subdivided the sulfide deposits within the Pyhäsalmi area into three groups based on their lithological associations. Our evidence also suggests that several deposit types may exist within the Vihanti–Pyhäsalmi–Rautalampi belt. For example, in the Iberian Pyrite Belt, massive sulfide deposits are also hosted in both felsic volcanic rocks and shales (Tornos 2006). This demands further investigation and classification of the volcanic architectures favorable for VMS deposition in the Vihanti–Pyhäsalmi–Rautalampi belt.

5. Conclusions

The Pyhäsalmi volcanic complex is described as a felsic submarine dome complex. This setting displays similarities to major VMS camps, such as the Skellefte district (Sweden), Noranda district (Canada), and the Iberian Pyrite Belt (Spain–Portugal). The facies architecture based on 18 defined lithofacies indicates that volcanism took place in a submarine, below wave base depositional environment, and was mainly of non-fragmental nature, erupting either as lavas and/or (crypto) domes. Locally abundant peperitic and hyaloclastic facies, combined with the absence of voluminous felsic pyroclastic deposits, suggest shallow intrusion of felsic magmas into a deep marine (turbiditic–hemipelagic; graphite- and carbonate-bearing) sedimentary pile. This was followed by flows and fissure eruptions of mafic extensional magmatism on the seafloor. The volcanogenic sedimentary facies association shows evidence of deposition of abundant detrital volcaniclastic material, suggesting a possible link to syn-eruptive re-sedimentation of proximal or distal products of explosive volcanism. However, the source of this material remains unclear.

The Pyhäsalmi VMS deposit formed as sub-seafloor replacement style mineralization within the hyaloclastic facies at the margins of the rhyolite domes or lavas and adjacent to the overlying clastic volcanogenic sedimentary facies. Close to the ore, these facies show pervasive hydrothermal alteration, indicating that they acted as permeable conduits for fluids circulating beneath the seafloor. The hanging wall sediments may have acted as insulation for the hydrothermal cell. In contrast, the Mullikkoräme VMS deposit is dominated by coherent lava or dome facies, inferred to have undergone more limited hydrothermal fluid circulation. The Pyhäsalmi and Mullikkoräme deposits occur at broadly equivalent stratigraphic levels but show slight variations in lateral position or facies association within an otherwise contemporaneous volcanic succession, as no evidence supports a repeated and overlain sequence of two similar volcanic successions (i.e., division between the Pyhäsalmi Group and the Vihanti Group). A better understanding of the volcanic and sedimentary facies allows for a comprehensive belt-scale mineral system analysis and provides new exploration space for future VMS discoveries in the underexplored Vihanti–Pyhäsalmi–Rautalampi belt.

Acknowledgements

This research was carried out as part of the Geological Survey of Finland's mineral system research. Special thanks are addressed to the team at the GTK Loppi Drill Core Archive: M. Tuohimaa, M. Salonen & J. Riikonen. We also thank First Quantum Minerals Ltd. for providing access to the Pyhäsalmi Mine drill core facilities. T. Mäki, T. Häkkinen, P. Salminen, J. Avellan, J. Köykkä & P. Sorjonen-Ward are acknowledged for their support and useful discussions. We also sincerely thank the reviewers, Marcello Imaña and Kari Strand, for their constructive comments and suggestions, which greatly improved the manuscript. We further thank the Editor-in-Chief J. Heinonen and the Handling Editor S. Yang for their editorial oversight and constructive comments on the manuscript.

Authorship contribution statement

J. Hokka – conceptualization, analytical work, writing, interpretation, visualization, editing; V. Järvinen – analytical work, data curation, writing, interpretation, editing.

References

Allen, R. L., Weihed, P. & Svenson, S.-Å., 1996. Setting of Zn-Cu-Au-Ag sulfide deposits in the evolution of facies architecture of a 1.9 Ga marine volcanic arc, Skellefte District, Sweden. Economic Geology 91, 1022–1053. https://doi.org/10.2113/gsecongeo.91.6.1022

Allen, R. L., Weihed, P. & The global VMS research project team., 2002, Global comparison of volcanic-associated massive sulphide districts. In: Blundell, D. J., Neubauer, F. & Von Quadt, A. (ed.), The Timing and Location of Major Ore Deposits in an Evolving Orogen. Geological Society, London, Special Publications 204, pp. 13–37.

Allen, R. & Svenson, S.-Å., 2004. 1.9 Ga Volcanic Stratigraphy, Structure, and Zn-Pb-Cu- Au-Ag Massive Sulfide Deposits of the Renström area, Skellefte District, Sweden. In: Rodney, A. Olof, M. & Pär, W. (ed.), Svecofennian Ore-Forming Environments Field Trip Volcanic-associated Zn-Cu-Au-Ag and magnetite-apatite, sediment-hosted Pb-Zn, and intrusion-associated Cu-Au deposits in northern Sweden. Society of Economic Geologists Guidebook Series 33.

Allen, R. L., 2024, Volcanic-facies mapping and related hydrothermal alteration studies of the Buchans Camp, southern Buchans-Robers Arm Belt, Central Newfoundland: Current Research (2024). Newfoundland and Labrador Department of Industry, Energy and Technology Geological Survey, Report 24–1, pp. 1–30.

Bedrock of Finland – DigiKP, 2021. Digital map database [Electronic resource]. Geological Survey of Finland [referred 6.6.2025]. Version 2.3, Espoo.

Bogdanova, S., Gorbatschev, R., Skridlaite, G., Soesoo, A., Taran, L. & Kurlovich, D., 2015. Trans-Baltic Palaeoproterozoic correlations towards the reconstruction of supercontinent Columbia/Nuna. Precambrian Research 259, 5–33. https://doi.org/10.1016/j.precamres.2014.11.023

Cas, R. A. F., Allen, R. L., Bull, S. W., Clifford, B. A. & Wright, J. V., 1990. Subaqueous, rhyolitic dome-top tuff cones: a model based on the Devonian Bunga Beds, southeastern Australia and a modern analogue. Bulletin of Volcanology 52, 159–174. https://doi.org/10.1007/bf00334802

Cas, R. A. F., & Simmons, J. M., 2018. Why deep-water eruptions are so different from subaerial eruptions. Frontiers in Earth Science 6, 198. https://doi.org/10.3389/feart.2018.00198

Cas, R. A. F., 1992. Submarine volcanism—Eruption styles, products, and relevance to understanding the host-rock successions to volcanic-hosted massive sulfide deposits. Economic Geology 87, 511–541. https://doi.org/10.2113/gsecongeo.87.3.511

Cas, R. A. F., Yamagishi, H., Moore, L. & Scutter, C., 2003. Miocene submarine fire fountain deposits, Ryugazaki Headland, Oshoro Peninsula, Hokkaido, Japan: Implications for submarine fountain dynamics and fragmentation processes. In: White J. D. L., Smellie J. L. & Clague D. A. (ed.), Explosive Subaqueous Volcanism. Geophysical Monograph 140, American Geophysical Union, Washington, pp. 299–316. https://doi.org/10.1029/140gm20

Doyle, M. G. & Allen, R. L., 2003. Subsea-floor replacement in volcanic-hosted massive sulfide deposits. Ore Geology Reviews 23, 183–222. https://doi.org/10.1016/s0169-1368(03)00035-0

Druitt, T., Kutterolf, S., Ronge, T. A. et al., 2024. Giant offshore pumice deposit records a shallow submarine explosive eruption of ancestral Santorini. Nature Communications Earth and Environment 5, 24. https://doi.org/10.1038/s43247-023-01171-z

Eilu, P., Bergman, T., Bjerkgård, T. et al., 2013. Metallic Mineral Deposit Map of the Fennoscandian Shield 1:2,000,000. Revised edition (comp.). Geological Survey of Finland, Geological Survey of Norway, Geological Survey of Sweden, the Federal Agency of Use of Mineral Resources of the Ministry of Natural Resources of the Russian Federation.

Ekdahl, E., 1993. Early Proterozoic Karelian and Svecofennian formations and the evolution of the Raahe-Ladoga Ore Zone, based on the Pielavesi area, central Finland. Geological Survey of Finland, Bulletin 373, 137 p.

Franklin, J. M., Gibson, H. L., Jonasson, I. R., & Galley, A. G., 2005, Volcanogenic massive sulfide deposits, In: Hedenquist, J. W., Thompson, J. F. H., Goldfarb, R. J. & Richards, J. P. (ed.), Economic Geology 100th anniversary volume, 1905–2005. Littleton, Colo., Society of Economic Geologists, pp. 523–560.

FODD, 2012. Fennoscandian Ore Deposit Database. Geological Survey of Finland (GTK), Geological Survey of Norway (NGU), Geological Survey of Russia (VSEGEI), Geological Survey of Sweden (SGU), SC mineral. Online database accessed 10 July 2012, available at: http://en.gtk.fi/ExplorationFinlandExplorationFinland/fodd

Gaál, G. & Gorbatschev, R., 1987. An outline of the Precambrian evolution of the Baltic Shield. Precambrian Research 35, 15–52. https://doi.org/10.1016/0301-9268(87)90044-1

Galley, A. G., 2003. Composite synvolcanic intrusions associated with Precambrian VMS-related hydrothermal systems. Mineralium Deposita 38, 443–473. https://doi.org/10.1007/s00126-002-0300-9

Gibson, H. L., Morton, R. L. & Hudak, G. J., 1999. Submarine volcanic processes, deposits, and environments favorable for the location of volcanic-associated massive sulfide deposits. In: Barrie, C. T. & Hannington, M. D. (ed.), Volcanic-associated massive sulfide deposits: Processes and examples in modern and ancient settings. Society of Economic Geologists, Reviews in Economic Geology, 8, 13–51. https://doi.org/10.5382/rev.08.02

Gibson, H. L. & Galley, A. G., 2007. Volcanogenic massive sulphide deposits of the Archean, Noranda District, Quebec. In: Goodfellow, W.D. (ed.), Mineral deposits of Canada—A synthesis of major deposit-types, district metallogeny, the evolution of geological provinces, and exploration methods. Geological Association of Canada, Mineral Deposits Division, Special Publication 5, pp. 533–552.

Helovuori, O., 1979. Geology of the Pyhäsalmi ore deposit, Finland. Economic Geology 74, 1084–1101. https://doi.org/10.2113/gsecongeo.74.5.1084

Hettula, J., 2019, Hydrothermal alteration and host rock composition of the Pyhäsalmi volcanogenic massive sulphide deposit, Central Finland, University of Oulu, Faculty of Technology, MSc Thesis, 68 p.

Hokka, J. & Lahtinen, R., 2025. Facies architecture, ore genesis (Zn-Pb-Cu) and structural evolution of the Paleoproterozoic Aijala–Metsämonttu area, SW Finland. Ore Geology Reviews 184, 106707. https://doi.org/10.1016/j.oregeorev.2025.106707

Huhtala, T., 1979. The geology and zinc-copper deposits of the Pyhäsalmi-Pielavesi district, Finland. Economic Geology 74, 1069–1083. https://doi.org/10.2113/gsecongeo.74.5.1069

Huhma, H., Kousa, J. & Luukas, J. 2021. Geochronology of the Paleoproterozoic Pyhäsalmi–Vihanti district, central Finland. Geological Survey of Finland, Open File Research Report 8/2021, 31 p.

Imaña, M., 2003. Petrography, mineralogy, geochemistry and 3D modelling of the A zinc ore in the Pyhäsalmi Zn-Cu VMS deposit, central Finland. MSc Thesis, University of Turku, Department of Geology and Mineralogy, 72 p.

Imaña, M., Aspajo, H., Bueno, J. P. & Mota, J., 2019. The Cerro Lindo VMS deposit: Volcanic architecture, stratigraphy and hydrothermal alteration of a world class sulphide deposit, Central Peru. Conference Field Guide, Proexplo 2019, Lima, 6 p.

Islam, S. R., Heilimo, E., Kuva, J., Mäkilä, E. & Mäki, T. 2025. Decoding multiple ore mineral remobilization processes during polyphase deformational phases from the Precambrian Pyhäsalmi VMS deposit halo, Central Finland: new insights from mineralogy, mineral chemistry and micro-CT. International Journal of Earth Science 114, 727–747. https://doi.org/10.1007/s00531-025-02511-4

Kano, K., 2003. Subaqueous pumice eruptions and their products: a review. In: White, J. D. L., Smellie, J. L. & Clague D. A. (ed.), Explosive Subaqueous Volcanism. American Geophysical Union, Washington DC, pp. 213–229. https://doi.org/10.1029/140GM14

Kohonen, J., Lahtinen, R., Luukas, J. & Nironen, M., 2021. Classification of regional-scale tectonic map units in Finland. Geological Survey of Finland, Bulletin 412, 33–80.

Korsman, K., Koistinen, T., Kohonen, J., et al. (ed.), 1997. Suomen kallioperäkartta—Berggrundskarta över Finland— Bedrock map of Finland 1:1,000,000. Geological Survey of Finland, Espoo, Finland.

Kousa, J., Marttila, E. & Vaasjoki, M., 1994. Petrology, geochemistry and dating of Paleoperoterozoic metavolcanic rocks in the Pyhäjärvi area, central Finland. In: Nironen, M. & Kähkönen, Y. (ed.), Geochemistry of Proterozoic supracrustal rocks in Finland. IGCP Project 179 "Stratigraphic Methods as Applied to the Proterozoic Records" and IGCP Project 217 "Proterozoic Geochemistry". Geological Survey of Finland, Special Paper 19, pp. 7–27.

Kousa, J., Ekdahl, E., Isomäki, O.-P., Luukas, J., Mäki, T., Nurmi, P., Papunen, H., Pelkonen, K. & Penttilä, V.-J., 1997. Geology and mineral deposits of the central Ostrobothnia. Regional geology. In: Weihed, P. & Mäki, T. (eds), Research and Exploration—Where Do They Meet? Proceedings of the 4th Biennial SGA Meeting, August 11–13, Turku, Finland, Excursion guidebook A2: volcanic hosted massive sulphide and gold deposits in the Skellefte district, Sweden and western Finland. Geological Survey of Finland, Guide 41, pp. 43–46.

Kousa, J., Luukas, J., Huhma, H. & Mänttäri, I., 2013. Paleoproterozoic 1.93–1.92 Ga Svecofennian rock units of the Raahe-Ladoga Zone, Central Finland. Geological Survey of Finland, Report of Investigation 198, pp. 91–96.

Kähkönen, M., 2017. 3D-valokuvien hyödyntäminen Pyhäsalmen kaivoksella. University of Helsinki, Department of Geosciences and Geography, MSc Thesis, 81 p. (in Finnish).

Laine, E., Luukas, J., Mäki, T., Kousa, J., Ruotsalainen, A., Suppala, I., Imaña, M., Heinonen, S. & Häkkinen, T., 2015. The Vihanti-Pyhäsalmi Area. In: Weihed, P. (ed.), 3D, 4D and Predictive Modelling of Major Mineral Belts in Europe. Mineral Resource Reviews, Springer, pp. 123–144. https://doi.org/10.1007/978-3-319-17428-0_6

Laitala, J., 2015. Mineralogy and geochemistry of the pyrrhotite horizons in the Pyhäsalmi district, central Finland, University of Turku, Department of Geography and Geology, MSc Thesis, 86 p.

Lahtinen, R., 1994. Crustal evolution of the Svecofennian and Karelian domains during 2.1–1.79 Ga, with special emphasis on the geochemistry and origin of 1.93–1.91 Ga gneissic tonalites and associated supracrustal rocks in the Rautalampi area, central Finland. Geological Survey of Finland, Bulletin 378, 128 p.

Lahtinen, R., Korja, A. & Nironen, M., 2005. Paleoproterozoic tectonic evolution. In: Lehtinen, M., Nurmi, P.A. & Rämö, O.T. (ed.), Precambrian Geology of Finland—Key to the Evolution of the Fennoscandian Shield. Elsevier Science B.V., Amsterdam, pp. 481–532.

Marti, J., 2022. Volcano Geology Applications to Ancient Volcanism-Influenced Terrains: Paleovolcanism: In Németh, K (ed.), Updates in volcanology – Linking active and the geolocal record. IntechOpen, 184 p. https://doi.org/10.5772/intechopen.108770

Marttila, E. 1993. Pyhäjärven kartta-alueen kallioperä. Summary: Pre-Quaternary rocks of the Pyhäjärvi map-sheet area. Geological map of Finland 1:100 000, Sheet 3321. Geological Survey of Finland. 64 p.

McPhie, J., Doyle M. & Allen, R., 1993, Volcanic Textures: a Guide to the Interpretation of Textures in Volcanic Rocks. University of Tasmania Centre for Ore Deposit and Exploration Studies, Hobart, 198 p.

Miettinen, E., 2011. Detailed geology of the level—1275, Pyhäsalmi Mine, central Finland and genetic implications of rock inclusions within the ore body. MSc Thesis, University of Helsinki, 67 p.

Montelius, C., Allen, R. L., Svenson, S-Å. &Weihed, P., 2007. Facies architecture of the Palaeoproterozoic VMS-bearing Maurliden volcanic centre, Skellefte district, Sweden. GFF 129, 177–196. https://doi.org/10.1080/11035890701293177

Morgan, L. A. & Schulz, K. J., 2012, Physical volcanology of volcanogenic massive sulfide deposits in volcanogenic massive sulfide occurrence model. In: Shanks, W.C. Pat III, & Thurston, R. (ed.), Volcanogenic massive sulfide occurrence model: U.S. Geological Survey Scientific Investigations Report 2010–5070–C, 345 p.

Mäki, T.,1986, The Lithogeochemistry of the Pyhäsalmi Zn-Cu-Pyrite deposit, Finland. In: Prospecting in areas of glaciated terrain symposium, Sept. 1–2, Kuopio. Finland. Institute of Mining and Metallurgy, London, pp. 69–82.

Mäki, T. & Puustjärvi, H., 2003. The Pyhäsalmi massive Zn-Cu-pyrite deposit, Middle Finland—a Paleoproterozoic VMS-class "giant." In: Ashton, J. et al. (ed.), Europe's Major Base Metal Deposits. Irish Association for Economic Geology, Dublin, pp. 87–91.

Mäki, T., Imaña, M., Kousa, J. & Luukas, J., 2015. The Vihanti-Pyhäsalmi VMS Belt. In: Maier W., Lahtinen, R., O'Brien, H. (ed.), Mineral Deposits of Finland, 1st Edition. Elsevier, Amsterdam, pp. 507-530. https://doi.org/10.1016/B978-0-12-410438-9.00020-0

Ohtomaa, M., 2014. Pyhäsalmen alueen granodioriittien ja happamien vulkaniittien vertailu. University of Oulu, Faculty of Technology, MSc Thesis, 58 p.

Pichler, H., 1965. Acid hyaloclastites. Bulletin of Volcanology 28, 293–310. https://doi.org/10.1007/bf02596934

Puustjärvi, H, 1994. Pyhäsalmen Mullikkorämeen tutkimukset vuosina 1986–94, Outokummun malminetsintä, tutkimusraportti 001/3321 12D/HOP/1994, 91 p. (in Finnish).

Puustjärvi, H. (ed.), 1999. Pyhäsalmi modeling project. Technical Report. 13.5. 1997-12. 5. 1999. Geologian tutkimuskeskus, arkistoraportti, M19/3321/99/1/10, 251 p.

Pyhäsalmi mine website, 2025, cited on 2.6.2025, https://www.pyhasalmimine.fi/kaivoksen-tuotanto/

Rasilainen, K., Eilu, P., Halkoaho, T., Karvinen, A., Kontinen, A., Kousa, J., Lauri, L., Luukas, J., Niiranen, T., Nikander, J., Sipilä, P., Sorjonen-Ward, P., Tiainen, M., Törmänen, T. & Västi, K., 2014. Quantitative assessment of undiscovered resources in volcanogenic massive sulphide deposits, porphyry copper deposits and Outokumpu-type deposits in Finland. Geological Survey of Finland, Report of Investigation 208, 60 p.

Roberts, M. D., Oliver, N. H. S. & Lahtinen, R., 2004. Geology, lithogeochemistry and paleotectonic setting of the host sequence to the Kangasjärvi Zn-Cu deposit, Central Finland: implications for volcanogenic massive sulphide exploration in the Vihanti-Pyhäsalmi district. Bulletin of the Geological Society of Finland 76, 31–62. https://doi.org/10.17741/bgsf/76.1-2.003

Rosa, C. J. P., McPhie, J., Relvas, J. M. R. S., Pereira, Z., Oliveira, T. & Pacheco, N., 2008, Facies analyses and volcanic setting of the giant Neves Corvo massive sulfide deposit, Iberian Pyrite Belt, Portugal. Mineralium Deposita 43, 449–466. https://doi.org/10.1007/s00126-008-0176-4

Rosa, C. J. P., McPhie, J. & Relvas, J. M. R. S., 2010. Type of volcanoes hosting the massive sulfide deposits of the Iberian Pyrite Belt. Journal of Volcanology and Geothermal Research 194, 107–126. https://doi.org/10.1016/j.jvolgeores.2010.05.005

Ross, P.-S. & Mercier-Langevin, P., 2014. Igneous Rock Associations 14. The Volcanic Setting of VMS and SMS Deposits: A Review. Geoscience Canada 41, 365–377. https://doi.org/10.12789/geocanj.2014.41.045

Ross, P-S., Boulerice, A., Mercier-Langevin, P. & McNicoll, V., 2020. Volcanology, chemo-stratigraphy, geochronology, hydrothermal alteration and VMS potential of the Lemoine Member of the Waconichi Formation, Chibougamau district, Abitibi greenstone belt, Québec. Mineralium Deposita 55, 21–46. https://doi.org/10.1007/s00126-019-00884-6

Schlatter, D. M., 2007. Volcanic stratigraphy and hydrothermal alteration of the Petiknäs South Zn-Pb-Cu-Au-Ag Volcanic-hosted Massive Sulfide Deposit, Sweden. PhD Thesis, Luleå University of Technology, Sweden, 35 p.

Shanmugam, G., 2019. Slides, Slumps, Debris Flows, Turbidity Currents, Hyperpycnal Flows, and Bottom Currents. In: Cochran, J. K., Bokuniewicz, H. J. & Yager, P. L. (ed.), Encyclopedia of Ocean Sciences, 3rd Edition. Elsevier, pp. 228–257. https://doi.org/10.1016/B978-0-12-409548-9.10884-X

Simán, F., Jansson, N., Liwicki, F. S., Nordfeldt, E., Persson, M. F., Albrecht, L., Günther, C. & McDonnell, P., 2025. Stratigraphy, facies, and chemostratigraphy at the Palaeoproterozoic Rävliden North Zn-Pb-Ag-Cu VMS deposit, Skellefte district, Sweden. Ore Geology Reviews, 178, 106489. https://doi.org/10.1016/j.oregeorev.2025.106489

Simpson, K. & McPhie, J., 2001. Fluidal-clast breccia generated by submarine fire fountaining, Tropper Creek Formation, Queensland, Australia. Bulletin of Volcanology and Geothermal Research 109, 339–355. https://doi.org/10.1016/s0377-0273(01)00199-8

Soriano, C. & Marti, J., 1999. Facies analysis of volcano-sedimentary successions hosting massive sulfide deposits in the Iberian Pyrite Belt, Spain. Economic Geology 94, 867–882. https://doi.org/10.2113/gsecongeo.94.6.867

Strand, K., 2002. Volcanogenic and sedimentary rocks within the Svecofennian Domain, Ylivieska, western Finland—an example of Palaeoproterozoic intra-arc basin fill. In: Altermann, W. & Corcoran, P. L. (ed.), Precambrian Sedimentary Environments: A Modern Approach to Ancient Depositional Systems. International Association of Sedimentologists, pp. 339–350. https://doi.org/10.1002/9781444304312.ch15

Stow, D. A. V., Taira, A, Ogawa, Y., Soh, W., Taniguchi, H. & Pickering, K. T., 1998. Volcaniclastic sediments, process interaction and depositional setting of the Mio-Pliocene Miura Group, SE Japan. Sedimentary Geology 115, 351–381. https://doi.org/10.1016/s0037-0738(97)00100-0

Stow, D. A. V. & Johansson, M.D., 2000. Deep-water massive sands: nature, origin and hydrocarbon implications. Marine and Petroleum Geology 17, 145–174. https://doi.org/10.1016/s0264-8172(99)00051-3

Stow, D. A. V., Huc, A.-Y. & Bertrand, P., 2001. Depositional processes of black shales in deep water. Marine and Petroleum Geology 18, 491–498. https://doi.org/10.1016/s0264-8172(01)00012-5

Stow, D. & Smilie, Z., 2020. Distinguishing between Deep-Water Sediment Facies: Turbidites, Contourites and Hemipelagites. Geosciences 10, 68. https://doi.org/10.3390/geosciences10020068

Syme, R., 2007. Evolution of the Paleoproterozoic Flin Flon Belt and lithotectonic association of VMS deposits. VMS Short Course, November 15, 2007. Manitoba Geological Survey.

Tornos, F., 2006. Environment of formation and styles of volcanogenic massive sulfides–The Iberian Pyrite Belt. Ore Geology Reviews 28, 259–307. https://doi.org/10.1016/j.oregeorev.2004.12.005

Tornos, F., Peter, J. M., Allen, R. & Conde, C., 2015, Controls on the siting and style of volcanogenic massive sulphide deposits. Ore Geology Reviews, 68, 142–163. https://doi.org/10.1016/j.oregeorev.2015.01.003

Västi, K, 1989. Geology of the the Rauhala stratifrom massive Zn-Cu-Pb sulphide deposit. In: Kojonen, K. (ed.), The early Proterozoic Zn-Cu-Pb sulphide deposit of Rauhala in Ylivieska, western Finland. Geological Survey of Finland, Special Paper 11, 92 p.

Weihed, P., Weihed, J.B., Sorjonen-Ward, P. & Matsson, B., 2002. Post-deformation, sulphide-quartz vein hosted gold ore in the footwall alteration zone of the Palaeoproterozoic Långdal VHMS deposit, Skellefte District, northern Sweden. GFF 124, 201–210. https://doi.org/10.1080/11035890201244201