Otanmäki Excursion Guidebook

Kimmo Kärenlampi

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Cover figure: Otanmäki mine main hoist tower.

CONTENTS

1 INTRODUCTION

The Otanmäki area in central Finland has been subject of geological research since the gabbro-anorthosite hosted Otanmäki Fe-Ti-V oxide deposit was discovered in the late 1930s (Pääkkönen, 1943; 1956; Paarma, 1954; Kerkkonen, 1979; Lindholm and Anttonen, 1980; Nykänen, 1995; Huhma et al., 2018; Mäkisalo, 2019). This deposit is associated with a 2.06 Ga mafic intrusion intruded into Archean TTG basement gneisses. The Otanmäki deposit was mined between 1953–1985 and was an important global producer of vanadium during its operation (Kuivasaari et al., 2012). In total, 30 Mt of ore was mined grading 32–34% Fe, 5.5–7.6% Ti, and 0.26% V (Puustinen, 2003). Remaining resources at Otanmäki are still significant, as they are indicated to be 24 Mt of ore @ 28% Fe, 10% Ti, 0.21% V (Hokka and Lepistö, 2019).

The Otanmäki area is also of significance in that it records a rare occurrence of non-orogenic, ca. 2.05 Ga, A-type granites and related intermediate igneous rocks (Kärenlampi et al., 2019; Kärenlampi, 2021). These A-type rocks represent magmatism related to continental break-up of the Archean Karelia continent, which led eventually to the development of a continental passive margin and a nascent ocean basin, as witnessed by the 1.95 Ga Jormua ophiolite complex located 40 km to the northwest of Otanmäki. The Otanmäki suite A-type granites are also of special economic interest, as they contain significant rare earth element (REE), and high-field strength element (HFSE) enrichments (Kärenlampi et al., 2020).

In this excursion guidebook, the geology of the Otanmäki area is reviewed with an emphasis on the Otanmäki Fe-Ti-V deposit and REE-HFSE occurrences. The descriptions given below are based on available literature as well as field and drill core observations gathered by the author between 2016–2019. The locations and coordinates of suggested excursion stops are shown in Fig. 1 and Table 1 and short descriptions of each stop are given in the chapters below.

Table 1. List of excursion stops.

N:o	X-KKJ3	Y-KKJ3	Target	Location
1	3507284	7112879	Marginal amphibolite, Otanmäki intrusion, Otanmäki block	Rytisuo
2	3508320	7112246	Vari-textured gabbro, Lower Zone, Otanmäki intrusion, Vuorokas block	Rinneaho
3	3507827	7111729	Vari-textured gabbro and isotropic gabbro, Lower Zone, Otanmäki intrusion, Vuorokas block	Rinneaho quarry
4	3509148	7113015	Fe-Ti-V oxide ore, Ore Zone, Otanmäki intrusion, Vuorokas block	Vuorokas
5	3506198	7113416	Fe-Ti-V oxide ore, Ore Zone, Otanmäki intrusion, Otanmäki block	Metsämalmi
6	3508305	7112685	Gabbro and anorthosite autoliths, Upper Zone, Otanmäki intrusion, Vuorokas block	Vuorokas
7	3505349	7113367	Gabbro and anorthosite autoliths, Upper Zone, Otanmäki intrusion, Otanmäki block	Otanmäki hill
8	3502197	7115376	Kontioaho REE-HFSE mineralization, Otanmäki suite A-type granites	Luodesuo
9	3501106	7114223	Katajakangas REE-HFSE mineralization, Otanmäki suite A-type granites	Pieni-Katajakangas

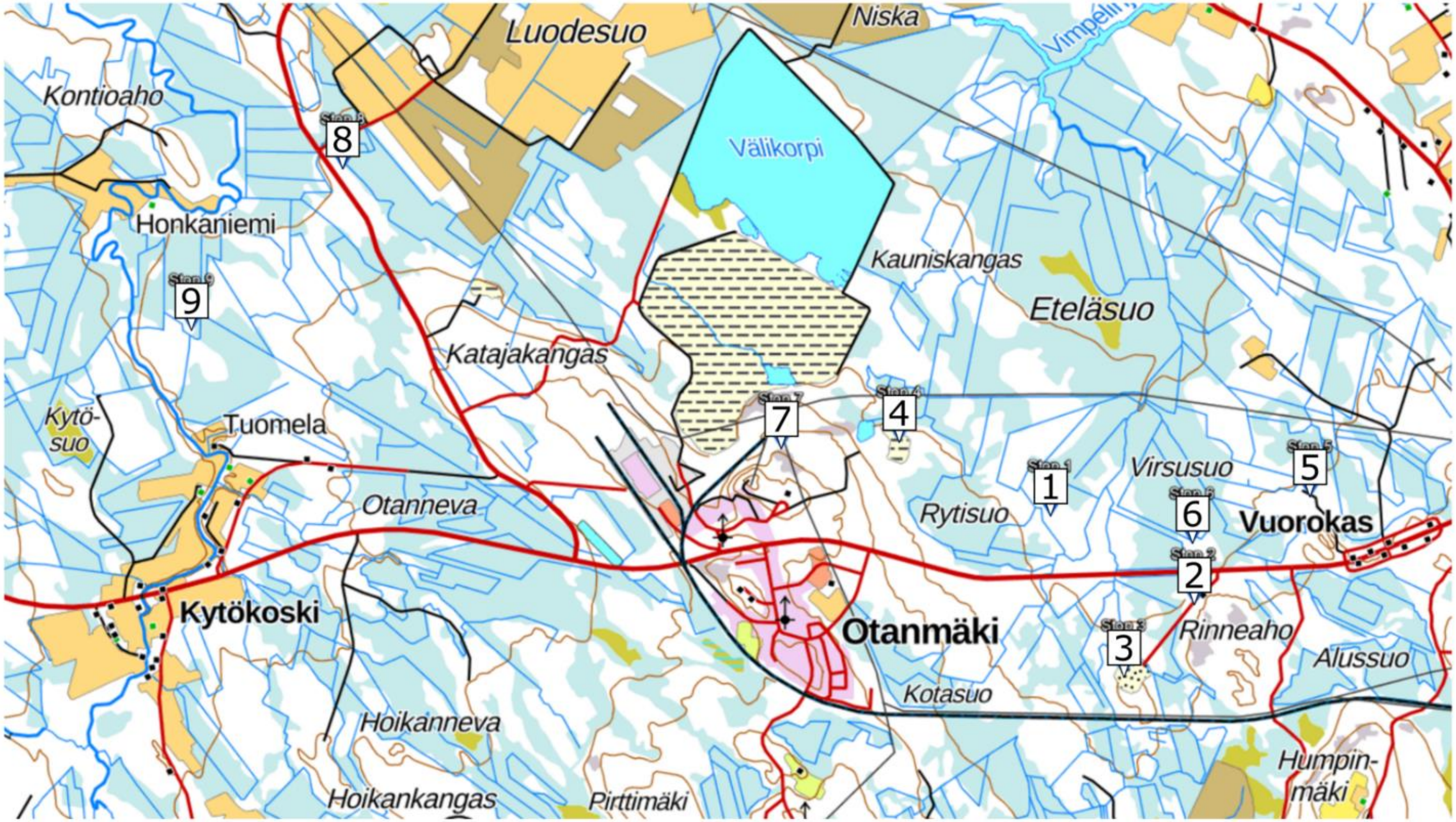

Figure 1. Location of excursion stops in the Otanmäki area (Basemap ©Maanmittauslaitos 2021).

2 GEOLOGICAL SETTING

The Otanmäki area is located at the southwestern margin of the Archean Karelia craton, central Fennoscandian Shield, just 20–75 km to the east of the major tectonic boundary between the Paleoproterozoic Svecofennian domain and the Karelia craton (Fig. 2a). The long geological history of the region involves at least four major tectonic stages: 1) Archean orogeny at ca. 2.6–2.8 Ga, 2) a period of cratonization, sedimentation, and extensional tectonics between ca. 2.0 and 2.5 Ga, 3) subsequent continental break-up of the Karelia craton between ca. 1.95 and 2.0 Ga, and 4) tectonic reworking in connection with the Svecofennian orogenesis (Laajoki, 2005; Lahtinen et al., 2010, 2015; Hölttä et al., 2012a,b). The present structural configuration of the area largely reflects the reworking during the Svecofennian collisional orogeny, which initiated at ca. 1.9 Ga and involved several stages of compressional folding and thrusting, resulting in burial of the southwestern margin of the Karelia craton under a massive overthrust complex transported from the west-southwest (e.g., Kontinen et al., 1992, Lahtinen et al., 2015; Hölttä et al., 2019a).

The Karelia craton margin around Otanmäki is composed mostly of ca. 2.6–3.2 Ga TTG migmatite-gneiss complexes and Paleoproterozoic cover sequences, with the latter being represented by the Karelian formations of the Kainuu belt (Fig. 2b; Laajoki, 2005, Hölttä et al., 2012a,b, 2019b). The supracrustal sequence of the Kainuu belt is traditionally divided into three main unconformity-separated units, Sumi-Sariola, Jatuli, and Kaleva (Laajoki, 2005; Lahtinen et al., 2015; Kontinen and Hanski, 2015). The supracrustal rocks of the Kainuu belt flanking the Otanmäki area in the east belong to the Jatulian (2.1–2.3 Ga) and Kalevian (1.9–2.1 Ga) formations. The Jatuli consists of cratonic-epicratonic deposits, and the Kaleva includes both rift-phase marine basin deposits (Lower Kaleva) and oceanic basin deposits (Upper Kaleva). The Upper Kaleva metawackes differ from the older, autochthonous sedimentary rocks derived dominantly from Archean sources in having a major Paleoproterozoic (1.92–2.0 Ga) detrital zircon population (Lahtinen et al., 2010). These wackes enclose fragments of mantle and oceanic crust, with the largest of them forming the 1.95 Ga Jormua ophiolite complex (Kontinen, 1987; Peltonen and Kontinen, 2004; Peltonen et al., 2008). The Upper Kaleva sediments and enclosed ophiolites have been interpreted as an allochthonous complex, which was thrust on the Karelia craton margin at ca. 1.9 Ga (Kontinen, 1987; Peltonen et al., 2008).

The area around Otanmäki also records several Paleoproterozoic magmatic episodes (Fig. 2b) as it contains a 2.44 Ga PGE-reefed layered intrusion (Junttilanniemi intrusion; Halkoaho and Niskanen, 2013), 2.3 Ga mafic-ultramafic intrusions (Kapustakangas suite; Huhma et al., 2018), 2.2–2.1 Ga mafic dikes and volcanic rocks (Huhma et al., 2018), 2.06 Ga Fe-Ti-V magnetite-ilmenite ore-bearing mafic intrusions (Otanmäki intrusive complex; Huhma et al. 2018; Mäkisalo, 2019), and ca. 2.05 Ga A1-type felsic to intermediate intrusions (Otanmäki suite; Kärenlampi et al., 2019, 2021) and at least two major episodes of late Svecofennian granitic magmatism, at ca. 1.86 and 1.80 Ga.

The Svecofennian metamorphic conditions in the Otanmäki area are estimated to have attained peak temperatures of ~550–600 ºC and a pressure of about ~4.0 kbar (bathograd estimates, garnet-biotite thermometry, and garnet-biotite-sillimanite-quartz barometry; Kärenlampi et al., 2019). The most plausible explanation to the observed Svecofennian heating is tectonic burial of the presently exposed rocks to depths of 15–20 km in association with the 1.8–1.9 Ga folding and thrusting event, although igneous underplating could have been an additional factor (Kontinen et al., 1992, 2013b,c; Tuisku, 1997; Korsman et al., 1999; Pajunen and Poutiainen, 1999; Kontinen, 2002; Kontinen and Paavola, 2006; Lahtinen et al., 2010, 2015). The peak-T conditions are considered to have occurred between ca. 1.87 Ga and 1.85 Ga, although the heating was protracted, with temperatures falling below ~500 ºC only after 1.80 Ga (Kontinen et al., 1992; Vaasjoki et al., 2001; Hölttä et al. 2019a).

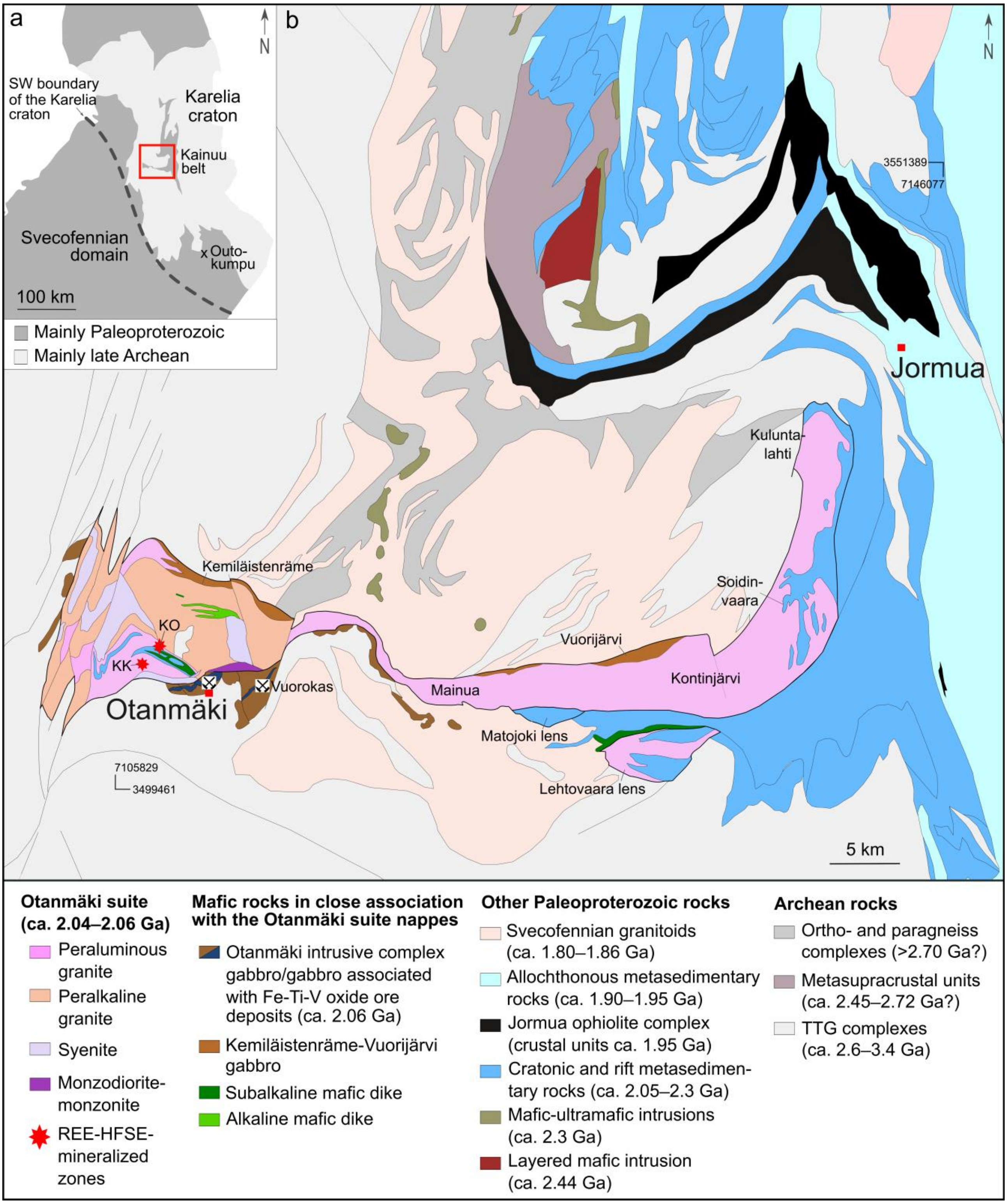

Figure 2. a) Location of the Otanmäki area (red rectangle) close to the SW margin of the Archean Karelia craton. b) Map showing the geological setting of the Otanmäki area (modified after Kärenlampi et al., 2021). Also shown are the locations of the closed Otanmäki and Vuorokas Fe-Ti-V mines. KO = Kontioaho and KK = Katajakangas.

3 ROCK UNITS AT OTANMÄKI

The bedrock of the Otanmäki area can be divided into three main units: 1) Archean rocks, 2) ca. 2.06 Ga Fe-Ti-V oxide ore bearing mafic intrusive rocks of the Otanmäki intrusive complex, and 3) ca. 2.04–2.06 Ga Otanmäki suite gneissic A1-type granites and intermediate rocks (Figs. 2b and 3).

3.1 Archean rocks

The Archean complexes in the Otanmäki area are mostly composed of TTG (tonalite-trondhjemite-granodiorite) gneisses, which belong to the of Manamansalo (ca. 2.6–2.7 Ga) and Iisalmi (ca. 2.6–3.2 Ga) Archean complexes (Hölttä et al., 2012, 2019b). At Otanmäki, the TTGs are migmatitic, biotite-bearing and contain occasional amphibolite or biotite-plagioclase gneiss mesosomes. They area also frequently intruded by metadiabase dikes. Archean migmatic amphibolite gneisses and mylonitized leucogranites have also been found occurring in a 2x3-km-sized block within the Otanmäki suite A1-type igneous rocks in the Luodesuo area (Kärenlampi et al., 2019; Fig. 3).

3.2 Otanmäki intrusive complex

The term ‘Otanmäki intrusive complex’ is used to cover the Otanmäki mafic intrusion and the six smaller satellite intrusions of mafic composition (Pentinpuro, Isonkivenkangas, Hautakangas, Itäranta, Koski, and Mäkrö) known within a 15-km radius from Otanmäki (Mäkisalo, 2019; Figs. 3 and 4). These intrusions host oxide ore bodies as lenses within gabbroic to anorthositic wall rocks. Structurally, they are in a similar position between Archean TTG gneisses and Otanmäki suite A-type rocks, forming together a discontinuous semi-circle at the margin of the Archean complexes (Fig. 3). This likely denotes that they represent the same magmatic event, although only the Otanmäki intrusion has been dated (2058 ± 15 Ma; Huhma et al., 2018). Also, at the northern contact between Otanmäki suite A1-type rocks and Archean gneisses lies the Kemiläistenräme mafic unit (Kärenlampi et al., 2019; Figs. 2b and 3). This lenticular, NW-SE-trending body consists of strongly sheared metagabbroic gneisses and has been traditionally grouped together with the Otanmäki gabbros, but it is not known to contain oxide ore mineralization and is relatively nonmagnetic on aeromagnetic anomaly maps (Fig. 4) unlike the ca. 2.06 Ga Otanmäki intrusion and its satellites.

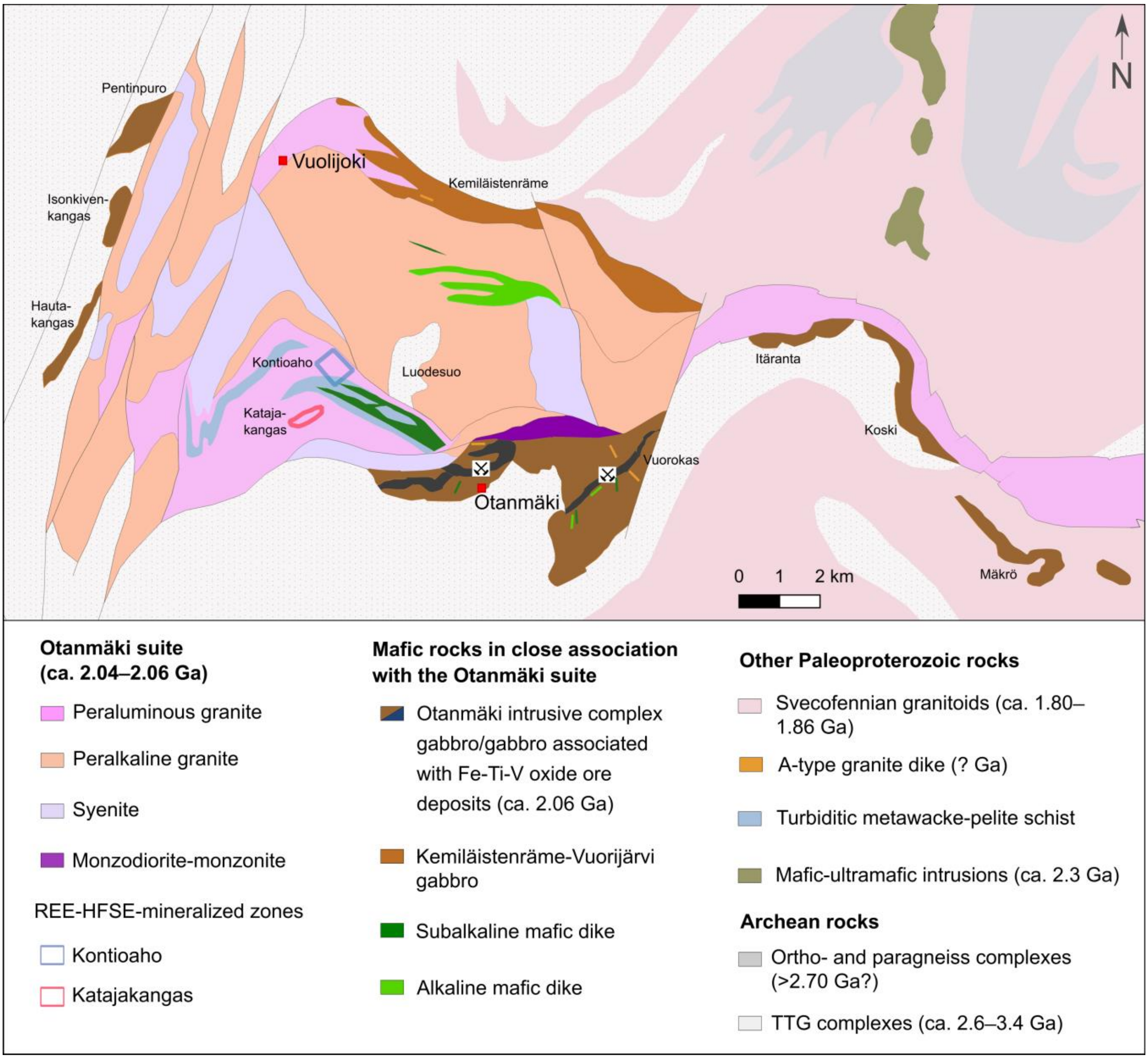

Figure 3. Geological map of the Otanmäki area (modified after Kärenlampi et al., 2019, 2020). Also shown are the locations of Otanmäki and Vuolijoki villages, Otanmäki and Vuorokas closed Fe-Ti-V mines, and Kontioaho and Katajakangas REE-HFSE-mineralized zones.

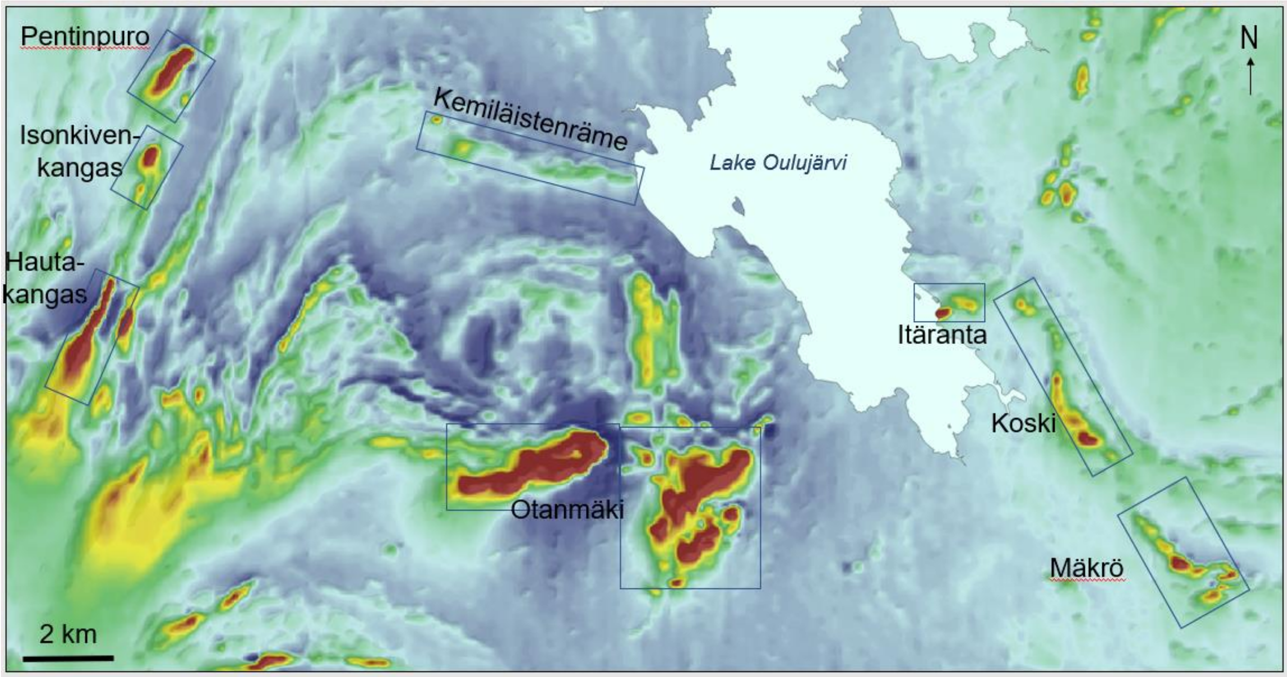

Figure 4. Aeromagnetic anomaly map (Otanmäki Mine Oy) of the Otanmäki area showing the Otanmäki Fe-Ti-V oxide ore bearing mafic intrusion and the six satellite intrusions (Pentinpuro, Isonkivenkangas, Hautakangas, Itäranta, Koski, and Mäkrö), and the lenticular Kemiläistenräme mafic unit.

3.3 Otanmäki suite

The Otanmäki suite records an uncommon occurrence of non-orogenic felsic to intermediate plutonism at the Archean Karelia craton without any clear counterpart elsewhere in the Fennoscandian Shield (Kärenlampi et al., 2019). This suite contains various rock types composed of peralkaline to peraluminous granites and related intermediate rocks, including syenite and monzodiorite-monzonite (Figs. 2b and 3). They show major and trace element characteristics similar to those of continental rift-related A-type granites (Kärenlampi et al., 2019). More precisely, they belong to the A1-type of Eby (1992) interpreted to result from differentiation of ocean island basalt (OIB)-like mantle-derived magmas (see Kärenlampi et al., 2019, 2021). The age of the Otanmäki suite magmatism has been constrained by U-Pb zircon dating of the granitic members, producing ages between 2040 and 2060 Ma, including a precise magmatic age of 2050 ± 2 Ma (Kärenlampi et al., 2019). These dates demonstrate that the magmatism took place during the 2.1–2.05 Ga rifting stage, which involved major rifting of the Karelia continent and eventually led to break-up at its western margin (e.g., Lahtinen et al., 2015).

The question of the original geologic setting of the Otanmäki suite is challenging because the A1-type plutons were disintegrated and metamorphosed under during the Svecofennian collisional orogeny (ca. 1900 Ma), i.e., 150–200 Ma after their initial emplacement. Consequently, the A1-type rocks are pervasively gneissic and occur in a lens-shaped, 3x8-km-sized body (Lehtovaara lens) and a 60-km-long, E- to W-trending thrust sheet (Otanmäki-Kuluntalahti nappe), both being nappes with faulted boundaries against the surrounding Archean TTG complexes and Paleoproterozoic units of the Kainuu belt (Fig. 2b). The eastern parts of the Otanmäki-Kuluntalahti nappe and the lens-shaped body are dominated by peraluminous granite, which appear to have been emplaced at a shallow crustal depths, as it has locally intrusive contact relationships with supracrustal rocks that resemble the Paleoproterozoic cover rocks deposited on the Karelia craton (Kärenlampi et al., 2019). The westernmost part of the Otanmäki-Kuluntalahti nappe (closest to Otanmäki area, Fig. 2b), consists mainly of peralkaline granite and associated syenite and monzodiorite-monzonite, which are mingled with blocks of peraluminous granite (Figs. 3 and 5). The Otanmäki REE-HFSE mineralization occurs within peraluminous granite wall rocks, but its origin is proposed to be related to nearby peralkaline granite (see Chapter 5; Kärenlampi et al., 2020).

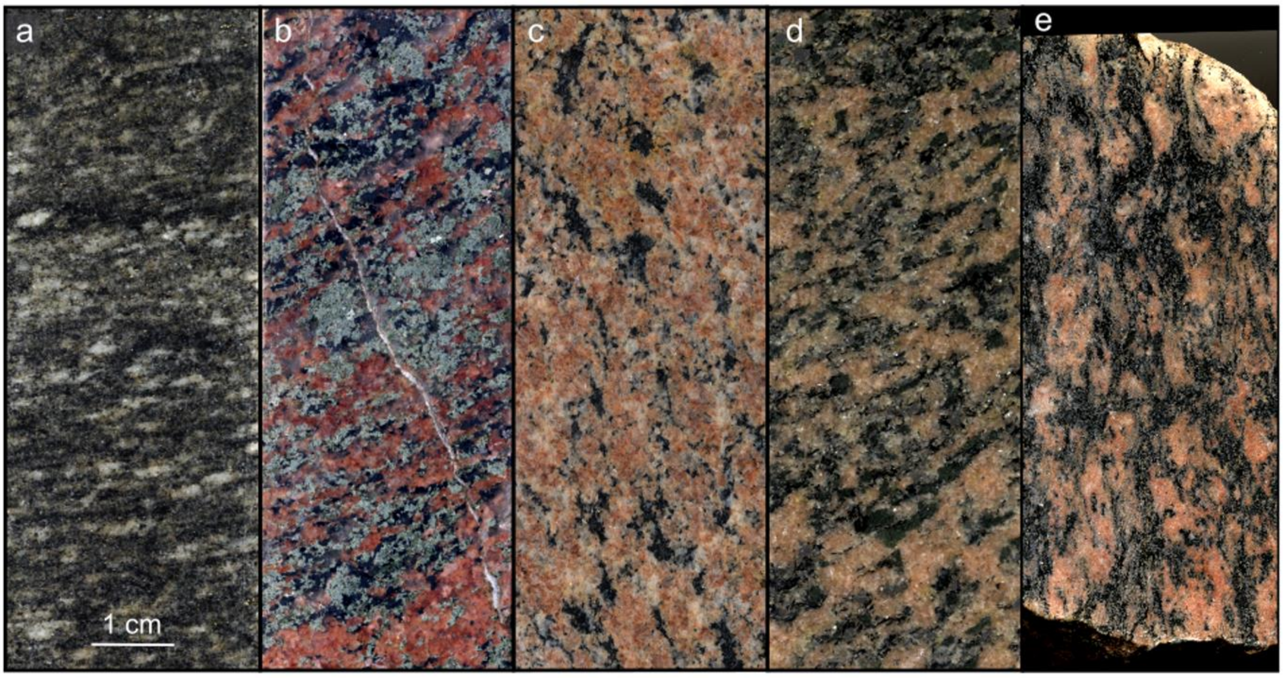

Figure 5. Photographs of polished slabs of typical Otanmäki suite granites and related intermediate rocks found in the Otanmäki area. a) Peraluminous granite containing biotite and feldspar phenocrysts, b) peralkaline granite containing aegirine and alkali amphibole, c) peralkaline granite containing aegirine-augite and amphibole, d) syenite containing clinopyroxene and amphibole, e) monzonite containing biotite and amphibole. Scale in all photos (a–e) as in a).

3.4 Mafic and felsic dikes

Several mafic dikes from few meters to tens of meters in width crosscut the main rock units in the Otanmäki area, including the Archean basement gneisses, Otanmäki suite A-type rocks, and Otanmäki intrusion complex mafic intrusive rocks (Fig. 3; Kärenlampi et al., 2019; 2021). Metadiabase dikes with subalkaline, Fe-tholeiitic affinities are met frequently within the Archean gneisses. The gabbros and A-type rocks are cut by subalkaline and alkaline mafic dikes with unknown ages. The subalkaline dikes show Fe-tholeiitic chemical affinity whereas the alkaline mafic dikes have an OIB-like chemical signature (Kärenlampi et al., 2021). The gabbros of the Otanmäki intrusion are also cut by meter wide granite dikes with an A-type granite trace element chemistry, but they have not been dated, rendering it unclear whether they belong to the Otanmäki suite (Kärenlampi et al., 2019). Smaller pegmatite granite dikes with a width anything between few cm to few m are also locally met cutting all older rock units. These dikes are likely late Svecofennian in age (ca. 1.80 Ga), as they are mostly undeformed.

4 OTANMÄKI Fe-Ti-V OXIDE DEPOSIT

4.1 Exploration and mining history

The first indications of the Otanmäki Fe-Ti-V oxide deposit were made in 1937, when two glacial boulders of magnetite-ilmenite ore, containing up to 53% Fe and 10% Ti, were found in Sukeva by two field assistants of Geological Survey of Finland (GTK), about 40 km southeast of Otanmäki (Pääkkönen, 1956). In 1938, the source of the ore boulders was located by ground magnetic survey to the remote Otanmäki hill, where the Otanmäki magnetite-ilmenite deposit was discovered. Further exploration revealed several smaller magnetite-ilmenite deposits in the satellite intrusions around Otanmäki (Pääkkönen, 1956). The state-owned company Otanmäki Oy was founded to exploit the Otanmäki deposit. Later Otanmäki Oy was merged with the state-owned steel producer Rautaruukki Oy.

The Otanmäki mine operated from 1953 till 1985 and total production was 7.6 Mt iron concentrates, 3.8 Mt ilmenite, 0.2 Mt sulfide concentrates and 55 545 tons of vanadium pentoxide (V_2O_5) (Otanmäki Mine Oy, 2017). Almost all mining was underground, as only some 250 000 tons were mined open pit. The Otanmäki mine consists of 975 kilometers of drilling, three shafts (Otanmäki, Suomalmi, and Vuorokas), and 125 kilometers of tunnels (Otanmäki Mine Oy, 2017). The mining method used at the beginning was shrinkage stoping, but after the 1970s mining operations moved to sublevel stoping. All processing was done in a mineral processing plant built near the mine. Processing included underground primary crushing, hoisting of ore to the secondary crusher on the ground level, two-stage milling, dry magnetic separation, wet magnetic separation (magnetite removal) and two stage flotation to produce ilmenite and pyrite concentrates. The mining operation also included a on site vanadium factory, which produced vanadium pentoxide from the magnetite concentrate.

4.2 Geology of the Otanmäki intrusion

The ca. 2.06 Ga Otanmäki mafic intrusion is hosted in Archean TTG-series gneisses (Figs. 3 and 6). The intrusive body was foliated and metamorphosed under amphibolite facies conditions during the Svecofennian orogeny (1.9–1.8 Ga). It is divided into three major blocks, Otanmäki, Vuorokas and Otanneva, which have mostly fault contacts against the surrounding Archean TTG gneisses and ca. 2.05 Ga A-type granites and intermediate igneous rocks (Fig. 6). Each block bears laterally continuous oxide ore zones, which are remarkably voluminous in relation to the small size of the whole gabbroic body (Fig. 6).

The Otanmäki and Otanneva blocks cover an area of 1.4 and 1.6 km^2, respectively, while the Vuorokas block extends over an area of 7 km^2. The Otanmäki block is known to extend at least to a depth of 800 m (Lindholm and Anttonen, 1980), but geophysical modelling suggests that the whole intrusion may continue at least to a depth of 2 km and occupy an approximate volume of 5 km^3 (Lahti et al., 2018). The area between Otanmäki and Vuorokas is complexly faulted and may consist of several smaller tectonic units (Mäkisalo, 2019). The contacts of the Otanmäki intrusion to its Archean country rocks are presumably fault bound apart from a small area at Vuorokas (Mäkisalo, 2019). In the north, the Otanmäki intrusion and Otanmäki suite A-type rocks are in a near vertical fault contact, which is traced to depth of 500 m.

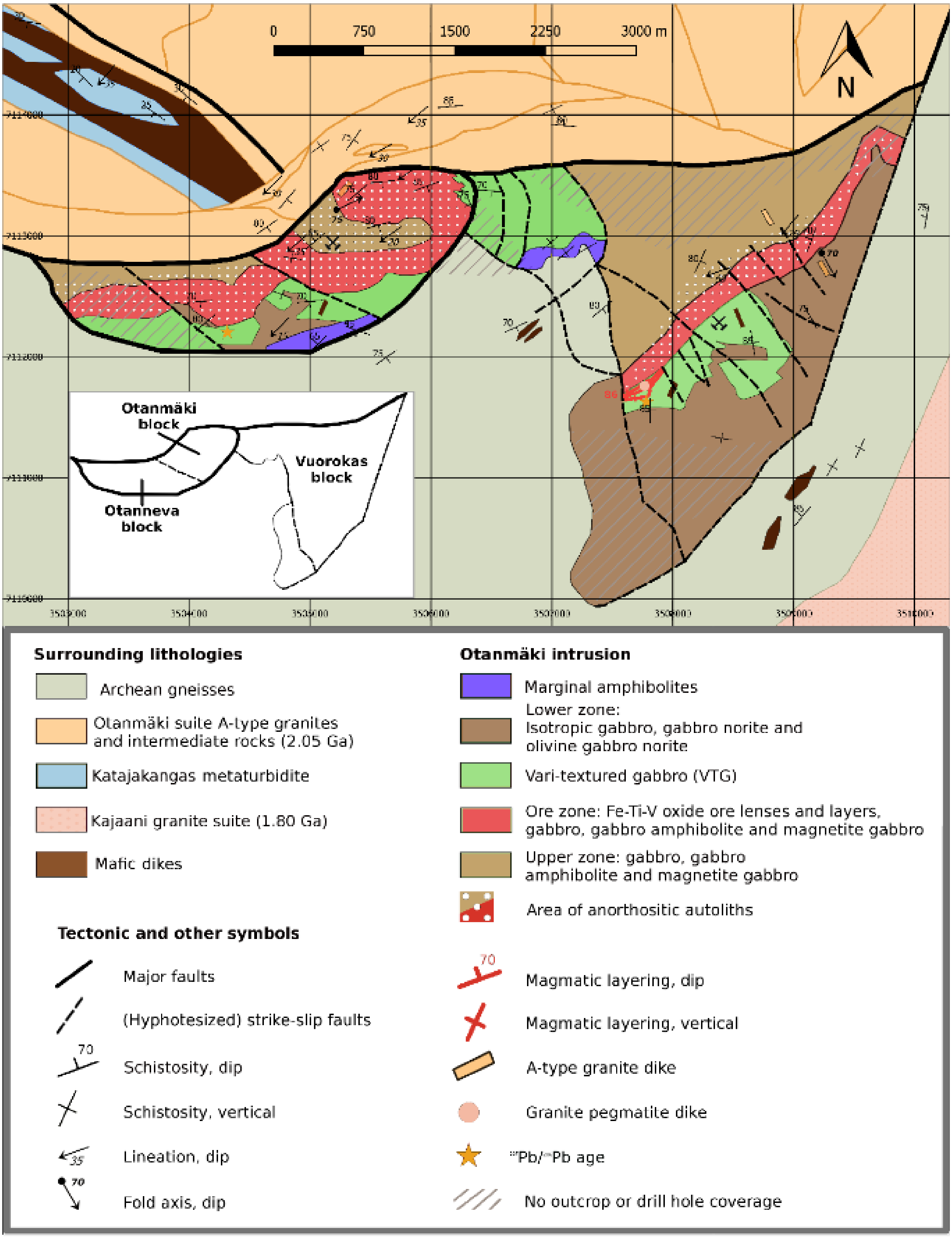

Figure 6. Geological map of the Otanmäki intrusion (Mäkisalo, 2019).

4.2.1 Structure of the Otanmäki intrusion

The Otanmäki intrusion has been historically referred to as a 'layered intrusion' (e.g., Kerkkonen, 1979; Nykänen, 1995). It has a differentiated, even layer-like structure, with the most prominent feature being the continuous, 30- to 200-m-wide oxide ore zone that extends through the whole intrusion. Furthermore, the Otanmäki intrusion shows evidence for the enrichment of Fe and Ti in the upper part of the magma chamber, which is typical to layered intrusions, as well as the occurrence of anorthosites in the upper parts (e.g., Maier, 2015). However, the Otanmäki intrusion lacks well-developed layering and a continuous stratigraphic horizon often associated with layered intrusions – if the heterogenous oxide ore zones are not regarded as such. Therefore, to avoid misinterpretation, the term "differentiated mafic intrusion" is preferred (Mäkisalo, 2019).

Based on field and petrographic observations, the Otanmäki intrusion can be divided into three major units, the Lower Zone, the Ore Zone, and the Upper Zone (Figs. 6 and 7; Mäkisalo, 2019). The rocks at the Lower Zone have relatively well-preserved magmatic mineral compositions and textures, but in the Ore Zone and Upper Zone, the rocks are foliated and show metamorphic mineral assemblages.

The Lower Zone consists of mostly of isotropic gabbro, which are associated with variable sized bodies of pegmatoidal vari-textured gabbro. The term vari-textured gabbro (also: varied-textured gabbro and VTG) has been applied at Otanmäki to all leucocratic gabbroic rocks that are anorthositic to leucogabbroic and show a large variation in grain size and color index on an outcrop scale and no clear modal layering.

The Lower Zone isotropic gabbros and VTGs have a sharp contact with the Ore Zone, which comprises semi-massive to massive oxide ore lenses and layers, gabbro, magnetite gabbro, and gabbro amphibolite. The Ore Zone rock assemblage changes progressively into the Upper Zone, which has the same assemblage (except oxide ore), but isotropic gabbro dominates. Both the Ore and Upper Zone portray occasional modal layering. Anorthositic autoliths of 1–30 meters in diameter are met throughout the Ore Zone and Upper Zone. Fine-grained marginal amphibolites, potentially representing chilled margins, are locally met at the intrusion borders.

4.2.2 Marginal amphibolite

Fine-grained, dark amphibolites have been observed at two locations between the Archean gneisses and Lower Zone gabbros and are referred to as marginal amphibolites (Figs. 6 and 7; Mäkisalo, 2019). They are superficially similar to the multiple diabase dikes in the Otanmäki area, but lack a diabasic texture and instead show pervasively recrystallized and variably sheared texture. The rock-forming minerals of the marginal amphibolites are amphiboles, minor plagioclase and accessory pyrite and Fe-Ti oxides (Mäkisalo, 2019). Based on their similar mineral composition with the Lower Zone gabbros, they are regarded as belonging to the Otanmäki intrusion and possibly representing a lower chilled margin of the magmatic body (Mäkisalo, 2019).

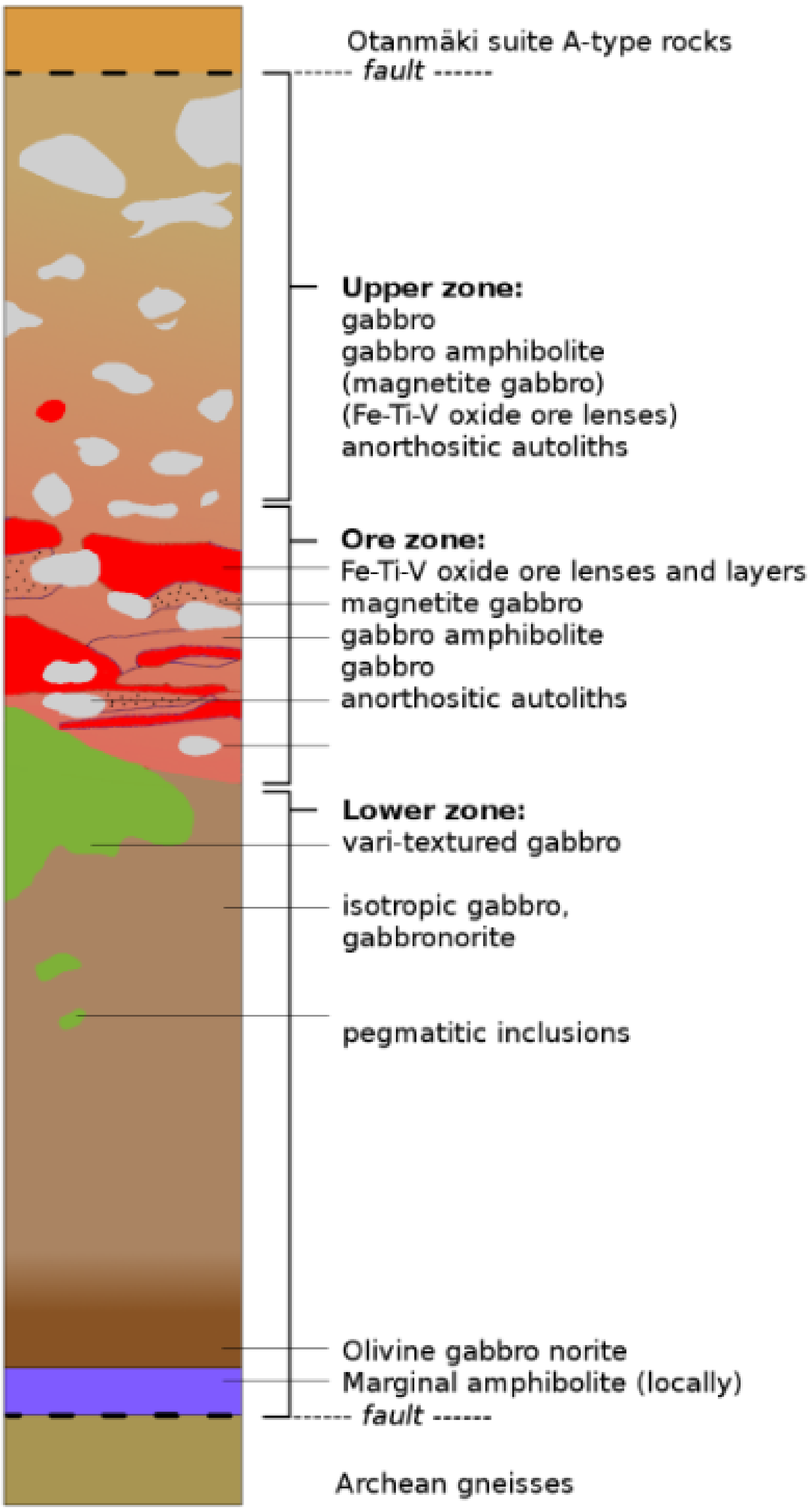

Figure. 7. Schematic magmatic stratigraphy in the Otanmäki intrusion (not to scale) (Mäkisalo, 2019).

A group of marginal amphibolite outcrops at Rytisuo (**Stop 1**. Y: 7112879, X: 3507284) is the only location where contacts of the Otanmäki intrusion and the adjacent TTG gneisses can be pinned down with an accuracy of a few meters. The contact is regarded as untectonized as the Vuorokas marginal amphibolites show relatively little tectonic strain (Mäkisalo, 2019). However, the degree of tectonic strain in the rocks is observed to increase steadily when moving N-NW towards the Otanmäki block, culminating to gneissose foliation at its margin near the Metsämalmi area (Mäkisalo, 2019).

4.2.3 Lower Zone

The Lower Zone is best exposed at the southern part of the Vuorokas block (at Rinneaho), which has many well exposed outcrops of isotropic, medium- to coarse-grained gabbros. The rocks in the Vuorokas Lower Zone vary from moderately schistose to non-schistose and have the best-preserved magmatic features, with primary plagioclase and occasional ortho- and clinopyroxene (Nykänen, 1995; Mäkisalo, 2019). The Lower Zone rocks usually show gabbronoritic mineral assemblage and are meso- and adcumulates with occasional disseminated ilmenite (Nykänen, 1995; Mäkisalo, 2019). In the Lower Zone gabbros, plagioclase often shows igneous lamination (subparallel alignment of tabular plagioclase crystals) and also in places even few tens of meter thick units with meter-scale rhytmic modal layering are observed (see **Stop 3**).

The Lower Zone gabbros at Rinneaho are regularly spotted by pegmatitic inclusions few decimeter to few meter in diameter with clear defined borders and a similar texture to the vari-textured gabbros in the Lower Zone (Mäkisalo, 2019). The vari-textured gabbros are a voluminous rock type in the upper parts of the Lower Zone, especially at Vuorokas. The variable grain size and mineral proportions in the VTGs appear usually on an outcrop scale of few meters. The degree of textural variation, however, fluctuates from place to place and results in some level of uncertainty when discriminating between Lower Zone gabbros and VTGs: a small outcrop of seemingly isotropic gabbro might just be a local, more homogenous fraction of VTG. Microscopic examination of Rinneaho VTGs reveals large primary plagioclase crystals, which are recrystallized at crystal margins (Mäkisalo, 2019). The VTGs display ad-, meso- and orthocumulate textures (Mäkisalo, 2019) and sometimes plagioclase lamination. Primary mafic minerals are rare; few samples contain primary bronzite (Mäkisalo, 2019). Amphibole group minerals typically constitute an intercumulus groundmass composed of cryptocrystalline to 1.0-mm-sized grains (Mäkisalo, 2019). The vari-textured gabbros at Rinneaho are also characterized by ubiquitous disseminated sulfides.

A good example of Lower Zone isotropic gabbro and vari-textured gabbro is found at Rinneaho near the Vuorokas mine tower (**Stop 2**, Y: 7112246, X: 3508320) and a nearby quarry (**Stop 3**, Y: 7111729; X: 3507827). The grain size variation in these outcrops is dramatic, and pegmatitic, up to 50-cm-long individual crystals of plagioclase are observed regularly. At Rinneaho, the coverage of outcrop is relatively good and the VTGs can be distinguished confidently from isotropic Lower Zone gabbros. In the quarry at Vuorokas, the VTGs show gradational change to rhythmically layered gabbros (Mäkisalo, 2019). This layered unit reaches an approximate width of 50 m and dips to the north at an angle of 85°. The outcrops of the layered unit are located close to the Ore Zone at Vuorokas.

4.2.4 Ore Zone

The Ore Zone hosts close to 100% of the known oxide ore bodies, and all the mining operations took place within it. The Ore Zone in the Otanmäki block is E–W-oriented, 3-km-long and mostly 100–200 m wide and vertical (Figs. 6 and 8). Additionally, one occurrence of ore is known at a distance of ca. 300 m from the main ore occurrences at Otanmäki block, close to the fault-defined contact against A-type granitic and syenitic rocks of the Otanmäki suite (Fig. 8). The SW-NE-oriented Ore Zone at Vuorokas is 30–250 meters in width and can be followed through the Vuorokas block (Figs. 6). The ore lenses and layers at Vuorokas are in a vertical position. The oxide ore at Otanneva block does not crop out and is regarded as subeconomic (Soininen and Paarma, 1959).

In the Ore Zone, the oxide ore is present as semi-massive to massive magnetite-ilmenite lenses, or, more rarely, in discontinuous layers, which are 3–50-m-wide and up to 200-m-long (Fig. 8; Kerkkonen, 1979; Lindholm and Anttonen, 1980). The ore lenses and layers are hosted by gabbro, gabbro amphibolite, and magnetite gabbro. The wall rocks differ in terms of their degree of tectonic strain and oxide mineral content. The Ore Zone gabbro is melanocratic and small to medium grained and varies texturally from isotropic to moderately foliated. The gabbroic rocks in the Ore Zone often have disseminated ilmenite and/or magnetite. The ilmenite grains in the gabbros also show recrystallization to rutile or titanite (Mäkisalo, 2019). In areas of high tectonic strain, the rock is recrystallized into gabbro amphibolite; a dark, hornblende-rich, fine-grained rock which is often tectonically strained to have an almost schistose appearance. The magnetite gabbro, a gabbro type with abundant disseminated magnetite, is present throughout the Ore Zone and in rocks above it (Mäkisalo, 2019).

The Ore Zone is also characterized by the presence of ubiquitous plagioclase-rich autoliths, which are present as lenticular bodies or as fragments of less than one meter to tens of meters in diameter (Mäkisalo, 2019). They lie typically parallel to the magmatic stratigraphy. The autoliths are mostly fine- to medium-grained and relatively monomineralic and anorthositic in composition, but some are texturally and mineralogically similar to the Lower Zone vari-textured gabbros (Mäkisalo, 2019). The autoliths are angular to rounded in shape and have contacts that may imply gravitational settling of variably solidified blocks on a semi-solidified substratum (Mäkisalo, 2019).

A major surface occurrence of oxide ore at Otanmäki block is present in the approximately 3-hectare Metsämalmi outcrop area (Fig. 9, **Stop 4**, Y: 7113416, X: 3506198), where the ore forms branched layers and lenses overprinted by strong tectonic reworking. Class I ore (>55 % Fe-Ti oxides) is often surrounded by class II ore (30–55 % Fe-Ti oxides) and magnetite gabbro (class III ore, <30% Fe-Ti oxides), with gradational contacts between the ore types (for definitions of ore classes see below). Gabbros at Metsämalmi are mostly recrystallized to amphibolite. Anorthositic to leucogabbroic autoliths are found within all rock types: oxide ore, magnetite gabbro and gabbro amphibolite.

At Vuorokas block, oxide ore crops out only in a small open pit (**Stop 5**, Y:7113015 X:3509148) representing a central part of the Vuorokas block, where it is present as bifurcated layers and lenses 2–10 m in width and more than 90 m in lateral continuation (Fig. 10). In its contact towards a large leucogabbroic autolith, the oxide ore displays structures that potentially represent magmatic lamination (Mäkisalo, 2019). The oxide ore in the Vuorokas open pit has a sharp southern contact to a small occurrence of mottled anorthosite, which is either a minor VTG occurrence or a large autolith (Mäkisalo, 2019).

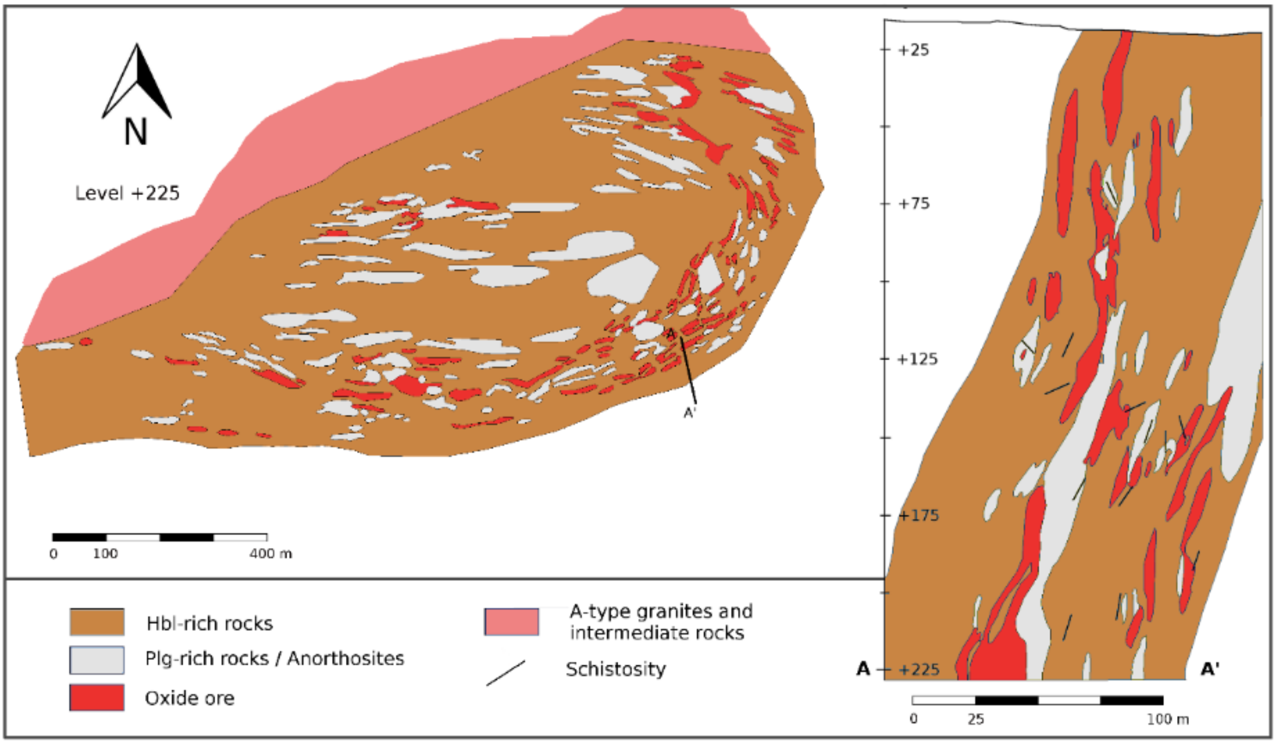

Figure 8. Structure of the Ore Zone at Otanmäki block (Mäkisalo, 2019). Mine map and cross section A–A' modified after Rautaruukki Oy and Lindholm and Anttonen (1980). The ore lenses and layers occur in a 100–200 m wide zone. An additional occurrence of ore is seen from a 300 m distance from the main ore zone. Hbl = hornblende, Plg = plagioclase.

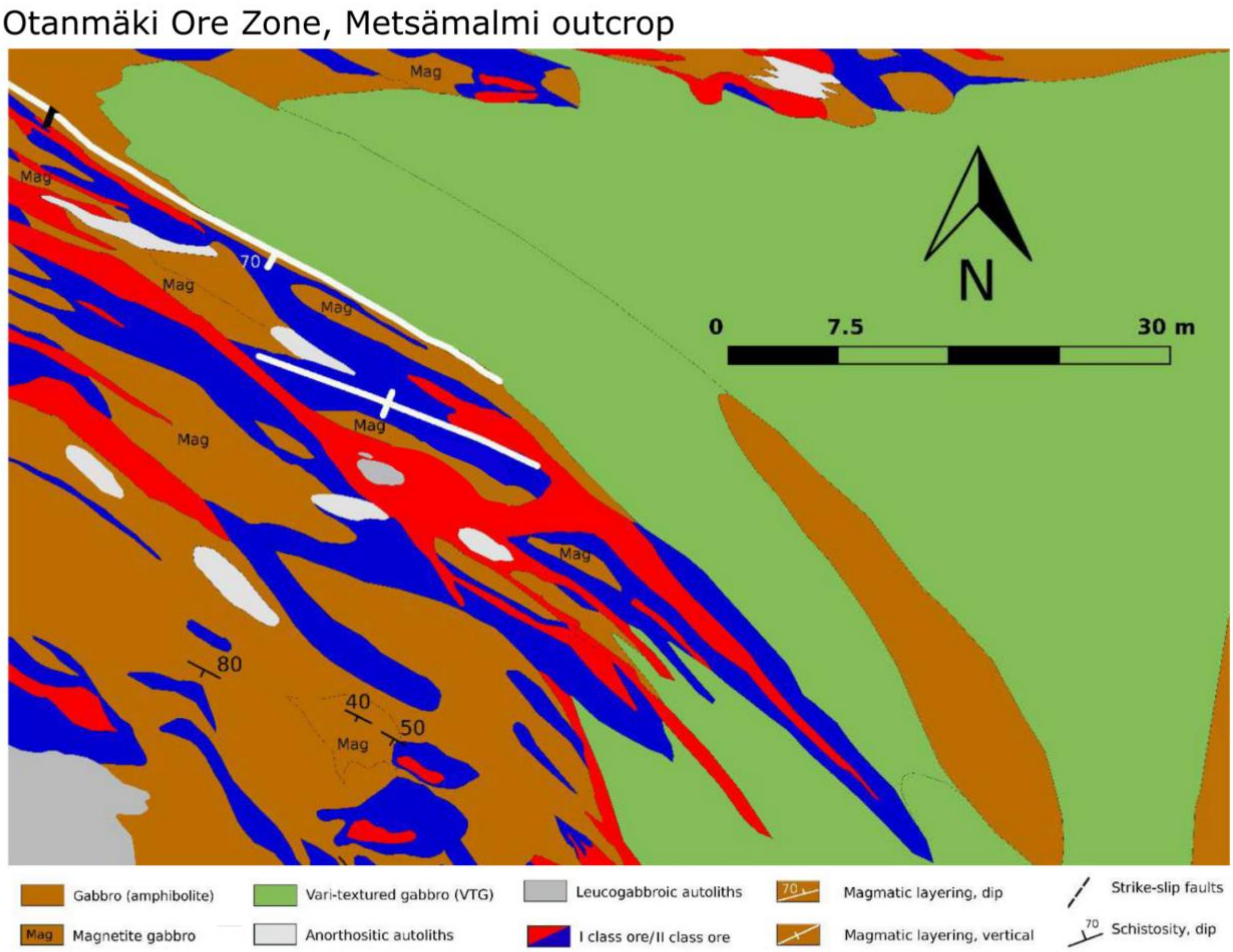

Figure 9. Detailed geological map from the SE part of the Metsämalmi outcrop area showing anorthositic to leucogabbroic autoliths in the Ore Zone at Metsämalmi, Otanmäki (Mäkisalo, 2019). Dominantly rounded autoliths of few meters in diameter are found in all Ore Zone rock types.

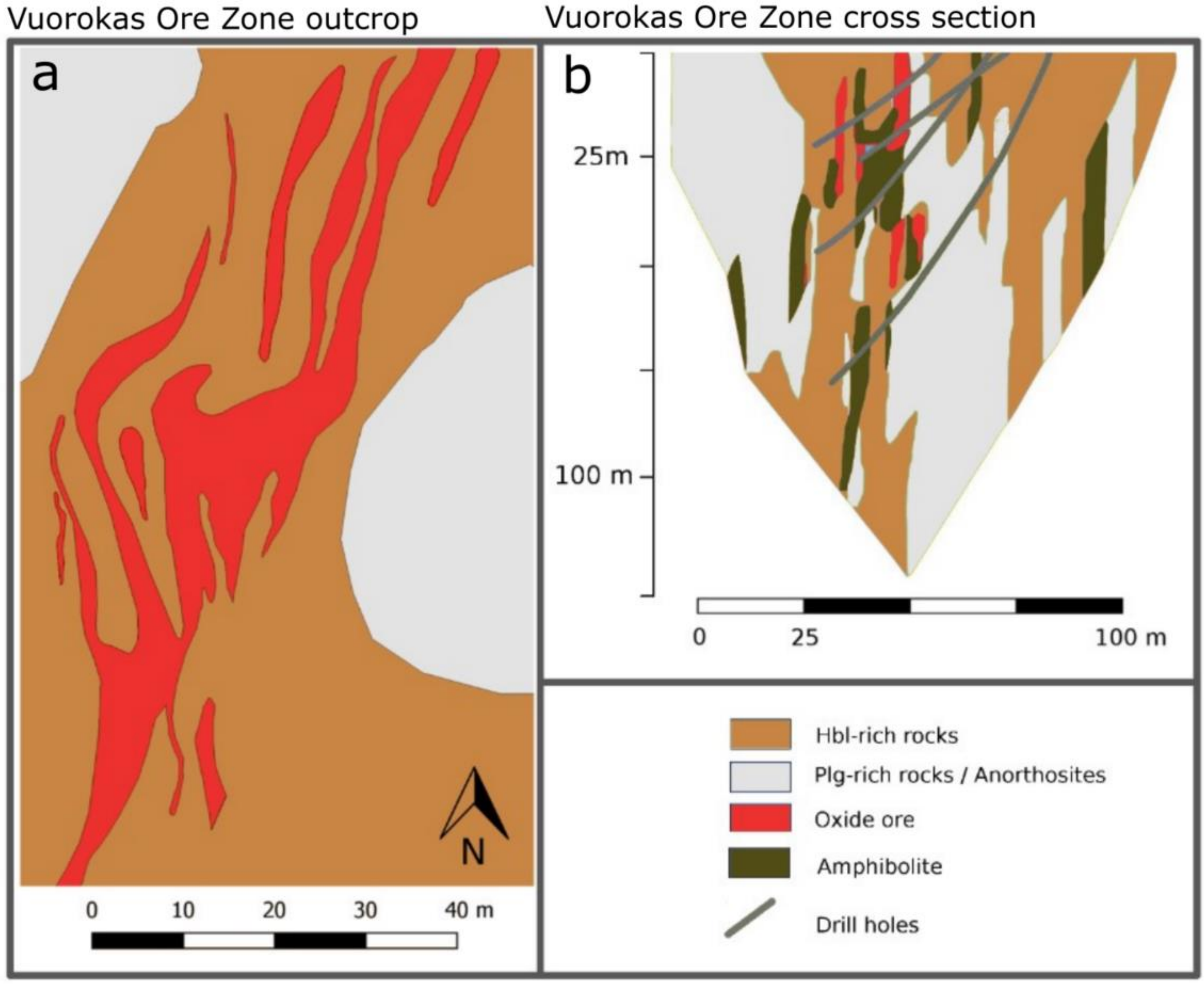

Figure 10. Structure of the Ore Zone at Vuorokas block (Mäkisalo, 2019, modified after Parkkinen, 2015). a) Surface map of the Vuorokas open pit area, NE of the underground mine. Modified after Rautaruukki Oy. b) Vertical cross section of the ore zone in the underground mine area. The cross section is a rough lithological model created using one inverse distance weighting (IDW3) interpolation. The amount of anorthositic rocks in this model is estimated disproportionately high.

4.2.4.1 Fe-Ti-V oxide ore

In the Otanmäki oxide ore, ilmenite occurs either as lamellae or inclusions in magnetite or as separate grains (Kerkkonen, 1979). The ilmenite exsolution lamellae in magnetite originates likely from magmatic processes, but the separate occurrence of magnetite and ilmenite is linked to the exsolution of ilmenite from the magnetite-ulvöspinel solid solution during metamorphosis (Kerkkonen, 1979). The occurrence of ilmenite depends on the amount of oxides and the intensity of recrystallization. When magnetite and ilmenite occur separately, their grain size is 0.2–0.8 mm (Fig. 11). Vanadium in present in both of them with concentration levels of 4400–4500 ppm in magnetite and 1000–2200 ppm in ilmenite (Nykänen, 1995).

The Rautaruukki Oy mining company divided the ore into three classes (Table 2; Kerkkonen, 1979). The classification is based on the total amount of magnetite and ilmenite, which is directly proportional to magnetic susceptibility, a quantity which was routinely measured in downhole geophysics in association with underground exploration and grade control (Paarma, 1961). The main gangue minerals in ore are chlorite, hornblende, and plagioclase (Table 2). The ore also contains 1–5% of sulfides, including pyrite, pyrrhotite, and/or chalcopyrite (Hokka and Jylänki, 2014).

Table 2. Different ore classes in the Otanmäki Fe-Ti-V oxide deposit with corresponding metal grades and mineral concentrations (Kerkkonen, 1979). Chl: chlorite, Hbl: hornblende, Plg: plagioclase.

Ore class	Magnetite	Magnetite + ilmenite	V	Main gangue
I	> 30 %	> 55 %	0.35 - 0.50 %	Chl
II	15 - 30 %	30 - 55 %	0.25 - 0.35 %	Hbl
III	< 15 %	< 30 %	0.15 - 0.25 %	Hbl + Plg

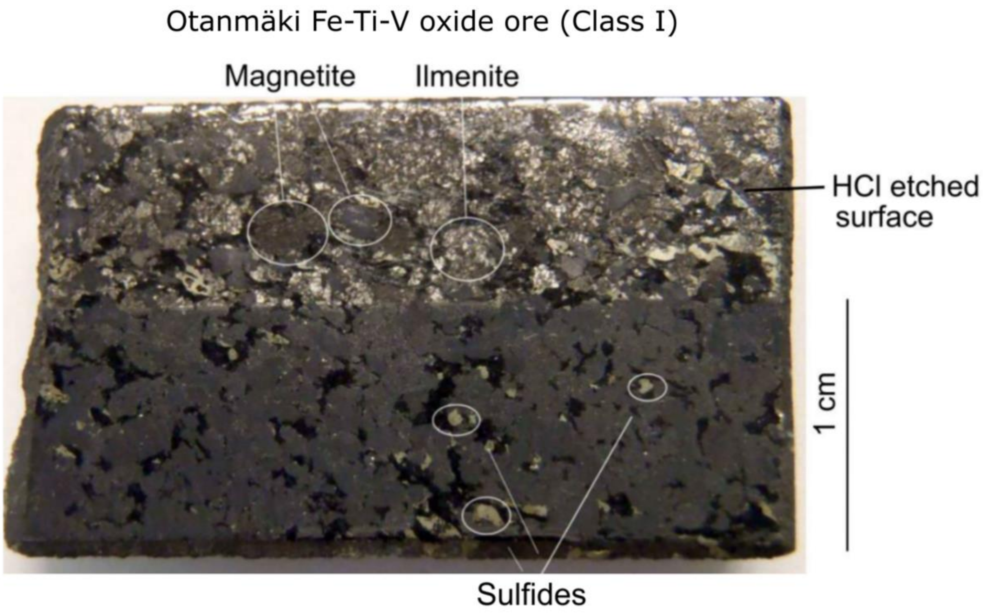

Figure 11. A polished sample of Class I Otanmäki ore where magnetite and ilmenite occur largely as separate grains (Hokka and Jylänki, 2014). When etching the sample with hydrochloric acid (HCl), magnetite turns to various brown colors and ilmenite turns pale.

4.2.5 Upper Zone

The Ore Zone rock assemblage changes gradually into the Upper Zone, where isotropic gabbro dominates and oxide ore is no longer present (Fig. 7). Anorthositic autoliths are met in almost all Upper Zone outcrops. At Otanmäki block, the outcrop coverage in the upper part is good, whereas at Vuorokas, most of the upper part is under a thick peat cover and the northernmost field observations are just 200 m north of the Ore Zone.

Small-scale modal layering is infrequently observed in the otherwise isotropic Upper Zone gabbros. At Otanmäki, this layering is present as subtle changes in mineral proportions in homogenous gabbro (Mäkisalo, 2019). Rarely, in the vicinity of autoliths, vertical layering is observed to be conformable with the autolith borders (Kerkkonen, 1979; Mäkisalo, 2019). However, layering in the Upper Zone is not a prominent feature and cannot be followed along strike for more than a few meters. The Upper Zone isotropic gabbro and autoliths of varying sizes are exposed at outcrops located just north of the Kokkola-Kajaani road at Vuorokas block (**Stop 6,** Y: 7112685, X: 3508305) and at the northern slope of the Otanmäki hill (**Stop 7,** Y: 7113367, X: 3505349).

4.3 Models of oxide ore genesis

Despite the long history of geological investigation since the 1940s, considerable uncertainty on many aspects of the geology and origin of the Otanmäki Fe-Ti-V oxide mineralization still prevail. Compared to typical oxide ores in layered intrusions, one distinct feature of the Ore Zone in Otanmäki is the distribution of ore in numerous discontinuous, lens-like oxide-rich bodies (Figs. 8–10). How this situation arouse is a big research question, and although several genetic models have been proposed to answer it, they remain largely conceptual and lacking strong supporting evidence.

The first investigators, Paarma (1954) and Pääkkönen (1956) recognized that the wall rocks of the Otanmäki oxide ore are metamorphosed igneous rocks and the ore resembles other titaniferous iron ores of magmatic origin. According to Paarma (1954), the ore was formed by direct crystallization from a Fe-Ti-rich magma. However, the generally strongly deformed nature of the ore bodies and their wall rocks made Pääkkönen (1956) to propose that the accumulation of oxide minerals and formation of the ore bodies were related to metamorphic segregation of primary (magmatic) disseminated oxide minerals from the gabbroic wall rocks.

Kerkkonen (1979) and Nykänen (1995) proposed that crystallization of pyroxenes, plagioclase and olivine from a Fe-Ti-rich tholeiitic parental magma under highly reducing and relatively high-pressure conditions (~7 kbar) resulted in Fe-Ti-V enrichment in the residual melt and abundant crystallization of oxide minerals in the Otanmäki magma chamber. Kerkkonen (1979) described that the rocks of the least deformed parts of the Ore Zone display magmatic cumulus textures, flow lamination, and turbulence structures around anorthosite autoliths. He suggested that two mechanisms were important in the Otanmäki magma chamber: 1) flotation and accumulation of plagioclase in the roof part of the magma chamber, particularly in the early stages of magmatic evolution, and 2) magmatic flow that enhanced density-driven differentiation resulting in high-density floor cumulates, and caused brecciation, entrapment and transport of the earlier formed plagioclase-rich roof cumulates to deposit as autoliths on the floor of the magma chamber. Based on the complex spatial association of the irregular-shaped oxide ore bodies with anorthositic autoliths and gabbroic wall rocks, Kerkkonen (1979) also suggested that turbulent magmatic flow on earlier formed basal cumulates, and around autoliths deposited on them, may have locally produced small-scale physicochemical heterogeneities in the magma, which promoted selective in-situ crystallization of magnetite only. Kerkkonen (1979) also showed that the metamorphic overprinting was important economically as recrystallization of magmatic ilmenomagnetite (magnetite with micro-intergrowths of ilmenite) produced separate grains of ilmenite and magnetite, which allowed their effective separation in the beneficiation of the ore.

Mäkisalo (2019) studied the anorthositic rocks found within the Otanmäki intrusion and interpreted that they represent strongly differentiated plagioclase adcumulates and represent fragments of a previously crystallized portion of rock enclosed in material from the same magma which solidified later to the Otanmäki intrusion. Mäkisalo (2019) proposed that the anorthosites may have originated from a massive roof anorthosite which was formed by periods of plagioclase buoyancy and later sank gravitationally into the lower parts of the magma chamber. Mäkisalo (2019) proposed that the sinking may have been triggered by massive Fe-Ti-oxide crystallization and subsequent decrease in the density of the residual melt and accompanied by gravitational movements of partially solidified cumulate slurries towards a subsided magma chamber center.

5 OTANMÄKI REE-HFSE MINERALIZATION

5.1 Exploration history

Exploration for REE in the Otanmäki area started in 1981 when GTK discovered radioactive glacial boulders having elevated concentrations of REEs and HFSE, such as Zr and Nb (Äikäs, 1990). The follow-up exploration drilling program of Rautaruukki Oy mining company between 1983 and 1985 led to the discovery of two REE-HFSE mineralized zones in bedrock, which were named Katajakangas and Kontioaho (Hugg and Heiskanen, 1986). According to the preliminary mineral resource estimates from that time, the Katajakangas mineralization contains 0.46 Mt of rock with 2.3 wt% total REE (TREE), 0.5 wt% Nb, and 0.8 wt% Zr (Hugg, 1985a) and the Kontioaho mineralization contains 4 Mt of rock with 0.6 wt% TREE, 0.08 wt% Nb, and 2.1 wt% Zr (Hugg, 1985b). In 1985, Rautaruukki Oy discontinued the REE project and concluded that the identified resources are either too small (Katajakangas) or the grade is too low (Kontioaho) to be economic and that their mineral processing is challenging (Hugg and Heiskanen, 1986). The decision to terminate the REE-project was made at the same time as Rautaruukki Oy decided to close all its exploration activities and the Otanmäki Fe-Ti-V mine. Otanmäki REE-HFSE occurrences were also briefly re-evaluated during GTK's high-tech metal project between 2009 and 2011 (Sarapää et al., 2013, 2015) and further explored by Tasman Metals Ltd between 2010 and 2013. Most recently, there have been exploration claims in the area by Otanmäki Mine Oy and Bambra Oy.

At present, the REE-HFSE occurrences at Otanmäki are more of geological and mineralogical than economical interest as their REE-HFSE mineral assemblages are unfavorably different from deposits being mined in other countries where REEs are hosted by fluorocarbonates (e.g., bastnäsite) and/or phosphates (e.g., monazite, xenotime) (e.g., Weng et al., 2015). In the Otanmäki occurrences, the REEs are hosted mainly by silicate and oxide minerals (Kärenlampi et al., 2020), which have not yet been economically exploited anywhere for the REE in an industrial scale and cannot be processed by the presently established REE extraction methods (e.g., Verbaan et al., 2015; Demol et al., 2019; Peiravi et al., 2021). In the Otanmäki REE-HFSE mineralization, allanite-(Ce) ($(Ce,Ca)_2(Al,Fe^{2+,3+})_3(SiO_4)_3(OH)$) is the major host for light-REEs (La-Sm) and Th. Zircon ($ZrSiO_4$) is the only major host for Zr and a minor host for Th, U, Nb, Y, and heavy-REEs (Gd-Lu) (Kärenlampi et al., 2020). A variety of Nb-REE-Th-U oxide minerals (e.g., fergusonite-(Y), samarskite-(Y)) are the major carriers of Nb, Y, heavy-REEs, Th, and U in the Katajakangas occurrence, but are less abundant in the Kontioaho mineralization in which titanite ($CaTiSiO_5$) is an important carrier of Nb, in addition to being a minor carrier of Y and REEs (Kärenlampi et al., 2020).

5.2 Local geology

The Otanmäki REE-HFSE mineralization is contained in two occurrences, Kontioaho and Katajakangas, which are located within a fault-bound block composed mostly of peraluminous A1-type granite gneiss (Figs. 3 and 12a). The enclosing granite has been dated using in-situ laser ablation inductively couple mass spectrometry (LA-SC-ICP-MS) analysis from two samples, yielding U-Pb zircon ages of 2055 ± 8 Ma and 2060 ± 29 Ma (Kärenlampi et al., 2019). The peraluminous granite wall rock also contains slivers of metaturbidite and amphibolite metamorphosed from mafic dikes and showing shallowly (~10–30°) southwards dipping foliation and lineation (Fig. 12a). The peraluminous granite block has a shallow footwall contact against the adjacent peralkaline granite whereas its flanks appear to be controlled by near vertical faults against the surrounding peralkaline granite and syenite. The nearby peralkaline granite bodies contain local metaluminous parts. Zircon fractions from two samples of the peralkaline granite have given ages of 2049 Ma ± 10 Ma and 2041 ± 5 Ma (LA-MC-ICP-MS analysis; Kärenlampi et al., 2019). The mineralogical characteristics of the A-type granites and syenite at Otanmäki are summarized in Table 3.

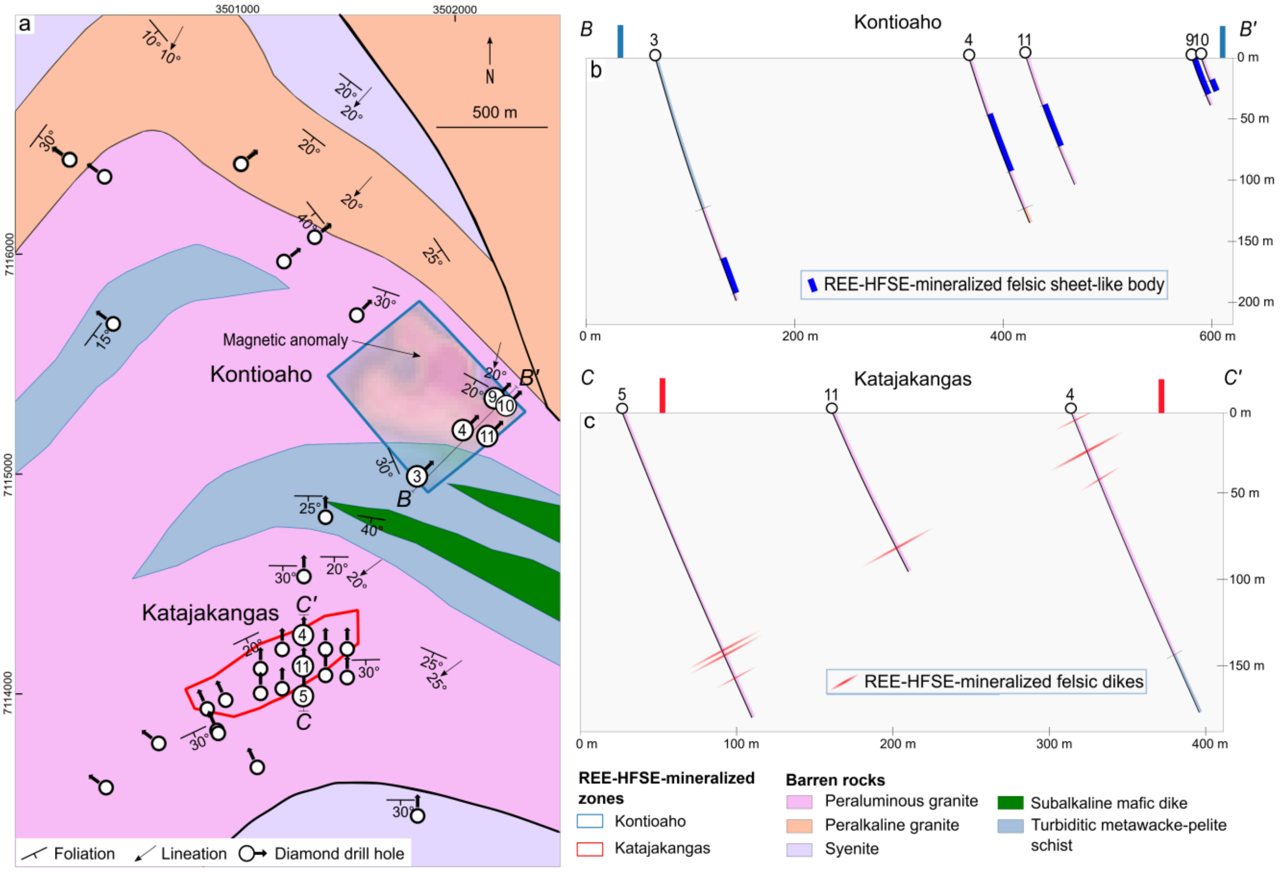

Figure 12. Local geology and occurrences of REE-HFSE mineralized zones at Otanmäki (Kärenlampi et al., 2020). a) Geological map showing the inferred surface projections of the Kontioaho and Katajakangas mineralized zones and diamond drill holes. b–c) Simplified vertical cross-sections of the mineralized rock units. The drilling profiles (B–B', C–C') shown in Fig. 12a.

Table 3. Mineralogical characteristics of the A1-type granites and syenite associated with the REE-HFSE mineralization in the Otanmäki area (Kärenlampi et al., 2020).

Rock type	Major minerals	Minor minerals
Peraluminous granite wall rock	Potassium feldspar, plagioclase, quartz	Biotite, magnetite
Peralkaline granite	Alkali feldspars, quartz	Aegirine/aegirine-augite, riebeckite/katophorite, (biotite), (aenigmatite), (magnetite)
Syenite	Alkali feldspars	Amphibole, clinopyroxene, (biotite), (magnetite), (quartz)

Minerals only occasionally present are indicated by parentheses.

5.2.1 Kontioaho occurrence

The Kontioaho occurrence consists of a 30- to 50-m-thick, felsic sheet-like body of mineralized rock surrounded by barren peraluminous granite (Fig. 12b). Its surface exposure is minimal, but on the basis of drill core data, the mineralized body dips 20° to the southwest, extending at least to a depth of 185 m (Kärenlampi et al., 2020). The drilling-tested strike length of the mineralized body is only 100 meters but based on the magnetic anomaly associated with the magnetite bearing mineralization, it extends at least 600 meters to the NW from the existing drilling profile (Fig. 12a). A magnetic inversion model suggests that the mineralized body reaches a depth of 200–300 meters (Lahti et al., 2018).

The mineralized rocks are pinkish to reddish-grey in color, fine-grained (<1 mm) and banded in texture (Fig. 13a–c). The main minerals are quartz, potassium feldspar, albite, magnetite, zircon, fluorite, allanite-(Ce), and titanite, occurring with small quantities of other minerals (Fig. 13c; Table 4). Internally, the mineralized body is divided into high- and low-grade zones, with the former containing >1.5 wt% REE-HFSE (Kärenlampi et al., 2020). The high-grade mineralization is confined to a ~12-m-thick zone, usually in the central part of the mineralized body (Kärenlampi et al., 2020). Allanite-(Ce), zircon, titanite, and Nb-REE-Th-U oxides are located along grain boundaries of quartz and feldspars, form bands or are enclosed in fluorite (Fig. 13c). The Kontioaho low-grade unit is exposed at a roadside outcrop (**Stop 8**: Y: 7115376, X: 3502197).

In-situ secondary ion mass spectrometry (SIMS) dating conducted on zircon grains from a sample from the Kontioaho REE-HFSE mineralization has yielded an average $^{207}Pb/^{206}Pb$ age of 2036 ± 4 Ma (Kärenlampi et al., 2020), which is (within error) close to the crystallization age of the peralkaline granite in the Otanmäki area (ca. 2.04–2.05 Ga; Kärenlampi et al., 2019). Altered domains in the analyzed zircon grains from Kontioaho also yield younger dates of ca. 1.9 Ga (Kärenlampi et al., 2020), which coincide with the initiation of the Svecofennian orogeny and regional metamorphism (e.g., Lahtinen et al., 2015), demonstrating effects of metamorphic overprint.

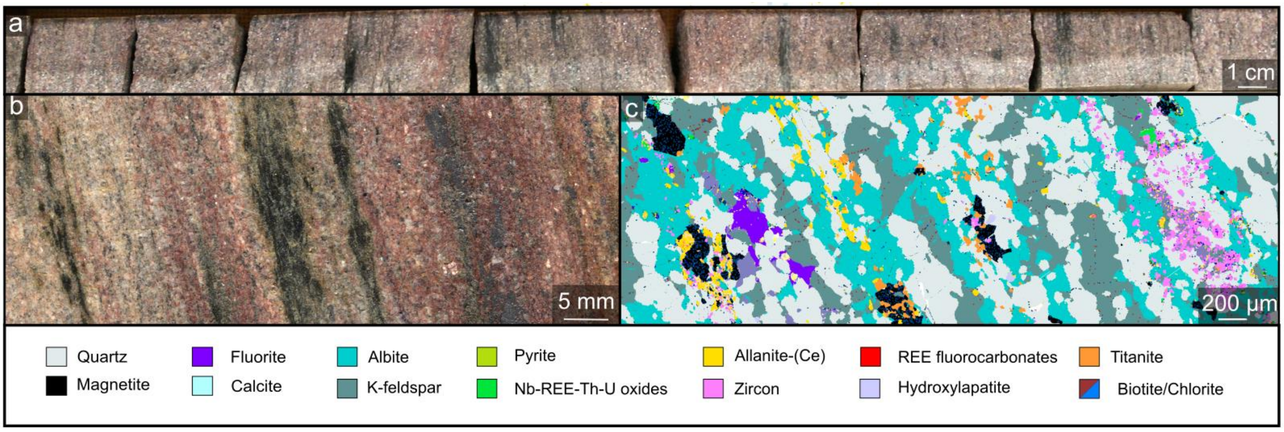

Figure 13. Images of rocks from the Kontioaho mineralization (Kärenlampi et al., 2020). a) Photograph of half-split drill core from the Kontioaho mineralization. b) Polished slab of a mineralized rock. c) FE-SEM scanning-based false color image of a polished thin section representing mineralization in the Kontioaho occurrence.

5.2.2 Katajakangas occurrence

The REE-HFSE mineralization at Katajakangas consists of single dikes or sets of few (~2–4) felsic dikes ranging from 0.1 to 1.4 m and averaging 0.5 m in thickness (Kärenlampi et al., 2020). Based on diamond drilling, the dikes are restricted to a tabular zone, which is aligned parallel to the foliation of the host rock, which dips 20–30° to the south (Fig. 12c). The zone has been traced southwards to a depth of 145 m and its NE-SW strike extension is at least 800 m. The dikes are typically spaced a few meters apart and seem to not cross-cut each other (Kärenlampi et al., 2020). The dikes have sharp contacts with the peraluminous granite wall rock (Fig. 14a). In general, there are no visible signs of chemical reaction in the wall rock, though calcite and/or fluorite-bearing “metasomatite” bands with a thickness of a few tens of centimeters occur locally at the margins of the dikes (Kärenlampi et al., 2020). In the mineralized zone, there are also sets of foliation-concordant calcite veins with a thickness of few mm to cm. Some of these veins contain minor amounts of fluorite (Kärenlampi et al., 2020).

The mineralized dikes are dark grey, very fine grained (<0.5 mm), and foliated (Figs. 14a–c). The main minerals are quartz, allanite-(Ce), albite, zircon, and Nb-REE-Th-U oxides, occurring with small quantities of other minerals, such as calcite, pyrite, and REE-poor hydroxylapatite (Fig. 14c; Table 4). Allanite-(Ce), zircon, and Nb-REE-Th-U oxides are evenly dispersed in the dikes, occurring as clusters within quartz and albite grains. Quartz represents the dominant gangue mineral (~60 wt%), being dark and smoky in appearance probably due to irradiation damage induced by the accompanying Th-U-bearing minerals (Kärenlampi et al., 2020).

The Katajakangas mineralized zone is buried under peat and till cover and does not naturally outcrop, but mineralized dike samples taken from it can be found near a closed sampling pit at Pieni-Katajakangas (**Stop 9**, Y: 7114223, X: 3501106).

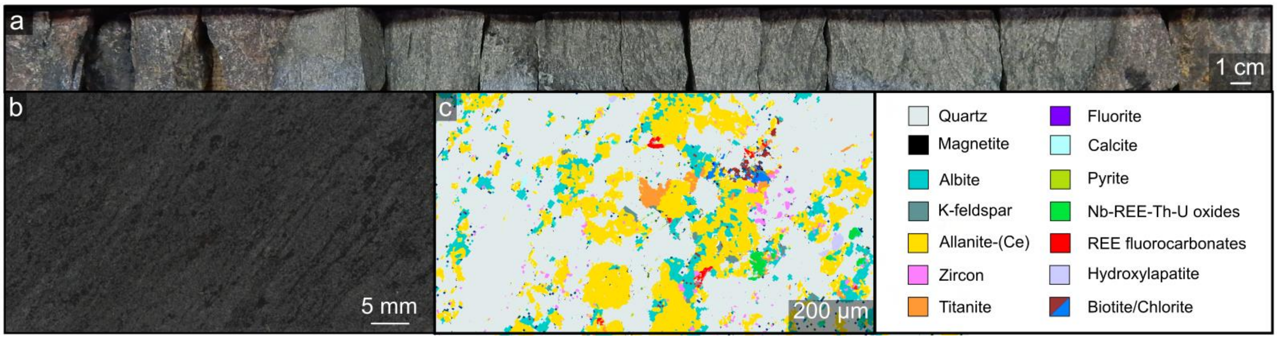

Figure 14. Images of rocks from the Katajakangas mineralization (Kärenlampi et al., 2020). a) Photograph of a half-split drill core interval showing a 30-cm-thick mineralized dike (dark-grey) in peraluminous granite wall rock (brownish grey). b) Photograph of a polished slab of a mineralized dike. c) FE-SEM scanning-based false-color image of a polished thin section.

Table 4. Minerals found in the Kontioaho and Katajakangas REE-HFSE-mineralized zones together with their structural formulae and abundances (wt%) in representative samples (Kärenlampi et al., 2020).

Mineral	Structural formula	Katajakangas mineralized dikes		Kontioaho sheet-like body	
Gangue minerals					
Quartz	SiO_2	59	61.4	48	36
Potassium feldspar	$KAlSi_3O_8$	0.4	0.3	25.4	19.5
Albite	$NaAlSi_3O_8$	5.9	6.2	2.3	26.8
Magnetite	Fe_2O_4	*nd*	*nd*	4.6	6.6
Fluorite	CaF_2	*nd*	*nd*	1.9	0.5
Calcite	$CaCO_3$	1.5	3.4	2.1	0.1
Biotite	$K(Mg,Fe)_3(AlSi_3O_{10})(F,OH)_2$	0.7	0.9	0.2	0.4
Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2(Mg,Fe)_3(OH)_6$	0.1	0.1	0.3	0.1
Amphibole	$(Na,Ca)_2(Fe^{2+}{}_4Fe^{3+})(Al_2Si_6O_{22})(OH)_2$	0.2	0.2	0.7	0.4
Andradite	$Ca_3Fe_2Si_3O_{12}$	0.2	0.2	0.1	1.2
Hydroxylapatite	$Ca_5(PO_4)_3(F,OH)$	0.5	0.6	0.1	0.2
Pyrite	FeS_2	2.5	2.5	*nd*	*nd*
REE-HFSE-bearing minerals					
Allanite-(Ce)	$(^*Ln,Ca,Y)_2(Al,Fe^{2+,3+})_3(SiO_4)_3(OH)$	19.5	14.7	4.4	2.8
Zircon	$(Zr,Hf,Ln,Y,Nb,U,Th)SiO_4$	2.3	2.5	5.5	2
Titanite	$(Ca,Y,Ln)(Nb,Ti,Si)O_5$	0.8	1.2	1.5	1.5
Nb-REE-Th-U oxides		2.8	4.3	0.6	0.3
Fergusonite-(Y)	$(Y,Ln,U,Th)NbO_4$				
Samarskite-(Y)	$(Y,Ln,Fe,U,Th,Ca)(Nb,Ta)_5O_4$				
Euxenite-(Y)	$(Y,Ca,Ln,U,Th)(Nb,Ta,Ti)_2O_6$				
Aeschynite group	$(Y,Ln,Ca,Fe,U,Th)Ti,Nb)_2O_6$				
Pyrochlore group	$(Ca,Na,Y,Ln,U,Th)_2Nb_2O_6(OH,F)$				
Columbite-(Fe)	$Fe^{2+}Nb_2O_6$				
Fersmite	$(Ca,Ln,Na)(Nb,Ta,Ti)_2(O,OH,F)_6$				
REE fluorocarbonates		0.4	0.5	0.6	0.4
Parisite-(Ce)	$Ca(Ln)_2(CO_3)_3F_2$				
Bastnäsite-(Ce)	$(Ln)CO_3F$				

*Ln = lanthanides; *nd* = not detected. Weight proportions of minerals determined by FE-SEM based automated mineralogy system (Mineral Liberation Analyzer; MLA) from polished thin sections.

5.3 Origin of the REE-HFSE mineralization at Otanmäki

Although the Otanmäki REE-HFSE enrichments have been known since the 1980s, they have attracted only limited research interest and their origin has remained poorly understood until recently (see Kärenlampi et al., 2020). Rautaruukki Oy geologists suggested a metasomatic origin for both the REE-HFSE-mineralized rock units and nearby 'alkaline granite', but without any proposition for the source of the hypothesized metasomatizing alkaline REE-HFSE-rich fluids (Hugg, 1985a,b; Hugg and Heiskanen, 1986). Kärenlampi et al. (2020) proposed that the formation of the Otanmäki REE-HFSE mineralization is explained by a multistep process, which involved generation of highly evolved silicate melts during the Otanmäki suite A1-type magmatism. The peraluminous granite wall rock is interpreted to be genetically unrelated to the mineralized rock units, as evidenced by whole-rock chemical and Sm-Nd isotope data and zircon U-Pb geochronology. Instead, the mineralization is considered to be intrinsically related to the crystallization history of the ca. 2.04–2.05 Ga peralkaline granite magmatism of the area, particularly later stages in its evolution (Fig. 15). The peralkaline granite related to mineralization is proposed to have crystallized from an evolved peralkaline felsic magma with high initial REE-HFSE content. The generation of the wt%-level enrichment of REE-HFSE in the Otanmäki area required extensive crystallization of this magma in order to accumulate REE-HFSE to the last residues of the silicate melt (Kärenlampi et al., 2020).

Based on the performed numerical modeling, Kärenlampi et al. (2020) established that extensive crystallization of alkali feldspar, quartz, and minor mafic minerals (aegirine, magnetite) from a peralkaline granitic starting magma composition can produce a residue with major element compositions (e.g., Si, Fe, and Ca enrichment relative to Al, K, and Na) similar to those of the Otanmäki REE-HFSE mineralized rock units, although the observed Ca enrichment likely required an additional process. Trace element modeling also shows that pure fractionation alone cannot be responsible of the extremely high REE-HFSE levels in the mineralization (Kärenlampi et al., 2020). Based on elevated F, CO_2 and S contents in the mineralized rocks units, it is suggested that further REE-HFSE and Ca enrichment took place due to complexing of REE, HFSE and Ca with volatile components (e.g., F^-, CO_3^{2-}, SO_4^{2-}), which strongly sequestered these metals to the very late-stage melts (Kärenlampi et al., 2020). The fluorine-dominant composition of the volatile phase at Kontioaho appears to have favored enrichment of Zr relative to Nb and REEs (Kärenlampi et al., 2020). At Katajakangas, the mineralized felsic dikes are more enriched in Nb and REE relative to Zr, and the volatile phase appears to have been more enriched in CO_2 and S relative to F (Kärenlampi et al., 2020). In addition, the Eu/Eu* ratio, which exhibits only a slight decrease in mineralized rocks compared to the peralkaline granites, points to an oxidized nature of the late-stage melts (Kärenlampi et al., 2020).

The above-mentioned processes are considered to have produced metaluminous, high-silica residual melts strongly enriched in REE-HFSE, Ca, and Fe relative to Na, K and Al from a peralkaline felsic parental melt (Kärenlampi et al., 2020). The final step in the process was accumulation of these last residues of silicate melt and their emplacement as highly fractionated felsic dikes and a sheet-like intrusive body (Fig. 15). The allanite-zircon-titanite-Nb-REE-Th-U oxide dominant REE-HFSE mineral assemblages evidently record some textural and compositional changes related to metamorphic re-equilibration, but the main mineral species/assemblages are interpreted to be essentially primary, reflecting the magmatic crystallization conditions in a relatively low-alkalinity (metaluminous), oxidized, Ca-, Si-, Fe-, Al-rich and P-poor and low-fCO_2 system (Kärenlampi et al., 2020).

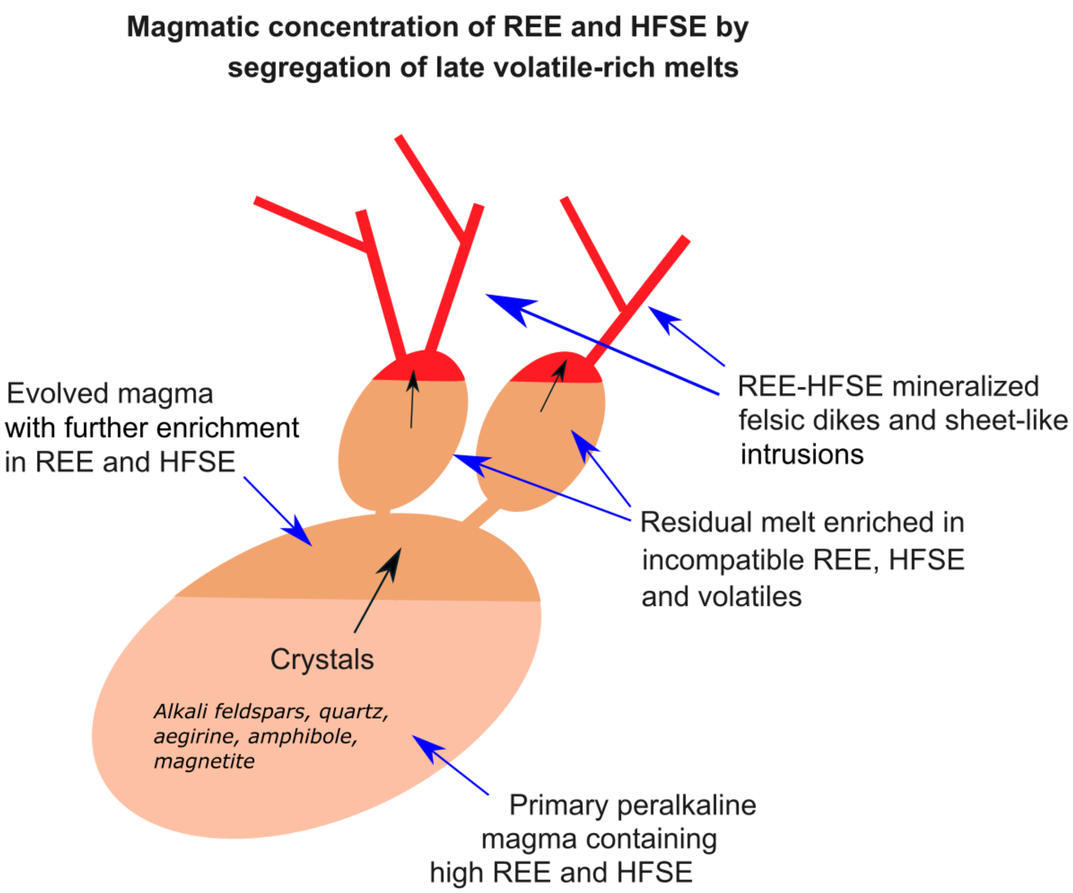

Figure 15. A schematic model of the origin of the Otanmäki REE-HFSE mineralization by extreme magmatic differentiation of a primary REE-HFSE- and volatile-rich peralkaline granite magma by alkali feldspar -dominant crystallization within separate batches of the parental peralkaline granite magma, which underwent varying degrees of fractionation (see Kärenlampi et al., 2020). The final step in the enrichment process was accumulation of the last residues of the REE-HFSE-rich silicate melt, apparently near the roof of the source peralkaline granite intrusions, followed by their emplacement as REE-HFSE-mineralized felsic sheet-like intrusions and narrow dikes above the intrusion roofs.

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