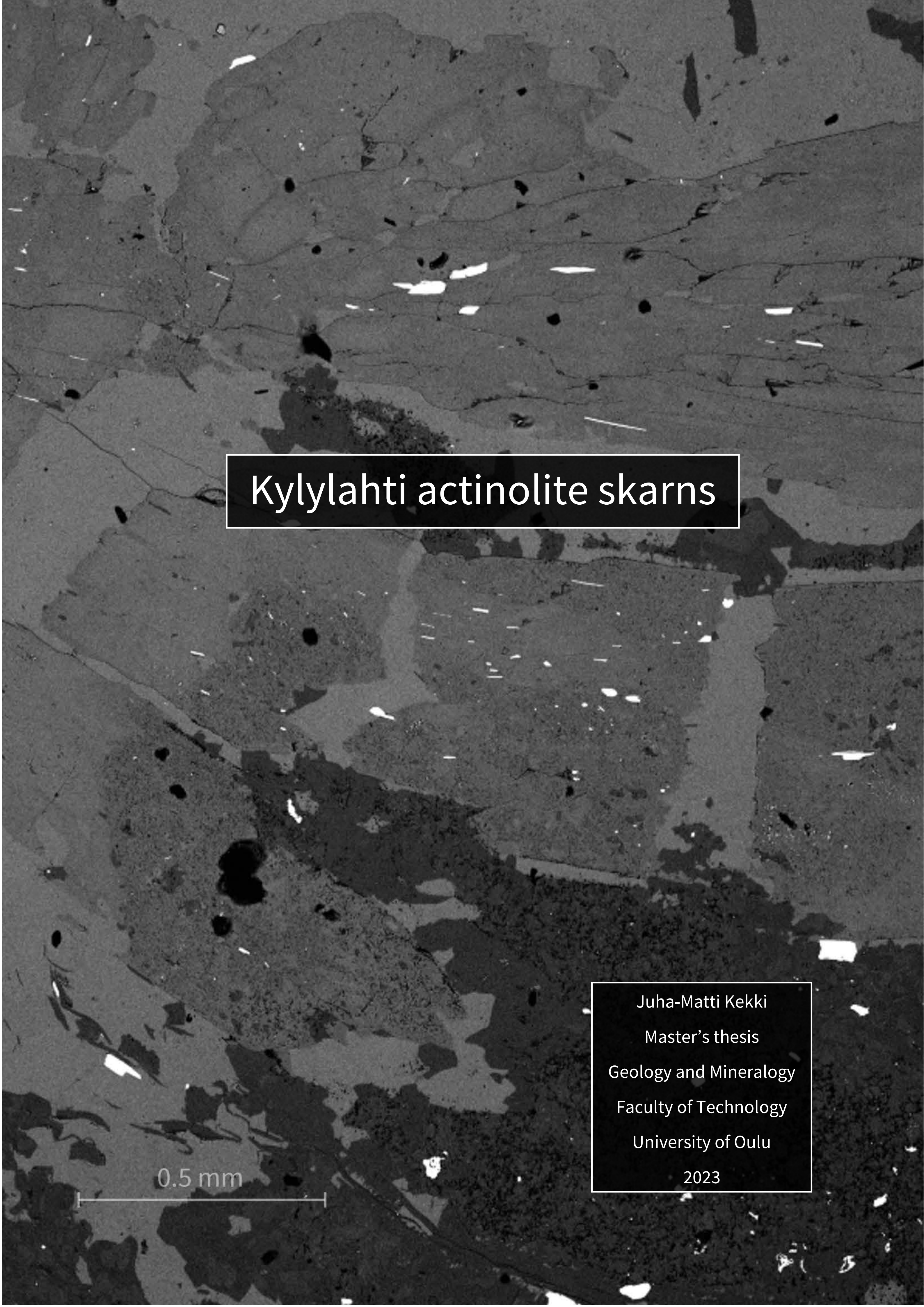

Kylylahti actinolite skarns

Juha-Matti Kekki
Master's thesis
Geology and Mineralogy
Faculty of Technology
University of Oulu
2023

Cover picture: FESEM backscatter image of a coarse tremolite crystal broken mechanically and partially replaced by light grey calcite. Pyrrhotite inclusions and unknown opaque pigment are present, too. The dark grey mineral is dolomite. Sample KU-917-304,05 belonging to OBA-Actska group.

ABSTRACT

Kylylahti is a Cu-Zn-Ni-(Co)-Au deposit found in year 1984 by Outokumpu Company and exploited by Altona Mining and Boliden in years 2012-2020. It locates in Polvijärvi, Eastern Finland, 20 kilometres northeast of the famous Outokumpu deposit with which it shares its main geological features. One of the main rock types in Kylylahti host rock assemblage is tremolite skarns, but also other types of rocks traditionally reported as skarns are present, such as actinolite skarns and cummingtonite skarns. In older mapping and core logging, actinolite skarn was the category in which all dark, amphibole bearing host/wall rocks were classified. Boliden felt it was necessary to improve the understanding and classification of the skarn types, especially in terms how the actinolite skarns differ from tremolite skarns. Drill cores of 10 holes in one profile that crosscuts the whole Kylylahti deposit were chosen to be completely re-logged. All darker, amphibole bearing rocks, customarily logged as skarns, were classified into four groups based on their mineralogical and textural features, and with the help of pXRF, their geochemical signatures. Three to five representative samples from each group were studied with polarizing microscope, FESEM, EDS and analysed for their whole rock geochemistry. Three of the groups comprised of hydrothermally altered refractory peridotites of the ophiolitic Kylylahti massif. One group was from carbonate±amphibole interlayers in the enveloping metasedimentary Upper Kaleva rocks. As expected, the 4 groups turned out to be both geochemically and mineralogically distinct from each other. Remarkably, in terms of the past naming convention, only one sample contained one crystal of actual actinolite. Dark amphiboles were mostly tremolites that were pigmented dark or completely black by fine sulphides, graphite and some unknown matter that could be graphite or sulphides but in so fine size that it was not recognizable in this study. Therefore, actinolite skarn is not a correct name for any of these rocks and should not be used. They are just tremolite skarns or carbonate-containing rocks that have some tremolite as accessory mineral.

CONTENTS

1. INTRODUCTION

1.1 Kylylahti mine

The Kylylahti Cu-Au-Zn-Ag-Co-Ni deposit is in Polvijärvi, Northern Karelia. Polvijärvi is 40km north-west from the province capital Joensuu and roughly 23km north-east from the famous mining camp of Outokumpu (figure 1). Ore mined from Kylylahti mine was transported 43km by trucks to Luikonlahti mill in Kaavi, Northern Savo.

Kylylahti deposit was discovered in 1984 by Outokumpu Mining. Boliden acquired the mine from Australia-based Altona Mining in 2014 along with the rights to local exploration targets. The average ore production was roughly 700 000 tons per year. Kylylahti was a quite traditional high grade – low tonnage sulphide deposit. Two main types of ores were mined – the massive sulphide Cu-Zn-Au ore and the disseminated (Au)-Ni-Co-Cu ore.

The main mining methods used in Kylylahti were transverse and longitudinal open stoping with cemented rock fill (CRF) and/or waste rock used as backfill. Transverse stoping was used in the wide parts of the orebody and longitudinal stoping in the narrow parts. The vertical distance between production levels was 30 meters. After transport to mill, both ore types were crushed and milled. Then, gold was separated by Knelson gravity concentrator and copper was extracted by flotation. After this, the massive – semi massive Cu-Zn-Au ore went to Zn floatation. When enriching the (Au)-Ni-Co-Cu ores, the flotation circuits were changed to float Ni-Co minerals instead of sphalerite that was collected from the massive – semi massive ore type. Therefore, simultaneous production of Ni-Co concentrate and Zn concentrate was not possible.

Ore in Kylylahti was depleted in November 2020 and the mine and mill were closed. Now, there are no running base metals mines in Outokumpu region (Figure 3). Exploration in the region however is still active. Hautalampi Co-Ni-Cu project located at Outokumpu town, right next to old Keretti mine is the most advanced target in the region.

It is owned by FinnCobalt and Eurobattery Minerals AB and presumably will be in production in few years.

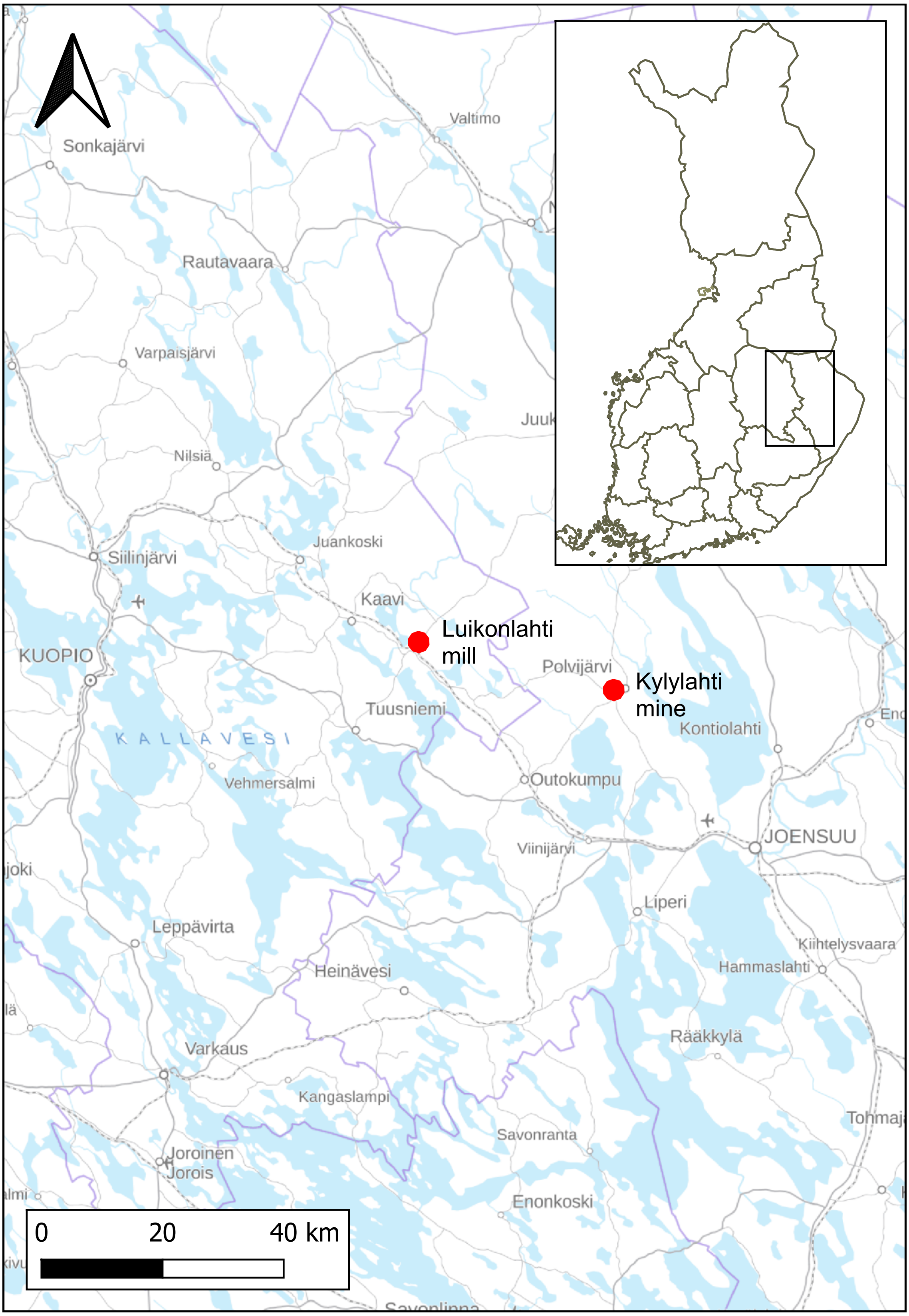

Figure 1. Map showing Kylylahti mine and Luikonlahti Mill. Modified from 1:320 000 Background map of National Land Survey of Finland 21.11.2022.

1.2 Outokumpu clarified

Kylylahti deposit belongs to Outokumpu formation. Outokumpu means ”strange hill”. Naming is ancient by the local population living in historical Kuusjärvi municipality in Northern Karelia. In 1908, digger operators Ossian Asplund and Axel Eskelinen, working in the Kivisalmi canal site found a large, 5m3 boulder of good quality copper ore. Operators and presumably their foreman, Johan Montin sent a sample to geological governmental office in Helsinki. The boulder was named Kivisalmi boulder and mountain engineer Otto Trüsted was appointed to try to find the source of the boulder. After 2 years of exploration, Trüsted and his team found the source at the strange hill (Kuisma, 1985). The deposit was therefore named Outokumpu, as well as the first mine and eventually the town that evolved next to the mine. Nowadays, the town has approximately 7000 inhabitants.

The discovery of Kivisalmi boulder sparked more than 100 years of continuous mining in the region. As a company, Outokumpu grew from a single mine operator into large, government owned business that had multiple mines running in Finland, Ireland, Sweden, and Australia. Currently Outokumpu has one working mine, utilizing the world class Elijärvi chromium deposit in Kemi, Finland. Nowadays Outokumpu is a public company listed at the Nasdaq Helsinki, but the Finnish government still is the largest shareholder through Solidium Oy. Outokumpu spawned also a widely known tech company Outotec, which is a global player in mining technology industry. Outotec merged with Metso in 2020 and became as Metso Outotec, the leading mining solutions provider in the world.

Outokumpu is also a name for the geological formation and mineralisation type. In this thesis, much like in the GEOMEX-report (Kontinen et al. 2006) terms such as ”Outokumpu rocks” or ”Outokumpu assemblage ” refer to all ophiolithic serpentinites and serpentinite-derived, metasomatically altered rocks like soapstones, calc-silicate rocks (skarns), carbonate rocks and quartz rocks found in the region. In addition, the mafic dykes, and larger mafic bodies, which are crosscutting all the above-mentioned rock types, are included in this term. In his personal comment in 2022, Asko Kontinen suggests that also the (Upper Kaleva) greywackes, black shales and their carbonate rock intercalations surrounding the ophiolite should be included in Outokumpu Assemblage (Figure 2).

The GEOMEX itself was a joint venture project between Outokumpu Mining Oy and Geological survey of Finland that started at the end of 1990's. The very thorough GEOMEX project's final technical report "*Description and genetic modelling of the Outokumpu-type rock assemblage and associated sulphide deposits*" was published in 2006 by Asko Kontinen, Petri Peltonen and Hannu Huhma. In this thesis, the word GEOMEX refers to this final report.

1.3 Aims of the study

The question about actinolite skarns in Kylylahti rose in 2015 when I was core logging and mapping the rocks underground at Kylylahti mine. The logging sheets of Boliden Kylylahti had a rock type called actinolite skarn which was used somewhat arbitrary by different geologists. Some used it as a trash can rock type for all dark, amphibole-bearing rocks. Problem was that these rocks had a big variation in their appearance and geochemical characteristics as measured with portable XRF device during the core logging. Many Kylylahti geologists doubted whether there is actinolite at all in Kylylahti, speculating that all dark amphiboles are just dark coloured tremolite and in some cases possibly hornblende. Thus, some improvement in classification of these "trashcan rock types" was obviously needed.

Another poorly researched rock type were the cummingtonite-skarns which occur in connection with serpentinites, quartz rocks and mafic units. These cummingtonite-bearing rocks are out the scope of this study and were left out. The overall amphibole mineralogy of Kylylahti looks quite complicated and I hope this thesis will shed some light into it.

Samples collected from an east-west oriented diamond drill profile, which crosscuts the whole deposit from surface down to approximately 1400 m depth, were used to study the amphiboles. All drill holes of the section were relogged with the help of pXRF analysing as a basis for the sampling. A representative set of the samples were subjected to a wide range of laboratory studies, including whole rock analysis as well as petrographic studies with a polarizing microscope and FESEM/EDS.

Using the information from the re-logging and lab studies I will classify the skarns/skarnoid rocks with dark amphiboles in main groups and determine their mineralogy. I will see what kind of variation there is between the rock types both mineralogically and geochemically.

1.4 Skarns in general

1.4.1 Historical and modern definition of skarns

If Outokumpu assemblage is a problematic term, so is skarn. Skarn is an old 19th century mining term from Persberg, Sweden, where it was used to refer to the waste rock of the mine. It was first brought in literature by A.E. Törnebohm in 1875 (Meinert et al. 2005). It has since been used inconsistently to name many metamorphic rock types from hornfels-like isochemical metamorphic rocks to metasomatically altered carbonate rocks. Einaudi et al. (1981) suggested to reserve the term to be used only about certain calc-silicate rocks that have “the right mineralogy”, forgetting all genetic restrictions. Complete skarn mineralogy list can be found in literature or from a very practical webpage by Lawrence “Larry” Meinert (Meinert, 2022).

IUGS Subcommission on the Systematics of Metamorphic Rocks, Zharikov et al. 2007 states: “Skarn is a metasomatic rock formed at the contact between a silicate rock (or magmatic melt) and a carbonate rock. It consists mainly of Ca-Mg-Fe-Mn- silicates, which are free or poor in water.”

In IUGS classification skarns are one family of metasomatic metamorphic rocks.

1.4.2 Skarns and most common types of skarn deposits

Skarns are metamorphic rocks that are found on all continents and although in most skarn assemblages carbonate rocks are present, they can be formed without them. Metamorphism is needed, but it can be either contact or regional. Fluids needed in the metasomatic process that forms skarns can be of any origin: magmatic, meteoric, metamorphic, or marine. And a combination of any of those. They usually occur near plutons, that produce the heat needed in the alteration process, but can also occur on shear zones, faults, sea floor, shallow geothermal systems and deeper in the crust (Meinert et al. 2005).

Parts of skarn formations holding economically significant mineralization are called skarn deposits. They can be divided in many ways: Endo- and exoskarn when describing the protoliths igneous or sedimentary origin. Terms magnesian skarn or calcic skarns refer to the protolith composition which affects the resulting skarn mineralogy (Meinert et al. 2005). One common way of classifying the skarn deposits is by their economical metal content: Au, Cu, Fe, Mo, Sn, W, and Zn-Pb (Meinert et al. 2005).

1.4.3 What is special about Outokumpu skarns

Outokumpu Alteration Assemblage skarns are not directly related to sedimentary or any organic carbonate rocks, although they are enclosed in such rocks. Kontinen et al. (2006) notes that Outokumpu skarns occur the thickest when flanked with Upper Kaleva black shales, that commonly contain carbonate-rich interbeds which have tremolite in them and could be called sedimentary related skarns. Outokumpu Alteration Assemblage skarns are derived from mantle ophiolite through multi-phase hydrothermal alteration. After their emplacement, later deformation and metamorphism events have affected these skarns by adding and removing material.

When looking at mineralogy, Kylylahti almost completely lacks the most common skarn minerals – garnet and pyroxene. Instead, the most abundant skarn mineral is tremolite. The reason for this is the compositional difference compared to most common skarns in the world.

In Kylylahti, some of the skarns occur as large masses. In these cases, probably Si-rich fluids have reacted with carbonates and formed the common skarn mineralogy in Kylylahti which consists of Cr-rich tremolite, dolomite and calcite and sometimes micas and quartz. Other common type of skarn in Kylylahti are replacement skarns that can be found in quartz rocks, formed probably by CO_2 rich fluids entering already completely leeched, mantle derived quartz rocks. These fluids also carried sulphides with Cu, Ni, Co, Zn and Au, which precipitated cogenetic with the crystallization of tremolite (A. Kontinen, personal comment 2023). Pictures of these replacement skarns can be found later in thesis. In Kylylahti, they are an important host lithology for disseminated (Au)-Ni-Co-Cu ores.

2. GEOLOGICAL SETTING AND THE ROCKS IN AND AROUND KYLYLAHTI

Most of the Outokumpu area belong to North Karelian Schist Belt (NKSB), which is surrounded by the Archaean craton in the east and northeast. Archean windows can be found inside NKSB both east and west of Outokumpu and Kylylahti. The road from Polvijärvi to Joensuu is crossing on one of these windows, known as Sotkuma dome. The Archaean windows consists of TTG gneisses. Southwest from NKSB there are the collage of Paleoproterozoic island arcs brought in contact with the Karelian Craton by the Svecofennian (Svecokarelian) orogeny (Peltonen et al. 2008 and references therein).

Oldest of the Paleoproterozoic rock units belonging in Karelian supergroup can be found east and north-east of lake Höytiäinen. They belong to tectofacies of Sariola-Jatuli (Kohonen & Marmo 1992). Sariola-Jatuli rocks differ quite a lot from each other. Kyykkä group consists of arkosites, and conglomerates are glaciogenic. Herajärvi group are alluvial quartzites. These quartzites can be seen when climbing on top of Koli, which is one the iconic national landscapes of Finland. Southernmost group is called Kyykkä, consisting of quartz- and sericite schists and some paleosols (Kohonen & Marmo 1992).

The western parts of North Karelian Schist Belt have traditionally been divided into autochtonous lower Kalevian Höytiäinen basin and into allochtonous Outokumpu region. Parts of the Höytiäinen basin are upper Kalevian but are considered autochtonous (Lahtinen et al. 2010). Lower Kalevian rocks are complex array of mica schists and mica bearing metasandstones. Upper Kalevian metamorphosed sedimentary rocks in Outokumpu/Kylylahti region are homogenous metagreywackes without vulcanite interlayers. Claesson et al. (1993) have dated Upper Kaleva detrital zircons using U-Pb method, and concluded, that the maximum depositional age is 1.92 Ga. In their own studies, Lahtinen et al. (2010) ended up having depositional ages of 1.95 – 1.92 Ga. Allochtonous parts were overthrust onto current location between 1.92 and 1.87 Ga ago (Peltonen et al. 2008). These Upper Kaleva rocks are surrounding Kylylahti on all sides and are drawn in light blue in figure 3.

In this thesis, the rocks are divided in and around Kylylahti into four units: Kalevian meta-sedimentary rocks, sulphide ores, ophiolithic meta-ultramafites (OUM) and mafites (OBA) and most importantly the hydrothermally altered, ultramafic derived carbonate rocks, quartz rocks and skarns (OME). The ultramafic-mafic unit with all hydrothermally altered former mantle rocks are called Outokumpu Alteration Assemblage (Fig. 2).

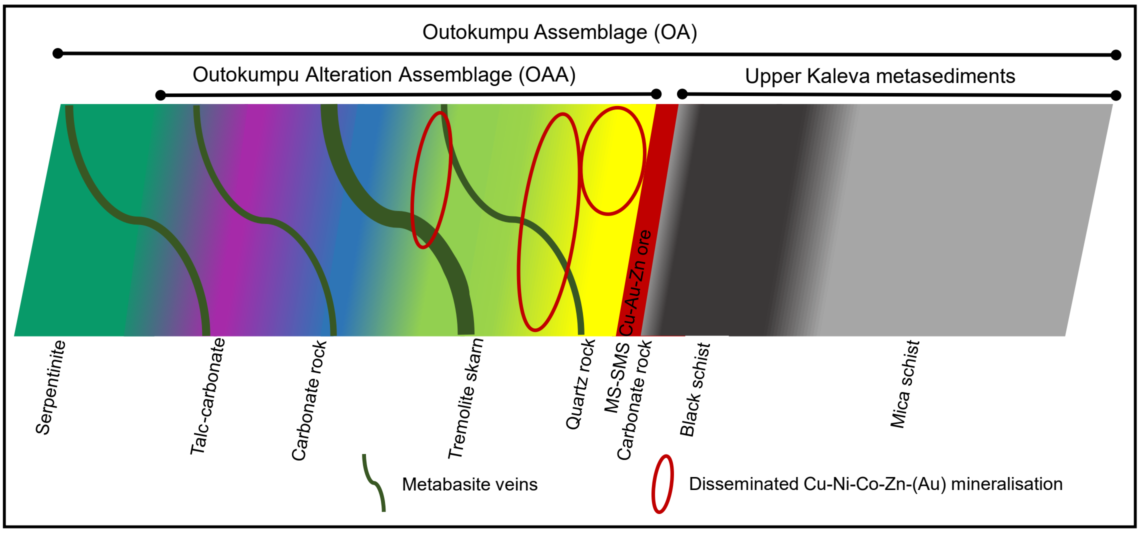

Figure 2. Simplified schematic picture of mineralized Outokumpu Assemblage in Kylylahti. Note the fading contacts of different rock types in OKU-assemblage versus sharp contact in both sides of massive ore.

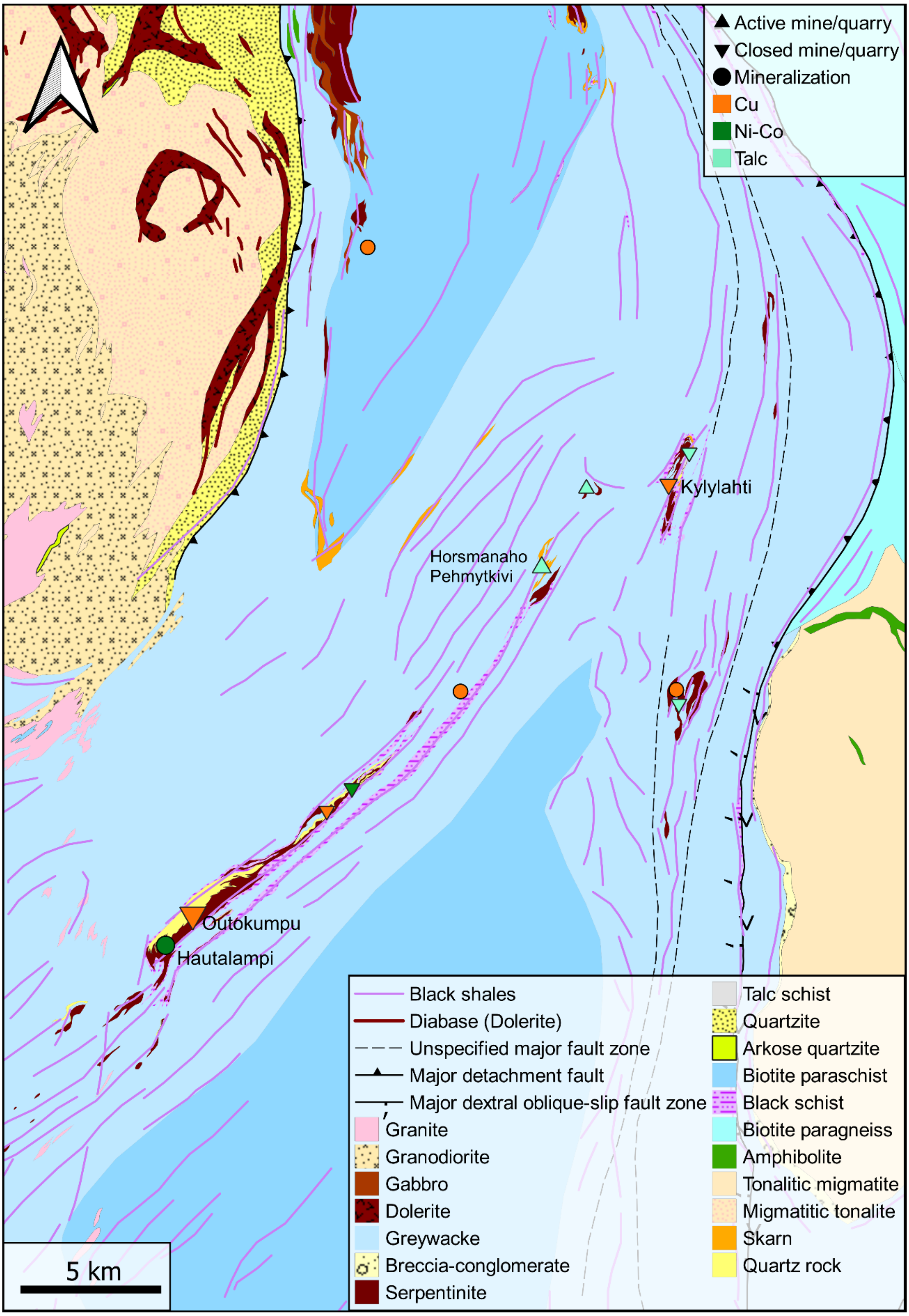

Figure 3: Detailed bedrock map of Outokumpu region. Compiled and modified from GTK's online map data of Bedrock of Finland 1:200 000 and Mineral Deposits of Finland 23.11.2022.

2.1 Upper Kalevian (Upper Kaleva) metasedimentary rocks near Kylylahti

2.1.1 Mica schists

The allochtonous (Peltonen et al. 1996) Upper Kalevian metaturbidites have metamorphosed into mica schists around Kylylahti deposit (Fig. 4). They are intensively folded and contain multiple sheets that have been pushed onto current location from direction that now lies in west. Mineralogy wise, these grey, monotonous (chemically and visually) metagreywackes consist of fine to medium-grained biotite, quartz and felspars. Any aluminous porphyroblasts, such as garnet or staurolite, are rarely present even though the metamorphic conditions would allow it (Kontinen et al. 2006). According to drill core observations, this applies well to Kylylahti.

Figure 4. Typical mica schist of Kylylahti showing compositional banding and varying grainsize of micas. Core diameter 57.5mm.

2.1.2 Black schists

Black schists in Kylylahti are multiply folded packs of banded, graphite and sulphide rich metamuds (Fig. 5). Main minerals are very fine-grained quartz, feldspars, micas, pyrite (sometimes pyrrhotite), clay minerals and of course graphite, which gives colour for the entire rock type. They have intervals of more siliceous, turbiditic material and sometimes even mica schists enclosed in the fold structures. According to Kontinen et al. (2006), these pose a clear proof of all Outokumpu black schists belonging into Upper Kaleva allochthon. In Kylylahti, P content is somewhat higher than elsewhere in Outokumpu. On average, black schists in Kainuu – Outokumpu area contain 7% S and C (Loukola-Ruskeeniemi, 1999).

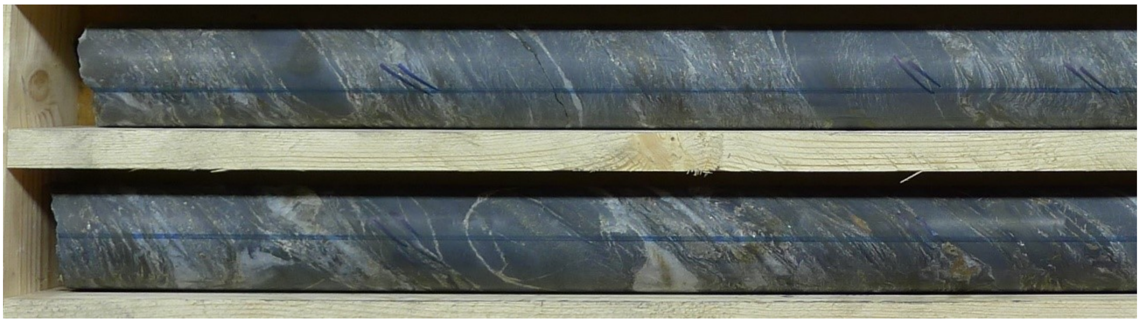

Figure 5. Typical sulphide rich black schist of Kylylahti with intense folding. Blue marks are from core orientation. Core diameter 57.5mm.

2.1.3 Upper Kaleva carbonate rocks

In Kylylahti, this tricky unit is located right at the contact of black schists and massive sulphide ore (leftmost light gray in Fig. 2). It is few tens of centimetres to couple meters wide, light grey calcite and possibly other carbonate dominated rock with occasionally occurring black tremolite porphyroblasts, iron sulphides and chalcopyrite. This unit is always present in the Kylylahti ore environment, and it is presently not established, whether it is after hydrothermal alteration of the black schists related to the ore forming processes, or just a carbonate rich layer within the metasedimentary rocks.

In GEOMEX report by Kontinen et al. (2006) it is mentioned that rocks with similar descriptions, such as “black tremolite skarns” have been core logged by Outokumpu Mining geologists. For this reason, some samples from this lithology were selected for analysis. These samples form the CRB-Actska group that is later introduced with pictures in section 3.2.2.

2.2 Ultramafic sequence

The ultramafic rocks in Outokumpu assemblage belong to partly discontinuous chain of ultramafic lenses that range from Outokumpu to Jormua in Kainuu. They are considered fragments of Paleoproterozoic ophiolite (Koistinen 1981). The ultramafics in Outokumpu region are crosscut with mafic magmatism that have same age with the mafic magmatism in Jormua ophiolite further north (Huhma 1986; Kontinen 1987;

Peltonen 2005). Unlike the complete stratigraphic ophiolite sequence in Jormua, the Outokumpu ophiolite only has mantle metaperidotites without pillow lavas, hyaloclastites, or other common ophiolite units.

Serpentinization, metasomatic alteration and regional metamorphism have all left their mark the Outokumpu peridotite massifs (Peltonen 2005). All the ultramafic bodies and their alteration products, described in chapter 2.3, are surrounded by upper Kaleva metasediments as shown in figure 6. Shape wise, these ultramafic bodies are somewhat cigar-shaped, elongated pods that can be hundreds of meters long. Mostly they consist of serpentinites and talc-carbonate rocks, which are also called soapstones. Chemically, they are equivalent to depleted mantle harzburgites, dunites and lherzolites (Säntti et al. 2006).

Based on isotope data, these ultramafic and crosscutting mafic rocks represent upper mantle rocks that were exposed while Karelian craton rifted open 1.97-1.95 Ga ago (Peltonen et al. 2005).

2.2.1 Serpentinites and metamorphic conditions of the area

Outokumpu ophiolite is considered to originate from shallow water rift system, where upper mantle peridotites were lying under very thin oceanic crust. Unaltered peridotites have not been found in Outokumpu region. Only the core parts of some chromite crystals have remained unaltered through multi-phase metamorphism (Säntti et al. 2006).

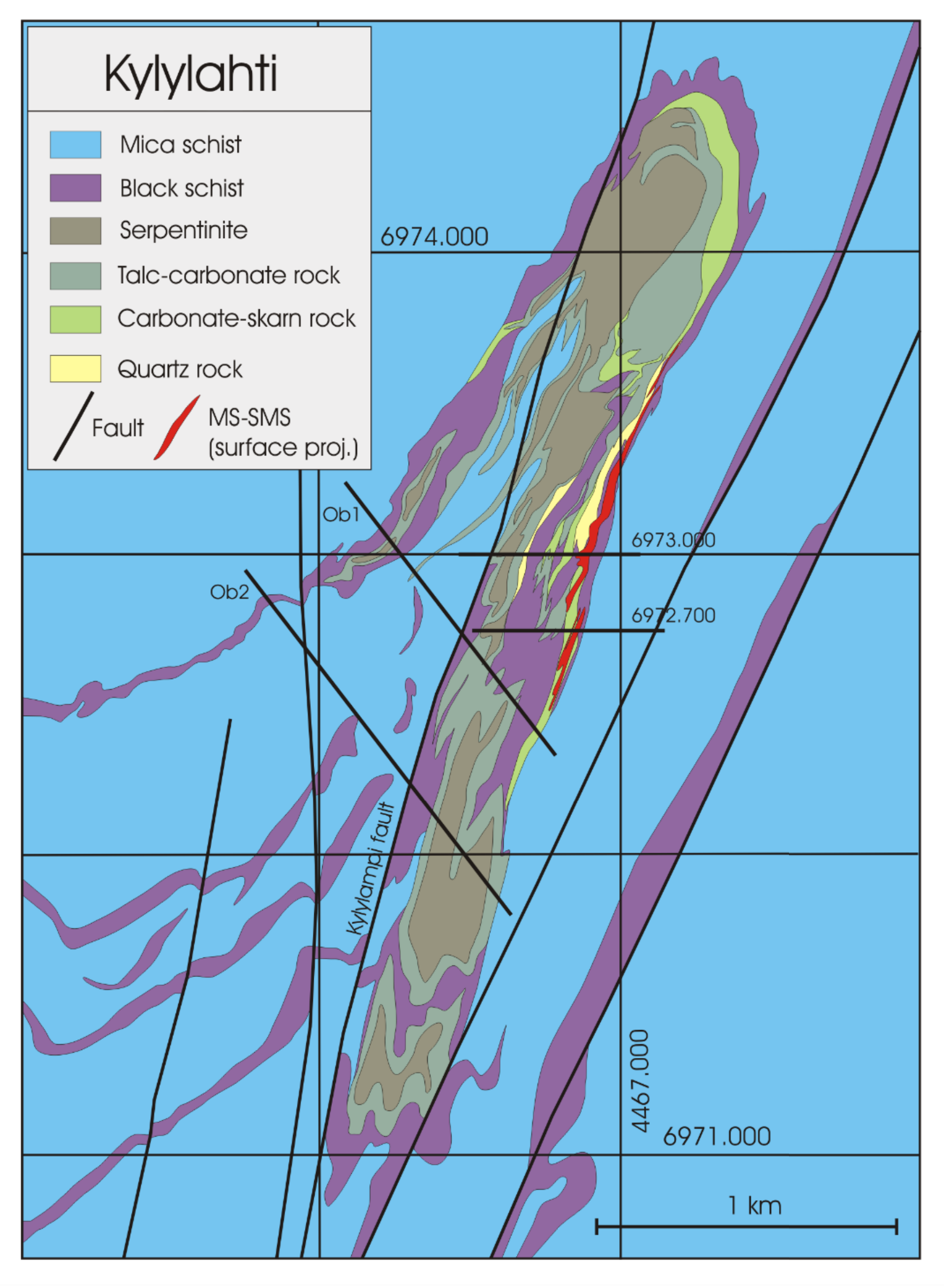

Figure 6: Kylylahti syncline and detailed geological map from Kontinen et al. (2006)

Väyrynen (1939) writes that the serpentinization of the ultramafic bodies was thorough before the Svecofennian orogeny, which eventually emplaced the ophiolite bodies in their modern locations. Säntti et al. (2006) inferred that the bodies were low-T serpentinites before their synorogenic metamorphism in the E in amphibolite facies conditions in roughly 500-550 C temperatures which resulted in antigorite serpentinites. Serpentinites around Kylylahti deposit belong to this zone. Towards S-SW, the intensity of metamorphism increases in the way outlined in Figure 8. The diagnostic mineral assemblages in cores of large ultramafic bodies (low-pCO_2) in the metamorphic zones distinguished by Säntti et al. (2006) are as follows:

A: 500-550°C antigorite ± olivine ± tremolite
B: 550-675 ˚C olivine + talc
C: 665-700 ˚C olivine + antophyllite ± cummingtonite
D: 700-775 ˚C olivine + enstatite ± antophyllite ± Mg-Al-spinel

In Kylylahti sometimes olivine porphyroblasts are present in serpentinites. These porphyroblasts are later altered into lizardite-chrysotile serpentine in retrograde metamorphism but the shape of olivine can still be seen (Fig 7).

Figure 7. Serpentinite with coarse grained carbonate vein on top left. Note the olivine porphyroblasts that have later altered in retrograde metamorphism into serpentine. Drillcore is pictured wet. Core diameter 40.7mm.

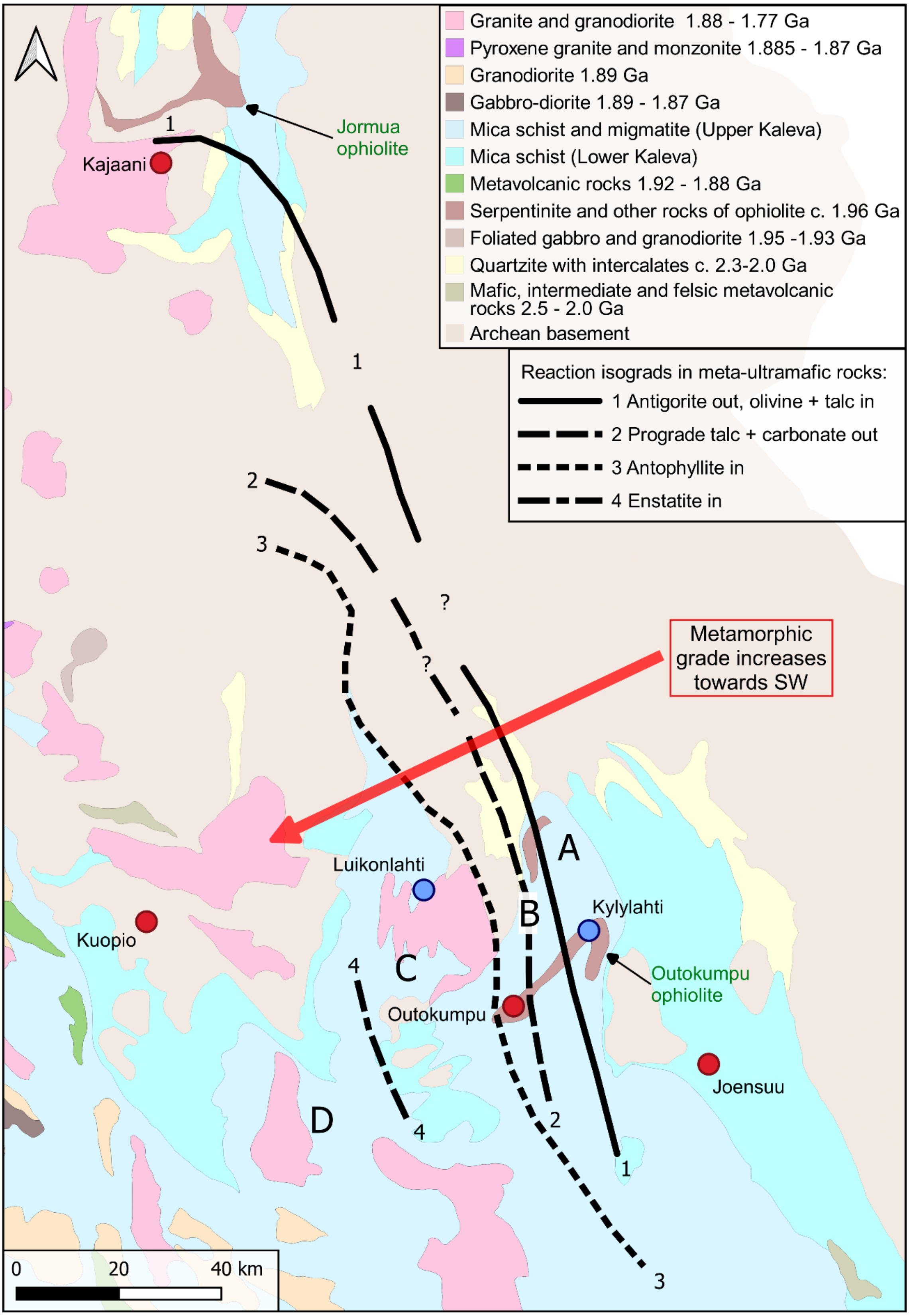

Figure 8. Metamorphic conditions of Outokumpu region, increasing towards SW. Modified from Säntti et al. (2006) and GTK's online map data of Bedrock of Finland 1:5 000 000 23.11.2022.

2.2.2 Talc-carbonate rocks

In metamorphic zone A (Fig. 8) characterized by antigorite, the outer parts of serpentinite massifs have altered into talc-carbonate rocks (Säntti et al. 2006). Kylylahti locates within this zone and there was a talc quarry right next to Kylylahti mine called Vasarakangas. Also, company called Elementis (formerly Mondo Minerals) mines talc from Horsmanaho-Pehmytkivi (Fig 3.) and Karnukka quarries. In Kylylahti, lots of soapstones and pure talc schists are present (Fig. 9). In terms of texture the soapstones vary from fine grained, almost massive rocks to high-talc rocks with coarse, round carbonate porphyroblasts. Contacts to serpentinite are usually gradual, and talc can sometimes be found in other Outokumpu Alteration Assemblage rocks, too.

Figure 9. From bottom right to upper left, porphyroblastic, talc-rich serpentinite fading into light grey talc-carbonate rock. Core diameter 39mm. Light conditions tint the rocks towards yellow.

2.3 Outokumpu metasomatically altered ultramafic rocks, the Outokumpu Alteration Assemblage OAA

Rocks belonging to this group, coloured blue, green, and yellow in Figure 2, are the main rock types in the ideal Outokumpu Alteration Assemblage, being carbonate, skarn and quartz rocks, respectively. This is the most common rock unit that was visible in Kylylahti mine as it hosts the disseminated ores that comprise the most voluminous ore units in Kylylahti. Contrary to the ideal assemblage, these different rock types were in many places in reworked order due to multi-phase isoclinal folding of the Kylylahti syncline (Kontinen et al. 2006).

In literature, this kind of alteration process is called listwaenite – birbirite alteration (Kontinen et al. 2006), but in common terms in formal and informal discussions and literature concerning Outokumpu rocks, those terms are rarely used. The best identification for Outokumpu Alteration Assemblage rocks is the high Cr content, which can reach up to several thousand ppm.

2.3.1 Carbonate rocks

According to Peltonen et al. (2008), the intervals of OAA carbonate rocks, that are coloured blue in figure 2, are usually only 1-5 meters thick. If thicker, they are a result of tectonic repetition. This is probably mostly true in Kylylahti, although there is a large, tens of meters wide area where relatively pure, metasomatic carbonate rock belonging to this sequence is the dominant rock type. Mainly, carbonate rocks of Outokumpu assemblage are coloured from light grey to creamy white (Fig. 10). Grainsize is commonly much coarser than in Upper Kaleva metasedimentary carbonates or in talc-carbonate rocks. Main minerals are dolomite, magnesite, calcite and tremolite. Commonly present are micas, that form bands or kidney-shaped ovoids/spheroids that remind the outer edges of pillow lavas. I sometimes mapped them as “pillow structure” although they have nothing to do with actual pillow lavas. Chromites are sometimes coarse enough to be visible with eye. Graphite is also common, but not in large quantities. In addition to slightly different colour and grain size, the best way to distinguish these OAA carbonate rocks from Upper Kaleva metasedimentary carbonate rocks described in section 2.1.3 is the high Cr content, which can be up to several thousands of ppm.

Figure 10. Outokumpu Alteration Assemblage carbonate rock. Tiny slightly elongated black specks are chromite crystals. Veinlets of coarser carbonate, usually calcite, cross-cutting through the dolomite-calcite-tremolite matrix. The amount of carbonate minerals greatly exceeds the amount of tremolite. Lighting conditions tilt the colour slightly towards yellow when compared to daylight. Hole KU-656, core diameter 40.7mm.

2.3.2 Skarns

In Kylylahti, skarns are practically always tremolite skarns. Diopside is rare, I encountered only few diopside skarns that in terms of core intervals were not longer than a couple of meters. However, diopside skarns are the dominant type in Outokumpu region where peak-metamorphic temperatures were higher than in Kylylahti (Kontinen et al. 2006). Skarns in Kylylahti have visual and geochemical variation, which was a reason for this thesis. The most common type is the usually light green to green tremolite skarns that typically occur between carbonate- and quartz rocks (Peltonen et al. 2008, figure 2). The green colour is sometimes faint and can be seen in wet rock, only. Mineralogy is quite simple: Tremolite, dolomite ± calcite and quartz (Fig. 11). Sometimes present are phlogopite and chromite. When close to metabasite veins, chlorite, titanite and rutile are present and Fe content is increased. Also, talc can sometimes be found, in such rocks tremolite, which usually occurs as slender prisms, tends to be partly fibrous. Tremolite skarns in Kylylahti almost always host a variety of disseminated sulphides, mainly pyrrhotite and pentlandite. Most of the time they are only lowly mineralized in Ni, but some tremolite skarn domains in Kylylahti host enough metals to be ores as is described in section 2.5.2.

One important skarn type in Kylylahti are the replacement skarns that occur in quartz rocks, being variably mineralized in Cu-Zn-Ni-Co-(Au) near the massive-semi massive ore bodies. Representative, mineralized example of replacement skarn can be seen in Figure 16.

Figure 11. Picture of wet, unmineralized tremolite skarn from hole KU-656. Green Cr-tremolite, dolomite, calcite, and some quartz. Core diameter 40.7 mm.

2.3.3 Quartz rocks

The outermost part of the Outokumpu Alteration Assemblage are the quartz rocks (Kontinen et al. 2006, yellow in Figure 2). They are the most Mg-leached part of the ophiolite/OAA and occur in Kylylahti in abundance, usually flanked by Upper Kaleva metasedimentary rocks, especially where there are graphite-sulphide rich black shales. They are banded, fine grained, sometimes schistose rocks that usually carry some graphite pigmenting them grey to dark grey (Kontinen et al. 2006). Main minerals are quartz and tremolite with some chromite, fuchsite, titanium minerals and often some disseminated sulphides, mostly pyrrhotite and sometimes pyrite (Fig. 12). In places, especially near the massive-semi massive ore bodies, quartz rocks of Kylylahti occur with replacement skarn that commonly hosts metals of economic value.

Figure 12. Left: Banded quartz rock of Kylylahti. Quartz, turquoise fine fuchsite, and not so common brown band that is most likely titanite and rutile or iron oxides, as is observed in similar Kylylahti quartz rock samples. Small, blackish specs are slightly elongated chromite crystals. Tape width is 26 mm. This sample nowadays belongs to Outokumpu Mining Museum collection. Right: Same minerals from drillhole KU-933. Core diameter 40.7mm.

2.4 Crosscutting mafic units

Kontinen et al. (2006) write the following: “*In addition to the thicker dykes and plugs of more or less clearly metagabbroic amphibolites, the Polvijärvi serpentinites locally contain also narrow (mostly 5 cm to 2 m) metabasite dykes, usually pervasively altered to chlorite schist, but occasionally with metagabbroic or amphibolitic core parts. Those dykes seem to be fairly abundant in parts of the in the Kylylahti and Sola massifs, especially.*” It needs to be noted, that Polvijärvi serpentinites refer also to other ophiolite fragments than Kylylahti. However, the mafic units in Kylylahti can be significantly wider than the 2 meters mentioned in GEOMEX, ranging from few centimetres to several tens of meters (Fig. 13). Sometimes they indeed have their core parts less altered and resemble amphibole-rich metagabbros and sometimes they are just pure chlorite schists. Lack of metagabbroic core parts could also be caused by tectonic repetition of thinner sills and dykes.

These mafic units cross-strike all other Outokumpu Alteration Assemblage rocks and serpentinites. They are marked with dark green in figure 2. Mafic units are not found in surrounding Upper Kaleva metasedimentary rocks. These mafic rocks also host the disseminated ores in some areas in Kylylahti.

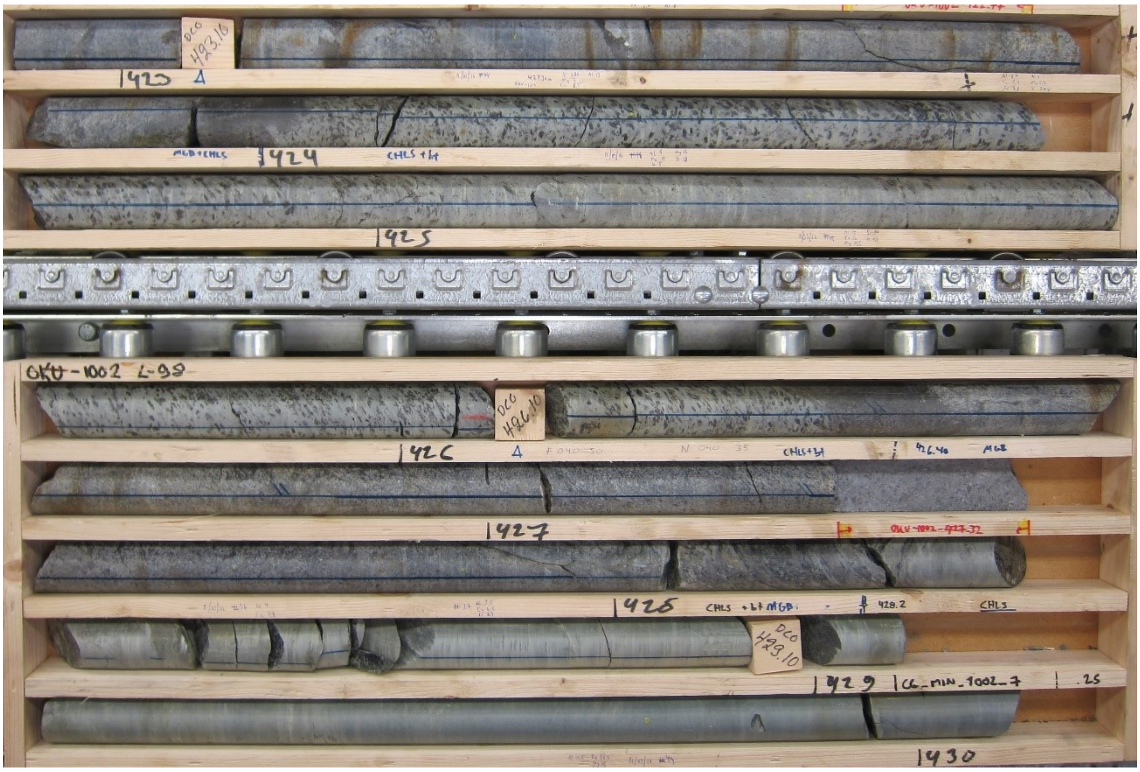

Figure 13. Variable mafic rocks within one sill/dyke. From 426.4 to 428.2 meters metagabbroic texture. On top of that, light green chlorite schist with biotite stacks that look like amphiboles. From 428.2 onwards, only silky, light green pure chlorite schist. Hole OKU-1002 from Kylylahti syncline’s western limb. Core diameter 50.6mm.

2.4.1 Chlorite schists

Chlorite schists are the most abundant form of mafic rocks in Kylylahti. They are mostly rather narrow <5 m dykes, but in some places, they could be tens of meters wide. Chlorite schists vary chemically (Kontinen et al. 2006) a lot and therefore, their appearance, especially colour, varies a lot. In serpentinites, they are from blue to dark green and therefore not particularly eye-catching. In talc-carbonate rocks they usually vary in shades of grey, green and light brown. Most common colour in mined areas in Kylylahti are different shades of dark green, although grey and brown variants are sometimes seen. Sometimes they contain, besides chlorite, also dark amphibole prisms that are usually unaligned, micas, magnetite, and different sulphides, mainly pyrrhotite. The chlorite schists are always schistose and may be folded. These dikes are almost always slightly undulating. Long straight contacts are rarely seen underground. In Kylylahti, some exchanges of elements have happened in the carbonate-skarn-quartz rock zone between the “wall rocks” and chlorite schists (Kontinen et al. 2006). This is clearly visible, especially when core logging with pXRF. Higher Fe and Ti are good indicators of this, along with the general, usually darker appearance and mineral assemblage that has Ti-minerals and chlorite in addition to tremolite skarns, carbonate minerals and quartz. Sample group OBA-Actska, introduced in section 3.2.5, consists of these rocks. Chlorite schists hold significant disseminated mineralization and were mined in some areas in Kylylahti.

2.4.2 Metagabbros

Metagabbros or amphibolites are not very common lithology in Kylylahti. Sometimes the core parts of wider chlorite schist intervals have more granular, amphibole and possibly plagioclase bearing rocks that have gabbroic texture, at least when compared to pure chlorite schists.

2.4.3 Cummingtonite skarns

Cummingtonite skarns are grouped under mafic rocks due to their chlorite content. Kontinen et al. (2006) have interpreted these rocks to be late fracture controlled, altered antigorite serpentinites. Indeed, in Kylylahti, cummingtonite is sometimes present in serpentinites. In addition to this, these cummingtonite skarns can be found far away from the serpentinite bodies. Their host mineral association is completely different though, consisting mainly of chlorite. Hannu Makkonen (pers. comment, 2019) suggests, that such rocks can be formed with hydrothermal alteration and mass transfer of chlorite schists and quartz rocks, which commonly occur together in Kylylahti. This rock unit needs more study as it also can host disseminated ores.

2.5 Mineralisation

Even after more than 100 years of mining and academic research, the origin of Outokumpu ores is still somewhat shrouded in mystery. The most complete, thorough model is presented in the GEOMEX ore modelling report by Kontinen et al. (2006), which has later been somewhat updated by Peltonen et al. (2008). Simplified, the model consists of three phases: In the first phase, Cu proto-ores were formed c. 1960–1950 Ma ago in an oceanic ridge or transform fault environment by seawater convection within a seafloor that consisted mainly of mantle peridotite. The second phase (c. 1900 Ma) happened during the obduction stage where parts of the mantle peridotite were thrust enclosed in Upper Kalevian greywackes and black shales on the Karelian craton. During and/or shortly after the obduction metaperidotite body margins became altered into listwaenite-birbirite type carbonate-quartz rocks described in section 2.3. The alteration freed nickel from Fe-Mg silicates (mainly olivine), which was incorporated into sulphide phase to form low grade Ni proto-ores. The sulphur for the nickel mineralization came from the enclosing black schists. In phase 3, both of these proto-ores were re-mobilized and mixed.

2.5.1 Massive-semi massive Cu-Co-Zn-Au sulphide mineralisation

At the last stages of phase 3, the Cu proto-ore was completely remobilised, mixed with Ni proto-ore, and hydrothermally emplaced in the quartz rock – black schist contact (Kontinen et al. 2006, Peltonen et al. 2008). These rich ores contain 25 to 60% sulphides. Main minerals are pyrite, chalcopyrite, sphalerite, quartz, and gold. Sometimes pyrrhotite is present, but it hosts practically no Ni-Co minerals such as pentlandite. Pyrite is almost always either massive or consists of recrystallized “blebs” roughly in size of adult fingerprint (Fig. 14). Part of the Fe in pyrite’s crystal lattice is replaced by Co, which causes anomalous Co grades in pyrite. Total Co grades in these massive – semi massive ores however were never economic because Co is in pyrite, not in much more favourable minerals like pentlandite. Boliden has an ongoing (2022) development project of finding an economically feasible process for recovering this refractory cobalt in pyrite that is stored in tailings ponds at Luikonlahti Mill.

Figure 14. 26cm wide massive Cu ore sample from Kylylahti mine. Chalcopyrite is slightly oxidized. Pyrite is in roundish “blebs”. This sample contains 15-20% Cu, some Zn, Co and Au.

Structure-wise, the massive - semi-massive mineralisation at Kylylahti occurs in three elongated lenses, which strike to the N-NE, dip near vertically to the northwest and plunge at between 25° and 40° to the S-SW. Total length of this system is approximately 1.5 kilometres. Lenses are 5 – 50 meters wide, always narrowest at the northern and southern ends. Height of these lenses were roughly 150 meters. Contact to footwall side metasediments is always rather sharp, although sometimes some chalcopyrite has “leaked” to carbonate metasedimentary rocks, the CRB-Actskas in this thesis. On hanging wall side, which is the side of Outokumpu Alteration Assemblage, the contacts can be sharp (Fig. 15) or somewhat fading. The fading effect of the contact zone could also be caused by the disseminated orebodies common location right next to the massive ore. Average grades for massive – semi massive Cu-Zn-Au ores mined in 2019 are presented in table 1.

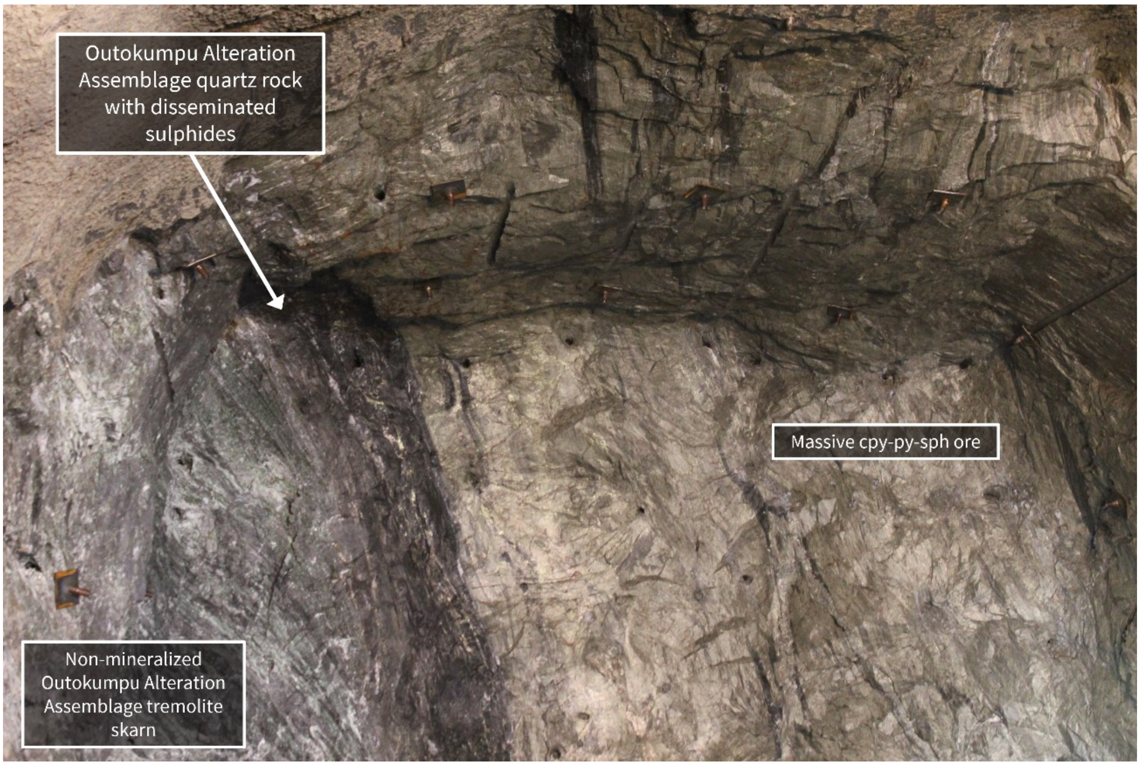

Figure 15. On the right side is massive, strained sulphide copper ore with chalcopyrite and pyrite as main minerals. To the left there is roughly 50cm wide interval of mineralized quartz rock followed by green tremolite skarn that has no disseminated sulphides present. Picture taken by unknown Altona Mining geologist from production level 470 that is roughly 550 meters below surface. Tunnel is roughly 4.5m wide.

Year	Cu %	Zn %	Au g/t	S %	Ni %	Co %	Mined Tonnes
2019	1.64	0.82	0.46	15.38	0.11	0.26	197669

Table 1. Average grades of massive – semi massive sulphide ores in year 2019. It needs to be noted that ores mined in Kylylahti were shifted towards disseminated zone towards the end of life of mine. In previous years the grades and tonnage of these ores were higher. Ni and Co concentrate was not extracted from this ore type.

2.5.2 Disseminated (Au)-Ni-Co-Cu-Zn sulphide mineralisation

Disseminated Ni-Co sulphide mineralization can be best described by a halo of pyrrhotite and pentlandite that is surrounding the massive – semi massive ores on their Outokumpu Alteration Assemblage side. At some locations, these sulphides have accumulated into ore grades and can be modelled into 3D-lenses plunging in the same, approximately -30-45-degree angle towards south as massive – semi massive orebodies. Sometimes no gold is present, and some lenses in the western side are lacking Cu almost entirely. Also, Kokka-type (Kontinen et al. 2006) Ni-mineralized zone can be found in Kylylahti that is characterized by mostly low mantle-like Co/Ni ratio as the quartz rocks in general. The disseminated ores and other mineralized areas in Kylylahti are hosted by wide range of rock types: carbonate rocks, tremolite skarns, chlorite schists and other mafic rocks, quartz rocks and cummingtonite skarns. Significantly back-ground exceeding mineralization are not found in talc-carbonate rocks or serpentinites (Fig. 2), so they seem to be restricted to the OAA environment only.

Mineralogy of the disseminated ores follow the host rocks composition: If the ore is hosted in tremolite skarns as in Figure 16, then the gangue minerals are obviously the common skarn minerals listed in section 2.3.2. Ore minerals include gold, chalcopyrite, pentlandite (various amounts of Co) linnaeite-polydymite and sphalerite. Trace ore minerals include violarite, cobaltite and still unnamed CoFeAsS mineral (geometallurgy study, Boliden Kylylahti 2018, not published). Average grades for these disseminated ores mined in year 2019 are presented in table 2.

Year	**Cu %**	**Zn %**	**Au g/t**	**S %**	**Ni %**	**Co %**	**Mined Tonnes**
2019	0.41	0.18	1.05	5.59	0.28	0.15	482989

Table 2. Average grades of all hanging wall disseminated zone ores mined in 2019. Zn concentrate was not extracted from this ore type.

Figure 16. Disseminated ore in tremolite skarn from Kylylahti mine. Ore minerals include chalcopyrite, pentlandite and linnaeite-polydymite. Main gangue minerals are coarse Cr-tremolite, quartz, pyrrhotite, pyrite, dolomite, calcite and phlogopite. Sample is unanalysed, but based on its appearance, this is a rich disseminated ore with high grades of Cu, Ni, Co, and most likely Au. Sample width is 24cm. Sample collected by Mathias Backman from unknown location at Kylylahti mine.

3. MATERIALS

3.1 Drillcore profile

When planning the study, we wanted to choose a drill core profile that would represent the geology of Kylylahti well, including not only the ore types but country rocks, too. Therefore, the profile should be a simple E-W crosscut that would go somewhat perpendicular to N-S trending Kylylahti formation and reach the depth of 1000m from surface. Such 500 meters wide E-W profile was found roughly at 6972600N in ETRS-TM35FIN coordinate system.

Total of 12 holes were selected to be inspected, including 10 study holes and 2 on reserve in case sampling was not possible from the primary holes, due to missing core or other issues (Table 3).

Drill site	Hole Id	Status
Surface	OKU-1000	relogged
Surface	OKU-1002	relogged
Surface	OKU-999	relogged
Underground	KU-584	relogged
Underground	KU-656	relogged
Underground	KU-681	relogged
Underground	KU-718	reserve
Underground	KU-900	reserve
Underground	KU-916	relogged
Underground	KU-917	relogged
Underground	KU-933	relogged
Underground	KU-934	relogged

Table 3. List of studied drill holes

3.2 Definition of 5 types of the study and related sample list

To make some sense to the rag-tag rock group called actinolite skarn in Kylylahti drill-core logs, the study needed a complete, more thorough re-logging of the core, in which the subject rocks were divided into four groups based on their visual appearance, chemical composition (pXRF), and surrounding rock types. Selected drill core profile provided a good array of different actinolite skarn samples. Portable XRF was vital a tool in this process and was regularly used in the core logging. Also, three extra samples from the same drilling profile were selected to act as pure “end member” type samples, such as Cr-rich tremolite skarn of sample KU-917-243.65. These were planned to act as reference for comparison to actinolite skarns. Asko Kontinen from Geological survey of Finland reviewed all chosen samples and gave suggestions. At the end of re-logging of the core, total of 4 different Actska sample groups and 1 end member reference sample group were established.

The first part of sample number comes from drill core and second number is the depth of sample in the drill core, not the actual depth from surface, as most drillholes are drilled from underground. For example, sample KU-681-102,78 is from hole KU-681 at hole depth of 102,78 metres.

All the following images in this thesis representing scanned drill core samples and scanned, polished thin sections were photographed in uniform lighting conditions to guarantee comparability of lighting and colours. Apart from their size, no other adjustments to images were made.

In the following the five different groups are described.

3.2.1 Reference samples

Two samples of what was considered typical tremolite skarn (Fig. 19) and similarly one sample of typical OAA carbonate rock were chosen to act as reference to which the actinolite skarn samples could be compared (Table 4).

Sample number **Sample lab numbers**	**Sample description**
KU-681-102,78 kwc-07, kag-07	Cu-bearing, Cr rich tremolite skarn type sample that could be used as a classic, Outokumpu Alteration Assemblage skarn rock. Either Si-rich fluid entered carbonate rock or vice versa.
KU-917-243,65 kwc-08, kag-08	Cu-void, bright green, very Cr rich tremolite skarn type sample that could be used as a classic, Outokumpu Alteration Assemblage skarn rock.
KU-916-194,85A and B kwc-11, kag-11	Interesting, yet typical sample of several different carbonate cycles in OKU-assemblage. Two separate thin sections were prepared from this core sample. Based on macro-scale examination, thin section B represents the earlier cycle and A has a vein that cuts through all previous cycles. These carbonation cycles have partially destroyed the skarn part of the sample.

Table 4. Reference samples

Figure 19. Sample KU-681-102,78 representing a common, Cu-bearing tremolite skarn rock that are abundant in Kylylahti. Core diameter 39 mm.

3.2.2 CRB-Actska, carbonate rocks at the contact to MS-SMS ore

This rock type is commonly located at the contact between massive - semi massive sulphide ore and black schists (leftmost light grey in Fig. 2). Sometimes this mainly dark-grey carbonate rock contains black, coarse amphiboles and therefore has been logged as actinolite skarn by some geologists and must be included in the study (Fig. 20). This unit is always low in Cr and geochemically appears as metasedimentary, Upper Kaleva rocks. According to GEOMEX report by Kontinen et al. (2006), Outokumpu drill core records commonly recognize rocks with similar description as “skarn black schists” or “black tremolite skarns”. Loukola-Ruskeeniemi (1991, 1999) also writes about tremolite-rich black schists and black calc-silicates that contain tremolite and/or diopside. Total of five samples were chosen to represent this group (Table 5).

Sample number **Sample lab numbers**	**Sample description**
OKU-1000-253,42 kwc-01, kag-01	Upper Kaleva carbonate-bearing metasedimentary rock near OAA-contact. Contains dark amphiboles.
KU-681-90,44 kwc-02, kag-02	Upper Kaleva carbonate-bearing metasedimentary rock at SMS-MS Cu-ore contact
KU-656-153,39 kwc-03, kag-03	Upper Kaleva carbonate-bearing metasedimentary rock near OAA-contact. Low S, no mineralization.
KU-656-82,66 kwc-04, kag-04	Upper Kaleva carbonate-bearing metasedimentary rock near OAA-contact. High S, some Cu.
KU-917-225,41 kwc-05, kag-05	Upper Kaleva carbonate-bearing metasedimentary rock near metres away from contact. Low S.

Table 5. CRB-Actska samples

Figure 20. CRB-Actska carbonate rock sample OKU-1000-253,42 with dark, coarse amphiboles, pyrite, and graphite in dark carbonate rock. Core diameter is 50.6 mm. Red marker shows area where thin section will be made.

3.2.3 OME-Actska, Outokumpu metasomatically altered actinolite skarn

This is an important sample group. Compared to other actinolite skarns, typical characteristics of this Actska are lighter green colour, but darker and more blue than traditional, green tremolite skarns in Outokumpu Alteration Assemblage in figure 19. The rock contains lots of carbonates and reacts well with hydrochloric acid. High chromium is always present in this unit. A representative sample is shown in figure 21. Five samples were chosen for this group (Table 6).

Sample number **Sample lab numbers**	**Sample description**
KU-681-19,66 kwc-18, kag-18	OAA actinolite skarn with bluish tint.
KU-934-90,34 kwc-19, kag-19	Coarse grained OAA actinolite skarn
OKU-1000-140,44 kwc-20, kag-20	Actska with dark carbonate rock
KU-916-242,82 kwc-21, kag-21	Actska with roughly 2 meters distance from OUM contact. Dark amphiboles.
KU-917-478,95 kwc-22, kag-22	Short skarn interval between OUM-units

Table 6. OME-Actska samples

Figure 21. OME-Actska with coarse dark and green amphiboles, carbonates, and pyrrhotite with minor pentlandite and chalcopyrite. Sample KU-934-90,34. Note the typical bluish tint of the rock. Core diameter 40.7 mm.

3.2.4 OUM-Actska, Outokumpu ultramafic sequence soapstones with dark amphiboles

These dark amphibole-bearing rocks consisting of talc and carbonates are sometimes present at the gradual contacts of talc-carbonate rocks and the actual tremolite skarns of OAA or enclosed in other OAA rocks, except quartz rocks. Carbonates are usually dark and fine grained, even massive (Fig 23). High in chromium. List of the three selected samples is presented in Table 7.

Sample number **Sample lab numbers**	**Sample description**
KU-681-21,19 kwc-24, kag-24	Dark grey, most likely soapstone interval inside OME-unit
OKU-1000-192,42 kwc-25, kag-25	Soapstone with darker amphiboles
KU-917-430,70 kwc-26, kag-26	Soapstone with darker amphiboles

Table 7. OUM-Actska samples

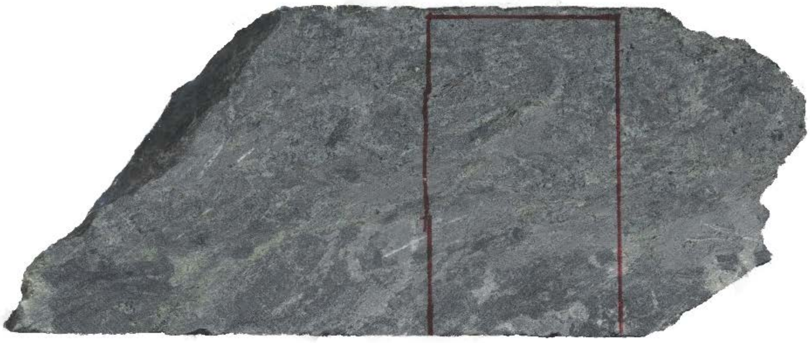

Figure 23. Fine-grained talc-carbonate rock with coarse, dark amphiboles. Sample OKU-1000-192,42. Core diameter 50.6 mm.

3.2.5 OBA-Actska, Outokumpu mafic component containing actinolite skarn

These actinolite skarns are located close to mafic rocks and may contain chlorite-group minerals (Fig. 22). These skarns have elevated in titanium and iron. Four samples were selected (Table 8).

Sample number **Sample lab numbers**	**Sample description**
KU-681-66,68 kwc-27, kag-27	Actska with high Ti and S
KU-681-118,30 kwc-28, kag-28	Actska with high Ti
KU-916-325,80 kwc-29, kag-29	Actska with chlorite
KU-917-304,05 kwc-30, kag-30	Fine grained dark rock with dark amphiboles. Contains chlorite and is close to OUM-unit.

Table 8. OBA-Actska samples

Figure 22. Sample KU-916-325,80. Dark amphiboles, chlorite, pyrrhotite. Core diameter 40.7 mm.

4. METHODS

After sampling, one thin section per each sample was prepared, except sample KU-916-194,85 that has two thin sections. Rest of the sample was crushed, milled, and sent to whole rock analysis. First, thin sections were studied by microscope and then further inspection was done by EDS to confirm petrographic observations. Finally, results from whole rock analysis from different groups were compared and visualized in diagrams.

4.1 Whole rock characterisation

All geochemical analysis were conducted by Bureau Veritas Minerals ACME Analytical Laboratories Ltd in Vancouver, Canada in 2016. Two different commercial standard samples provided by Geostats Pty Ltd were analysed together with both the agate and tungsten carbide milled sample sets, so a total of 4 standard samples were analysed.

4.1.1 Sample preparation

After cutting the samples from core and a selected piece from them for thin section, they were first crushed in jaw crusher. Then, a part of the crushed sample was extracted by spoon paying attention to carefully mixing the sample before extraction and making sure the selection included both fine and coarser rock fragments. This part was used in XRF whole rock major oxide characterisation. Identification codes of these samples start with “kwc” prefix.

Another part of the same crushed sample was milled in agate mill for ICP-MS trace element analysis and LECO total C, S and graphite analysis. These sample names start with “kag” prefix.

The sample preparation was carried at Oulu Mining School laboratory by me, except core cutting, which was done at Boliden Kylylahti facilities in Polvijärvi by Boliden personnel. Polished thin sections were prepared by Sari Forss at Oulu university.

4.1.2 Analytical methods for samples milled in tungsten carbide mill (kwc-xx)

Most common rock forming elements in oxides were analysed by X-ray fluorescence (XRF) in Vancouver using analytical package labelled XF700. Instead of an agate pan, a tungsten carbide pan was chosen for pulverization of these samples to prevent contamination by silica in the milling process. Analysed oxides are SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, Na_2O, K_2O, MnO, TiO_2, P_2O_5, Cr_2O_3, Ba, SO_3 and Sr. The results are reported in Table 9. Detection limits for each element are presented in Appendix 1.

4.1.3 Analytical methods for samples milled in agate mill (kag-xx)

Standard suite trace elements were analysed in Vancouver using analytical package code LF100-EXT, which includes procedure LF100 and AQ200. In addition, packages TC003 and TC005 were used. For all these samples, milling for analytical pulvers was done in agate pan to prevent contamination of W, C and Co as in tungsten carbide pan milling. Detection limits for each element is presented in Appendix 1.

Samples for LF100 were processed by lithium metaborate/tetraborate fusion and then dissolved in nitric acid before analysis by ICP-MS for the major elements and trace elements Ba, Be, Co, Cs, Ga, Hf, Nb, Rb, Sn, Sr, Ta, Th, U V, W, Zr, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb and Lu. These results are reported in Table 10.

In package AQ200, samples were digested in hot Aqua Regia and analysed by ICP-ES/MS for Au and volatile elements Mo, Cu, Pb, Zn, Ni, As, Cd, Sb, Bi, Ag, Au, Hg, Tl and Se. Total S and C were analysed using the LECO method in analytical package TC003. Graphite-bound C was analysed using analytical package TC005 involving nitric leach of carbonates before LECO analysis. These results are reported in Table 11.

4.2 Petrographic studies

Polished thin sections were prepared by Sari Forss at University of Oulu into the standard 0.03 mm thickness.

Petrographic studies were conducted by the Author in 2016 at University of Oulu using a polarizing petrographical microscope. All samples were studied both in transmitted and reflected light. The focus of the study was on the main minerals rather than identification of all different trace minerals, which are abundant in Kylylahti.

4.3 Electron optics

After studying each thin section with the optical microscope, several samples with interesting yet representative minerals from each polished thin section were chosen for further study with FESEM (Field Emission Scanning Electron Microscope) combined with EDS (Energy Dispersive Spectroscopy). The idea was to confirm the amphibole mineralogy using the EDS. The device used was Zeiss ULTRA plus FESEM at Centre for Material Analysis at University of Oulu. The following analytical conditions were used for the EDS analyses: an accelerating voltage of 15 kV, a current of 4.8 nA, and working distance of 8.5 mm. The measured elements included all elements in periodic table from C to U. Commonly, overall EDS analytical accuracy (relative) is ± 1-2%. The results are given normalized to 100%.

5. RESULTS

5.1 Whole rock geochemistry

In tables 4-6 all the assay results, for the five different sample groups, are listed and colour coded. Figures 24 and 25 characterize the overall geochemistry of the groups and individual samples. Results are discussed in more detail in section 6.

			CRB-Actska					Reference samples			OME-Actska					OUM-Actska			OBA-Actska			
Code	Analyte	Unit	kwc-01	kwc-02	kwc-03	kwc-04	kwc-05	kwc-07	kwc-08	kwc-11	kwc-18	kwc-19	kwc-20	kwc-21	kwc-22	kwc-24	kwc-25	kwc-26	kwc-27	kwc-28	kwc-29	kwc-30
XF700	LOI	%	15.1	4.7	31.7	11.3	27.4	7.8	8.1	35.9	17.5	11.3	10.9	14.3	16.1	26	15.2	27	5.9	4.5	9.7	18
XF700	Al_2O_3	%	7.74	1.14	1.42	7.6	1.63	9.25	3.38	1.41	0.49	1.55	1.33	0.66	0.4	0.05	0.39	0.31	4.3	14.2	6.87	2.55
XF700	Ba	%	<0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01
XF700	CaO	%	14.2	22.7	28.2	10.1	28.7	15	19.6	29.5	26.9	22.8	23.8	25.2	19.8	18.6	13.4	20.2	12.8	6.51	14.5	23.8
XF700	Cr_2O_3	%	0.02	<0.01	<0.01	0.02	<0.01	0.24	0.67	0.05	0.29	0.53	0.37	0.11	0.33	0.32	0.27	0.25	0.13	0.15	0.3	0.2
XF700	Fe_2O_3	%	9.02	12.1	2.13	17.3	4.06	5.07	3.73	3.45	5.29	5.03	5.98	5.66	3.64	7.46	5.1	4.61	14.3	11.3	7.31	8.13
XF700	K_2O	%	1.6	0.2	0.51	1.26	0.74	1.04	0.13	0.04	<0.01	0.01	0.02	<0.01	<0.01	<0.01	<0.01	<0.01	0.07	1.34	0.97	<0.01
XF700	MgO	%	12.7	14.1	17.7	9.75	15.8	11.2	18.1	18	15.7	15.1	14.9	14	20.9	21.9	24.2	21.5	17	10.7	19.2	16.3
XF700	MnO	%	0.09	0.08	0.16	0.06	0.17	0.06	0.05	0.05	0.06	0.06	0.1	0.06	0.05	0.07	0.08	0.07	0.04	0.04	0.08	0.07
XF700	Na_2O	%	0.49	0.07	0.05	0.32	0.03	2.69	0.35	0.05	0.05	0.08	0.12	0.06	0.03	<0.01	0.04	0.01	0.32	2.76	0.22	0.04
XF700	P_2O_5	%	0.51	0.09	0.06	1.2	0.03	0.05	<0.01	0.03	0.01	<0.01	0.02	0.01	0.02	<0.01	<0.01	0.01	0.14	0.5	0.1	0.03
XF700	SO_3	%	>10	>10	1.94	>10	4.57	7.72	3.91	2.9	4.18	4.08	5.41	3.02	0.02	6.88	3.69	0.39	>10	>10	4.51	4.47
XF700	SiO_2	%	32.2	25.6	15.9	40	15.6	42.4	42	7.91	29	40.2	37	37.1	38.9	20.1	38.3	24.5	43.8	42.6	36.7	26.7
XF700	Sr	%	0.019	<0.002	0.005	0.003	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002	0.003	<0.002	<0.002
XF700	TiO_2	%	0.43	0.08	0.09	0.46	0.11	0.34	0.05	0.03	0.01	0.02	0.03	0.05	<0.01	0.01	<0.01	<0.01	0.93	3.81	0.98	0.07

Table 9. Major oxides by XRF.

			CRB-Actska					Reference samples			OME-Actska					OUM-Actska			OBA-Actska			
Code	Analyte	Unit	kag-01	kag-02	kag-03	kag-04	kag-05	kag-07	kag-08	kag-11	kag-18	kag-19	kag-20	kag-21	kag-22	kag-24	kag-25	kag-26	kag-27	kag-28	kag-29	kag-30
LF100	Ba	ppm	57	4	23	108	27	64	8	8	<1	1	1	1	<1	<1	<1	<1	8	131	114	1
LF100	Be	ppm	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1	1	<1	<1	<1
LF100	Co	ppm	84.6	102.8	26.9	19.8	26.7	294.1	180	53	73.2	129	72.3	68.5	86.5	93.6	81.2	83	171.4	1372.3	203.4	79.8
LF100	Cs	ppm	5	0.6	1.9	3.3	2.9	2.8	0.3	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	4.5	3.2	<0.1
LF100	Ga	ppm	11.3	2.9	1.4	9.8	1.5	9.4	3.6	<0.5	<0.5	1.1	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	3.2	40.3	5.6	1.6
LF100	Hf	ppm	1.9	0.3	0.3	1.8	0.4	0.7	0.4	0.5	<0.1	<0.1	0.2	0.2	<0.1	<0.1	<0.1	<0.1	1.2	1.9	1.2	<0.1
LF100	Nb	ppm	5	0.9	1	5.4	0.9	1.5	0.9	0.6	<0.1	0.3	0.1	0.2	<0.1	<0.1	<0.1	<0.1	6.1	6.5	4.2	0.1
LF100	Rb	ppm	69.3	9.2	19.3	41.5	26.6	23.6	2.8	1.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.5	26.4	34.6	<0.1
LF100	Sn	ppm	<1	15	<1	2	<1	1	<1	<1	15	2	1	<1	<1	2	<1	<1	<1	4	7	<1
LF100	Sr	ppm	233	80.6	217.6	53.5	141.1	67.6	50.4	85.8	124.6	40.8	93.6	61.9	32.6	91.3	34.3	42.8	31.7	41.9	33	49.7
LF100	Ta	ppm	0.4	<0.1	<0.1	0.4	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.3	0.4	0.3	<0.1
LF100	Th	ppm	5.7	0.8	0.7	5	0.7	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	<0.2	0.3	<0.2	<0.2	<0.2
LF100	U	ppm	19.9	7.5	4.2	17.7	5.1	7.7	7.5	56.3	0.3	0.5	3.2	2	3.9	<0.1	<0.1	0.2	32.6	12.6	43.2	0.5
LF100	V	ppm	323	96	132	353	115	242	74	90	21	50	44	21	19	11	18	15	171	309	110	64
LF100	W	ppm	2.3	0.5	<0.5	1.3	0.8	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	2	<0.5	<0.5
LF100	Zr	ppm	68.5	10.5	12	69.8	14	16.1	11.4	12.9	0.6	0.6	7.7	5.1	0.3	0.5	0.5	0.9	30.7	60	40.3	2.2
LF100	Y	ppm	24.4	5	4.6	37.3	6.7	7.3	10.7	13.9	2.6	3.7	3.4	5.7	4.4	0.8	1.9	1.3	59.5	77.9	47.5	9.3
LF100	La	ppm	23	4.7	1.9	23.5	3.2	3	2.4	2.4	0.5	0.7	0.5	0.7	0.3	0.3	0.5	0.6	5.4	26.2	9.4	0.9
LF100	Ce	ppm	33.2	5	3.2	32.6	5.3	4	6.8	3.3	1.2	1.8	0.8	1.6	0.4	0.4	0.6	0.5	16.5	42.3	27.9	1.6
LF100	Pr	ppm	4.86	0.74	0.53	5.7	0.78	0.48	1.15	0.79	0.18	0.27	0.14	0.3	0.08	0.1	0.07	0.08	3.57	6.09	4.84	0.25
LF100	Nd	ppm	18.4	3.2	2.1	22.6	3	2.4	5.9	3.8	1	1.6	0.7	1.4	0.5	0.5	0.4	0.4	20	33	23.6	1.5
LF100	Sm	ppm	3.61	0.66	0.41	4.83	0.73	0.68	1.68	1.15	0.22	0.36	0.19	0.45	0.1	0.1	0.15	0.09	6.34	9.67	5.88	0.52
LF100	Eu	ppm	0.77	0.21	0.22	1.27	0.23	0.19	0.35	0.18	0.08	0.11	0.13	0.04	<0.02	0.03	0.12	0.04	0.34	1.23	0.65	0.07
LF100	Gd	ppm	3.88	0.69	0.57	5.74	0.73	1.04	1.97	1.43	0.32	0.49	0.33	0.64	0.27	0.1	0.19	0.12	8.34	12.42	6.87	0.93
LF100	Tb	ppm	0.61	0.11	0.09	0.95	0.12	0.17	0.32	0.25	0.05	0.09	0.06	0.1	0.05	0.02	0.03	0.01	1.45	2.18	1.23	0.19
LF100	Dy	ppm	4.03	0.59	0.5	5.84	0.69	1.2	1.96	1.82	0.32	0.57	0.45	0.73	0.36	0.12	0.27	0.11	9.43	14.22	7.72	1.28
LF100	Ho	ppm	0.83	0.14	0.13	1.28	0.17	0.3	0.39	0.39	0.06	0.13	0.13	0.17	0.12	0.03	0.06	0.02	2.16	3.17	1.69	0.31
LF100	Er	ppm	2.58	0.44	0.37	3.29	0.54	0.84	1.17	1.33	0.19	0.54	0.4	0.59	0.35	0.08	0.21	0.08	6.39	8.94	5.58	1.02
LF100	Tm	ppm	0.36	0.06	0.06	0.52	0.08	0.12	0.17	0.19	0.03	0.07	0.06	0.09	0.05	0.02	0.04	<0.01	0.98	1.27	0.78	0.16
LF100	Yb	ppm	2.39	0.37	0.45	3.26	0.64	0.88	1.06	1.25	0.26	0.45	0.5	0.59	0.39	0.1	0.2	0.07	6.24	8.12	4.72	1.16
LF100	Lu	ppm	0.39	0.07	0.06	0.47	0.1	0.13	0.17	0.21	0.03	0.07	0.09	0.09	0.06	0.02	0.03	0.01	0.92	1.2	0.72	0.2

Table 10. Trace elements by ICP MS.

			CRB-Actska					Reference samples			OME-Actska					OUM-Actska			OBA-Actska			
Code	Analyte	Unit	kag-01	kag-02	kag-03	kag-04	kag-05	kag-07	kag-08	kag-11	kag-18	kag-19	kag-20	kag-21	kag-22	kag-24	kag-25	kag-26	kag-27	kag-28	kag-29	kag-30
AQ200	Mo	ppm	53.1	9.8	10	41	12.4	1.6	0.5	16.8	0.1	0.3	<0.1	0.3	<0.1	<0.1	<0.1	<0.1	5.3	1.5	0.2	0.1
AQ200	Cu	ppm	129	8930	239.5	556.3	225.3	7149	34.1	9	3.3	178.4	103.6	6.1	0.6	22.9	1.3	1.9	25.1	2981	244.6	10.8
AQ200	Pb	ppm	43	16.8	6	33.9	10.2	7.9	7	21	2.3	2.2	4.2	4	3.3	2.9	1	1.2	16.6	8.9	17.5	2.4
AQ200	Zn	ppm	3097	1283	1010	3986	791	473	4	24	4	6	4	2	3	6	4	4	8	48	32	6
AQ200	Ni	ppm	2484	489	570	1500	488	364	5762	1875	1358	1750	1616	1326	642	1970	1799	1119	2459	3255	5150	583
AQ200	As	ppm	317.2	92.7	2.5	1.5	31.1	28.9	1779	118.5	<0.5	2.5	<0.5	0.5	690.9	<0.5	3.6	4.6	<0.5	0.6	1.4	<0.5
AQ200	Cd	ppm	25	4.4	4.7	23.3	4.2	0.8	<0.1	0.3	0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1
AQ200	Sb	ppm	2.6	2.3	0.4	3.4	0.7	0.5	1.5	0.2	0.1	0.2	0.1	<0.1	4.2	0.3	<0.1	<0.1	0.3	0.5	<0.1	0.1
AQ200	Bi	ppm	0.3	0.2	<0.1	0.3	0.1	0.1	0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.2	<0.1	<0.1
AQ200	Ag	ppm	1.7	1.9	0.5	2.6	0.7	1.5	0.2	0.1	0.5	0.1	0.6	0.3	<0.1	0.8	0.2	<0.1	1.8	0.3	0.2	1.3
AQ200	Au	ppb	1.6	53.5	0.9	2.9	2	96.7	0.7	2.1	1.8	1.7	<0.5	<0.5	29	1.7	<0.5	6	<0.5	105.3	<0.5	<0.5
AQ200	Hg	ppm	1.18	0.89	0.45	1.74	0.45	0.36	0.01	0.01	<0.01	<0.01	0.04	0.01	<0.01	<0.01	<0.01	<0.01	0.01	0.05	<0.01	0.02
AQ200	Tl	ppm	4.8	1.2	1.8	2.4	2.4	1.6	0.2	0.1	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	1.4	2.7	<0.1
AQ200	Se	ppm	36.3	16.6	5.3	21.3	6.8	2.1	4.4	<0.5	1.3	<0.5	6	<0.5	<0.5	4.5	<0.5	<0.5	8.2	7.2	<0.5	1.5
TC003	Total C	%	9.58	5.81	10.14	5.75	9.94	2.45	2.47	10.98	6.27	3.49	5.32	5.3	4.67	9.94	4.67	7.64	0.88	0.06	3.04	6.38
TC003	Total S	%	7.47	8.25	0.99	7.68	2.09	2.49	1.81	1.29	2.02	1.84	2.38	1.36	<0.02	3.02	1.81	0.22	6.12	5.25	1.99	2.26
TC005	Graphite	%	6.37	0.49	1.03	4.39	1.34	<0.02	<0.02	0.1	0.2	0.1	1.35	1.2	0.17	2.25	0.36	1.24	0.3	<0.02	0.37	0.81

Table 11. Common ore forming elements dissolved in Aqua Regia and analysed with ICP ES/MS. Total C, S and graphite from LECO method.

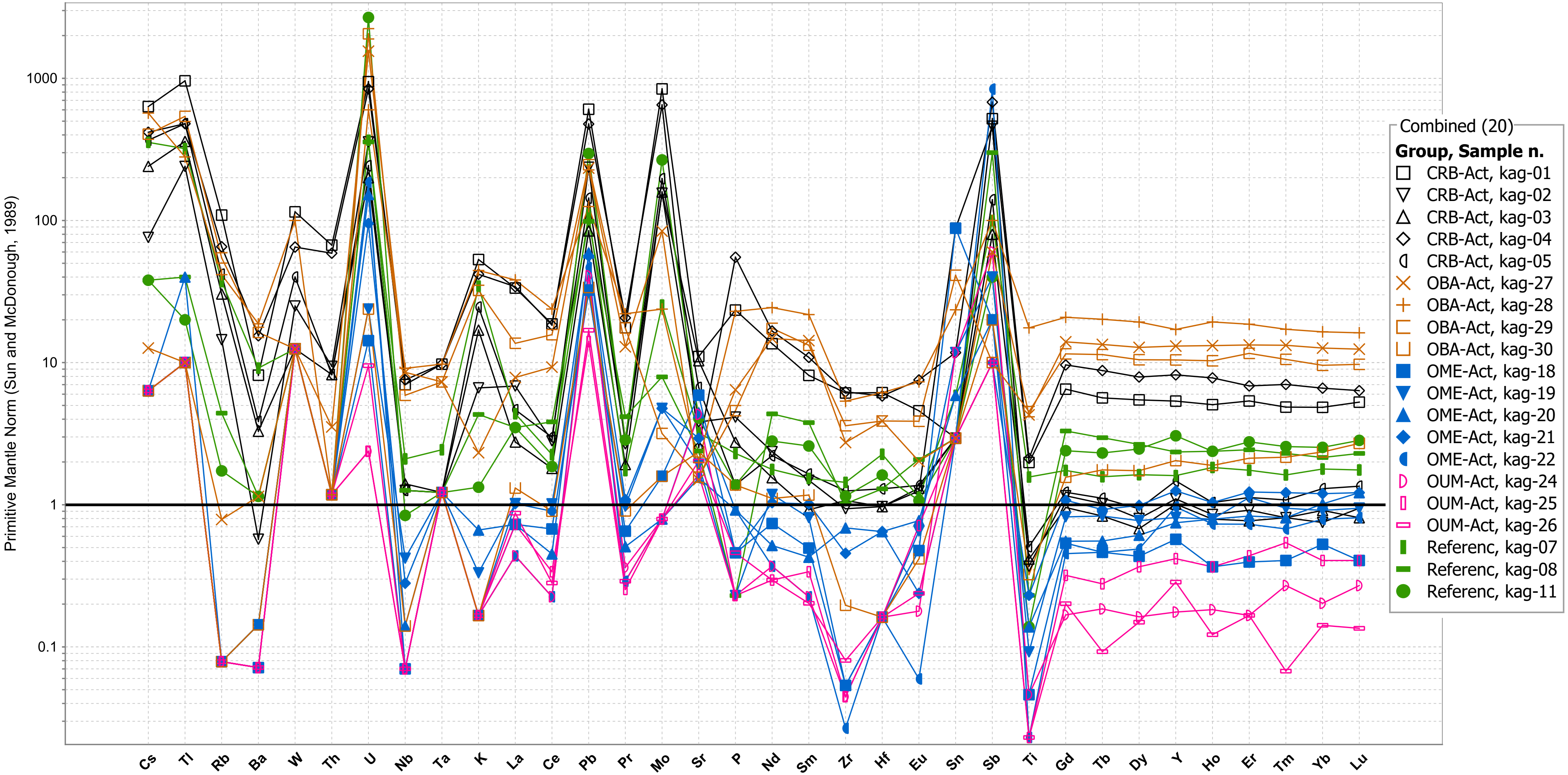

Figure 24. Trace elements of different sample groups plotted against primitive mantle by Sun and McDonough (1989). Many samples have same content in elements W, Ta, Th, Hf and Sn. That is caused by the actual content being lower than the element's lowest detection limit (appendix 1). In these cases, lowest detection limit was divided by 2 and resulting grade was used when drawing the diagram.

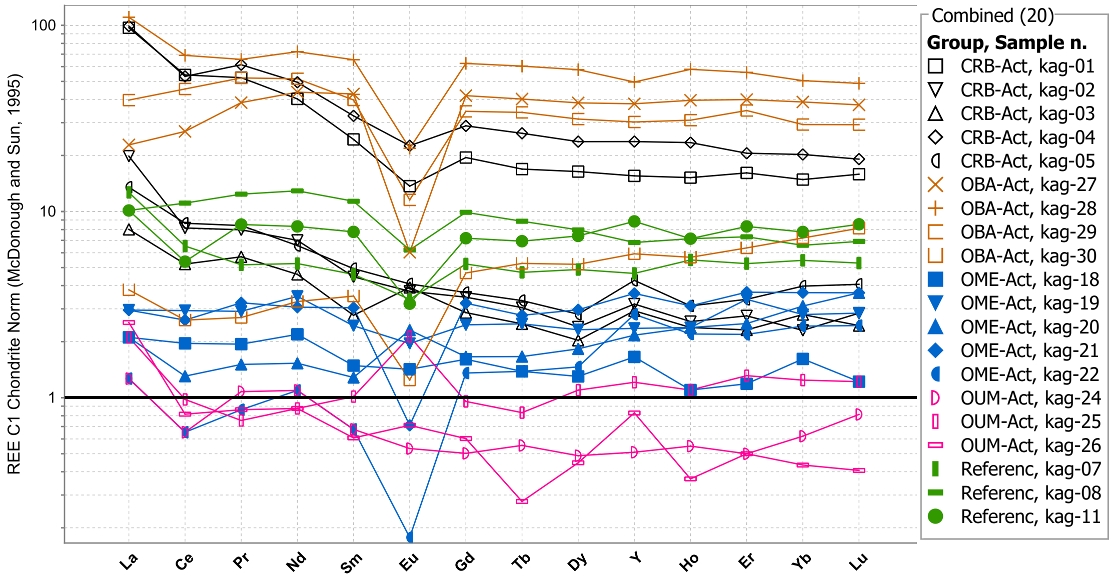

Figure 25. Rare earth elements of different groups plotted against C1 Chondrite norm by McDonough and Sun (1995)

5.2 Mineralogy and EDS analytics

An Excel sheet by Andrew J. Locock (2014) was used to define the precise mineral class and name of the amphiboles in question. The Excel sheet is based on the classification criteria and nomenclature of the amphibole supergroup by International Mineralogical Association (IMA) published in 2012 by Hawthorne et al. (2012).

The problem with this approach in this case is the lack of information on Fe^{2+}/Fe^{3+} ratio – as EDS only measures iron as metallic iron wt%. Therefore, the ratio of divalent/trivalent iron in amphibole crystal structure is calculated and prone to errors.

Tremolite is defined as having an $Mg/(Mg+Fe^{2+})$ ratio ≥ 0.9; actinolite has a ratio of 0.5–0.9 and ferro-actinolite has a ratio of less than 0.5 (Hawthorne et al. 2012).

One sample from each group is represented with general notes from the group. Rest of the thin section report cards are presented in appendix 2.

5.2.1 Reference samples

Two of the prepared polished thin sections were sampled from tremolite skarn and two were from more carbonate-rich rock with some amphiboles. Tremolite, calcite and dolomite are the most abundant minerals in these samples. Accessory minerals are phlogopite, chlorite, quartz, pyrrhotite, pyrite, pentlandite with variable amounts of Co, chalcopyrite, plagioclase, graphite, and gersdorffite(?)

Sample KU-681-102,78 (kag-07), the other “pure” tremolite skarn type sample somewhat differs from the others. Main minerals are quartz, tremolite, micas, calcite, chlorite and plagioclase with sulphides and Ti minerals.

Tremolite Cr and Al contents vary a lot in reference samples (Fig. 31). Some tremolite crystals are completely void of Cr. On figure 32, Fe content stays under other OAA groups but higher than CRB-Actska group.

Complete thin section report cards are presented in Appendix 2.1.

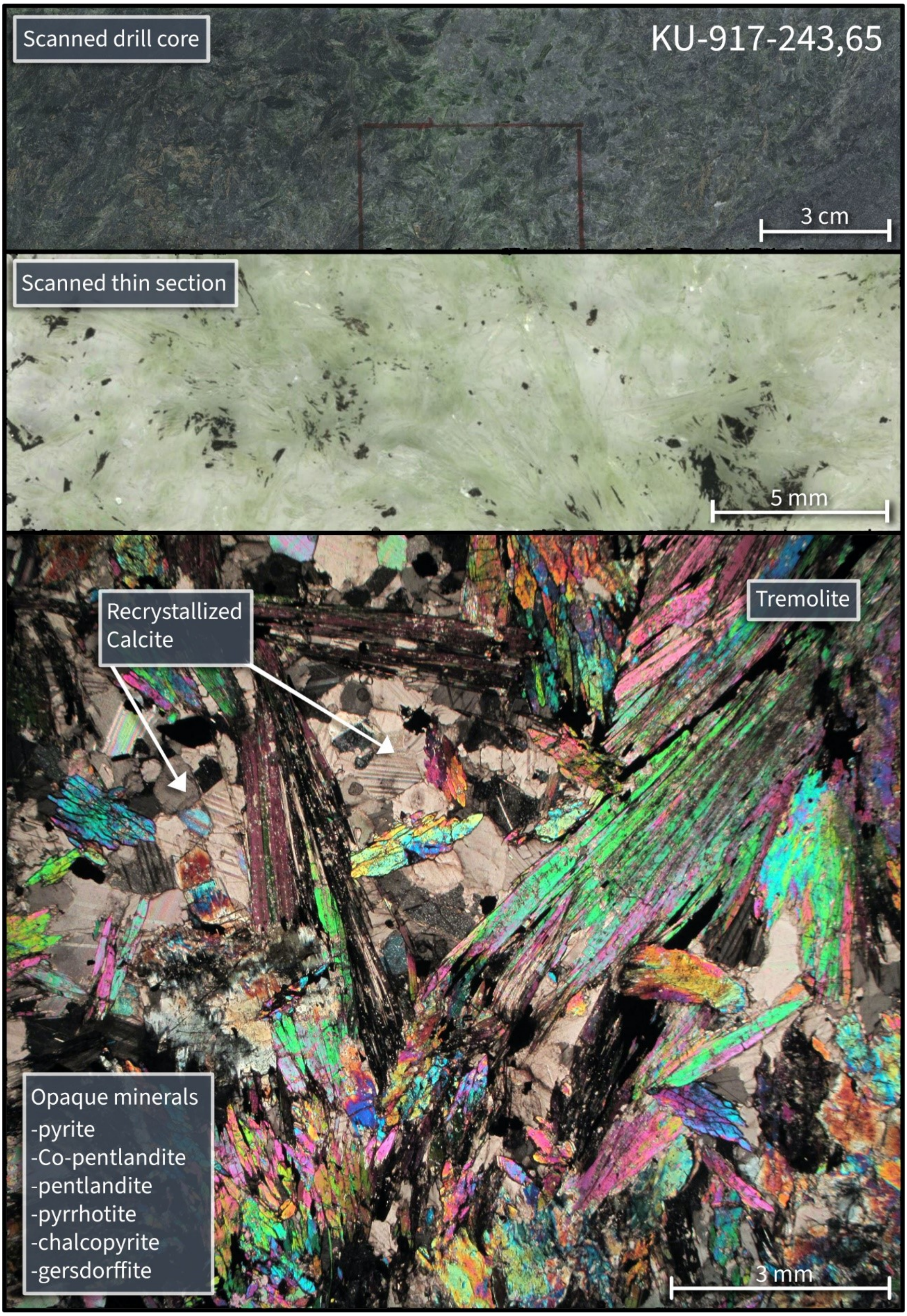

Figure 26. Collage of porphyroblastic tremolite skarn sample KU-917-243,65 that is used as a type sample. Such tremolite skarn is very common in Kylylahti deposit. Coarse, euhedral, Cr-rich tremolite with recrystallized calcite showing typical ~120° triple junctions. Opaque minerals include several different sulphide minerals and trace magnetite. Cross-polarized light in bottom picture.

5.2.2 CRB-Actska

Main minerals in these rocks are carbonates (calcite and dolomite). The dark amphiboles are all tremolite that are pigmented black (Fig 27) by graphite, sulphides, and unknown material, that most likely is very fine graphite. No actinolite was found. Some samples are rich in sulphides, mainly pyrite, pyrrhotite and chalcopyrite. Graphite is always present in these samples. Some micas (mainly phlogopite), quartz and anorthite was found, too. Titanite, rutile, chlorite, sphalerite, apatite, magnetite, and hematite were present in small quantities in some samples. Interesting discovery was grain of halite as inclusion in tremolite crystal. The carbonate matrix in these samples is always fine to medium grained, sometimes oriented. Recrystallization can sometimes be seen.

As could be expected from their sedimentary origin and whole-rock analysis, which lacks Cr almost entirely, none of the EDS-measured tremolite crystals in CRB-Actska group contain chromium (Fig 31). Tremolite crystals in these sedimentary carbonate rocks are also the poorest in Fe and relatively rich in Mg and form a distinctive group (Fig. 32).

Complete thin section report cards are presented in Appendix 2.2.

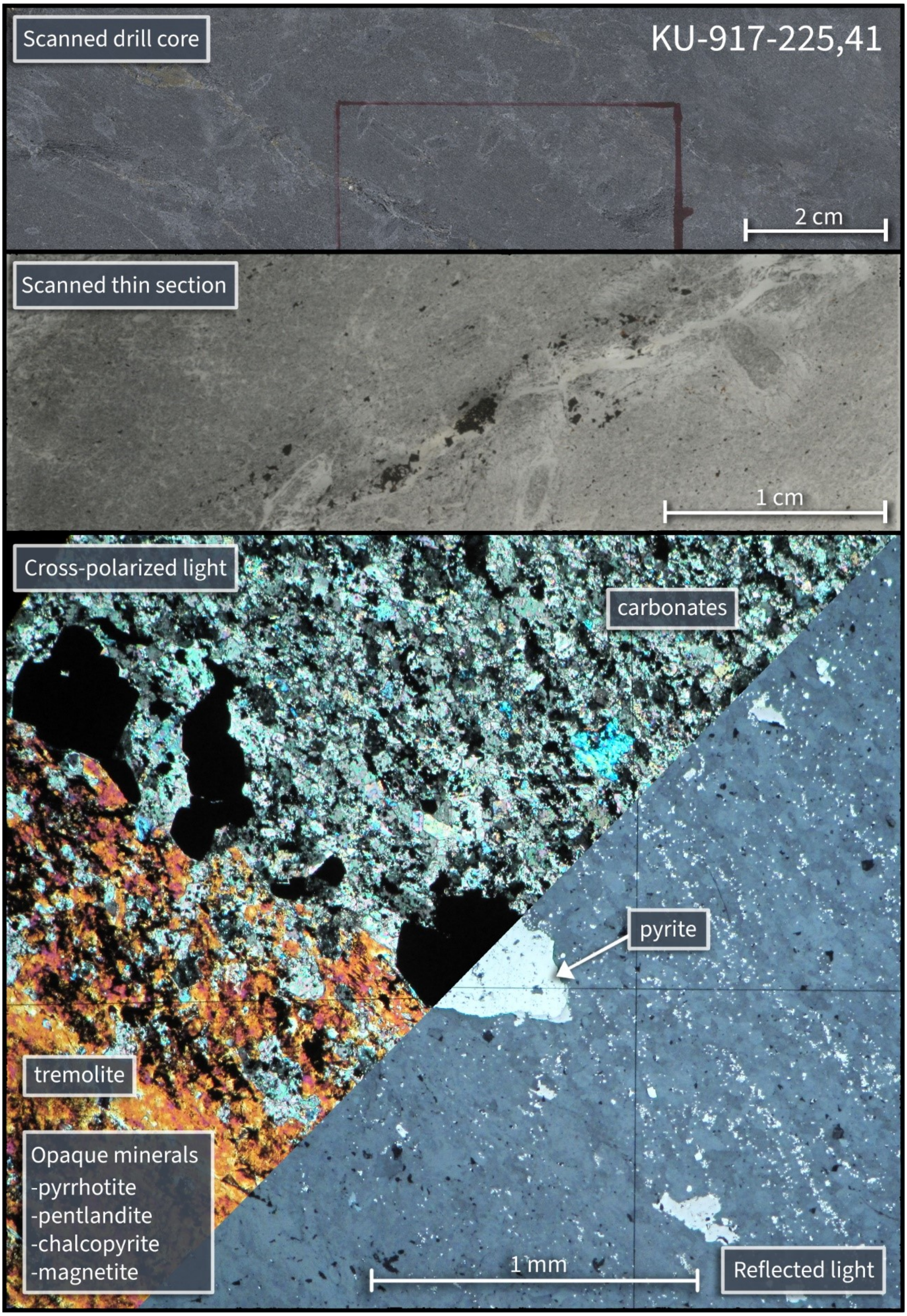

Figure 27. Picture collage of sample KU-917-225,41 belonging to CRB-Actska group. Bottom part of the picture is a combination of transmissive and reflective light from the same spot. In this sample, most of the opaques are fine pyrite. Coarse tremolite crystal has experienced alteration on the edges.

5.2.3 OME-Actska

Although this group is coloured darker and bluer compared to tremolite skarns of the type sample group, they are still tremolite skarns. One actinolite crystal was discovered from sample KU-916-242,82. Rest of the measured (EDS) amphiboles in this group were tremolite. Other main rock forming minerals are calcite and dolomite that can be separated from each other in backscatter image because of their density difference (Fig. 28, central part of the lowermost picture). Micas, chlorite, and quartz were present in one sample each. Accessory minerals include pyrrhotite, pentlandite, titanite, rutile, chalcopyrite, graphite, apatite and zincochromite.

OME-Actska tremolites are generally poorer in Al than reference group (Fig. 31).
Fe/Mg ratio is among the highest (Fig. 32).

Complete thin section report cards are presented in Appendix 2.3.

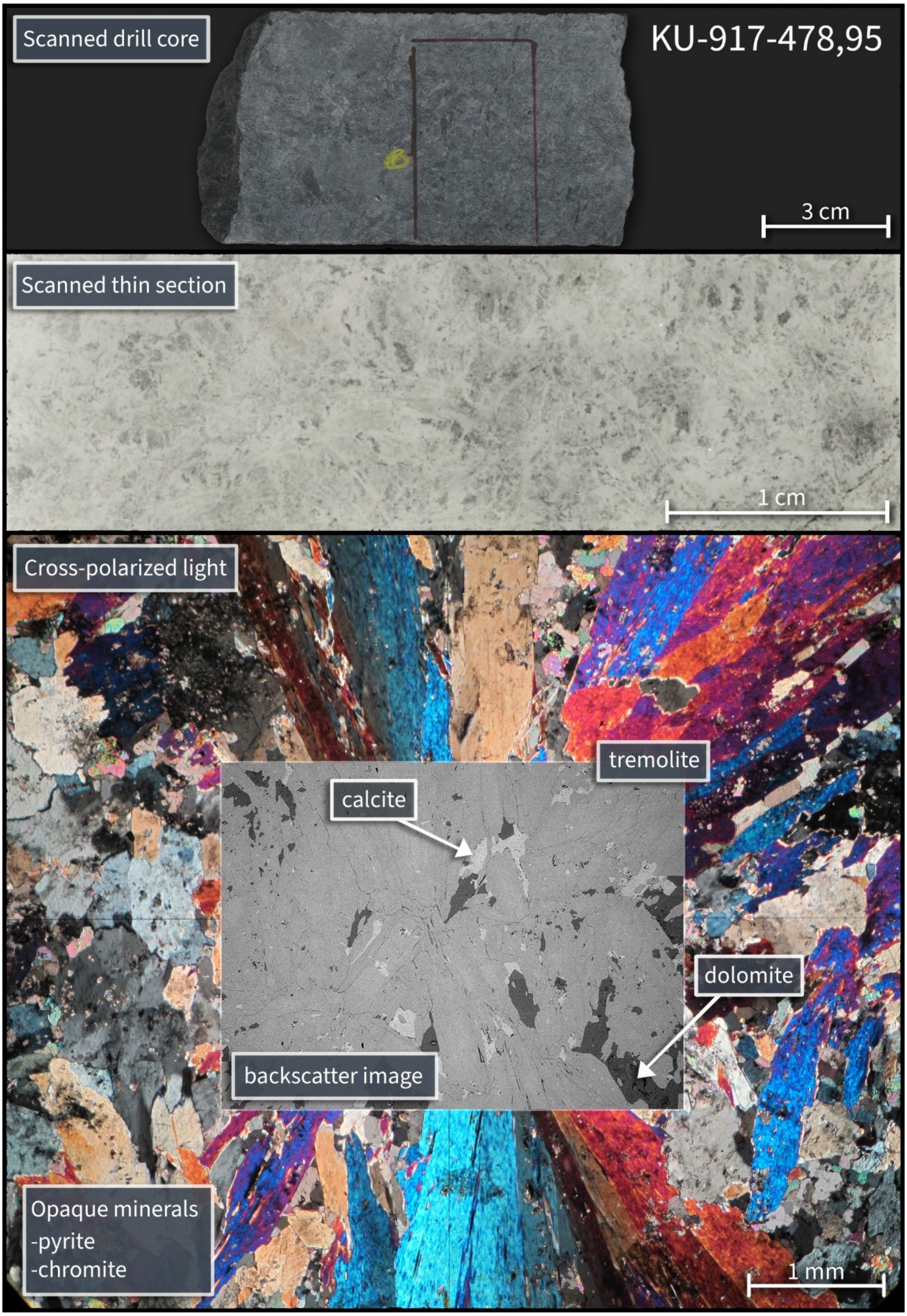

Figure 28. Sample KU-917-478,95 of the OME-Actska group. Electron microscope backscatter image planted into regular microscope picture showing the same spot.

5.2.4 OUM-Actska

Carbonates and talc are the main minerals in these samples representing amphibole-bearing soapstones. Dark amphiboles are tremolite. In all three samples, tremolites were partially altered into carbonates (Fig. 29) and in some cases, contained inclusions and staining of unknown opaque material, possibly graphite. Accessory minerals are chromite (also zincochromite), pyrrhotite, phlogopite, pentlandite, pyrite, serpentine, and rutile.

Cr content of these soapstone's tremolites is roughly in line with other sample groups (Fig. 31) but has the lowest Al content. This group has the least amount of EDS measured tremolite crystals that lack Cr completely in Outokumpu Alteration Assemblage samples. Fe/Mg ratio is the highest (Fig. 32).

Complete thin section report cards are presented in Appendix 2.4.

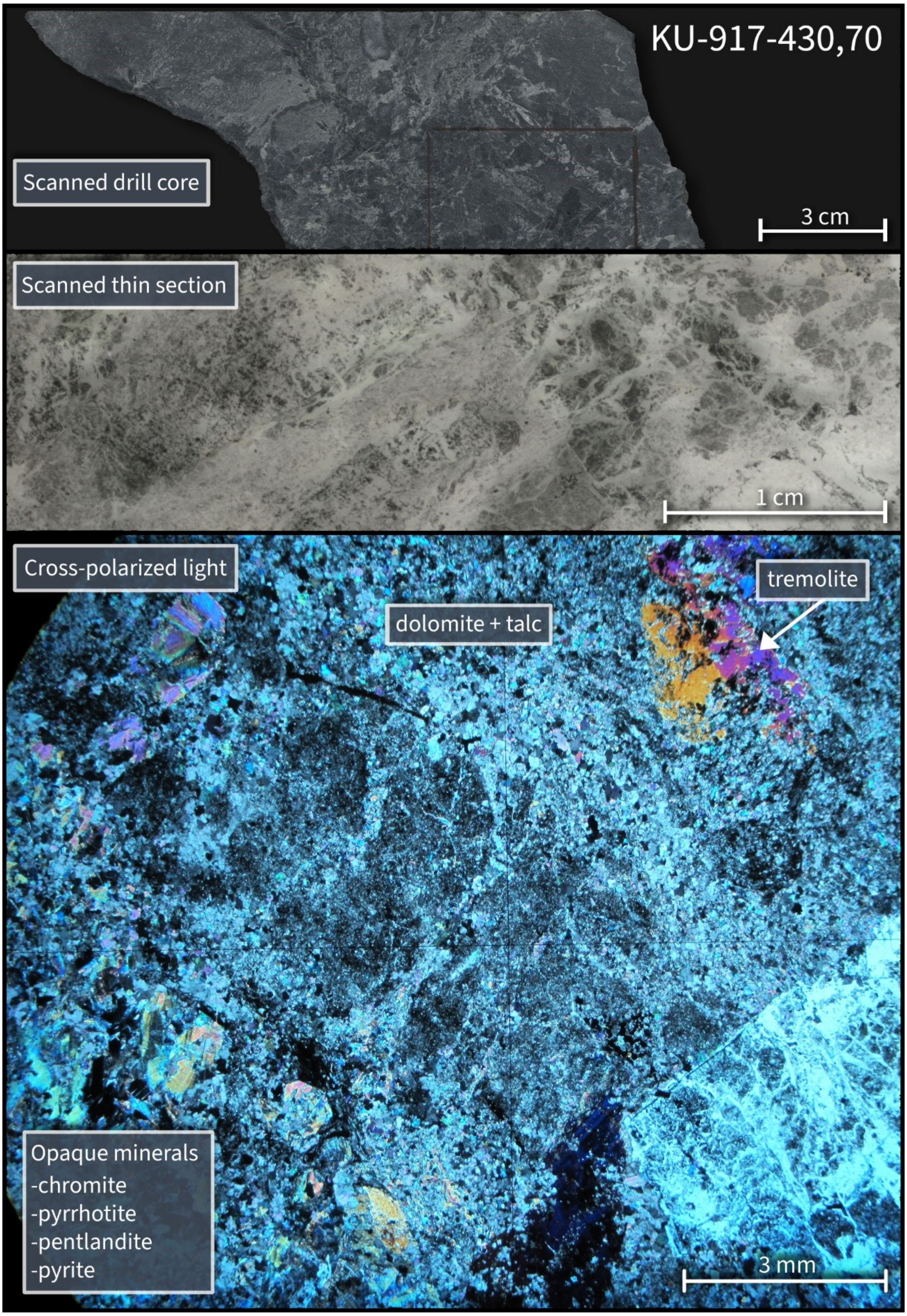

Figure 29. Relict of a large crystal, possibly tremolite, in the middle. Matrix is fine-grained carbonates and talc. Visible tremolite crystals have altered on the sides.

5.2.5 OBA-Actska

This sample group is the richest in terms of different minerals. Most abundant are tremolite, carbonates, chlorite (Fig.30), phlogopite, quartz and plagioclase. Chlorite is rich in Cr. Accessory minerals include talc, titanite, rutile, apatite, allanite and some other, unknown REE-mineral. The mineralised samples are rich with pyrrhotite, pentlandite and chalcopyrite. Magnesio-hornblende was found in two samples, but some of the EDS measurements yielding Mg-hornblende (Fig. 31 and 32) are caused by internal compositional variation of a single large tremolite crystal. This same reason is behind the few “actinolite” results in same EDS diagrams – none of them is actinolite. OBA-Actska amphiboles are the richest in Al and Fe of all groups (Fig. 31 and 32).

Structure wise, these OBA-Actska rocks are mostly sheared or heavily strained. Some amphiboles are mechanically broken (cover picture).

Complete thin section report cards are presented in Appendix 2.5.

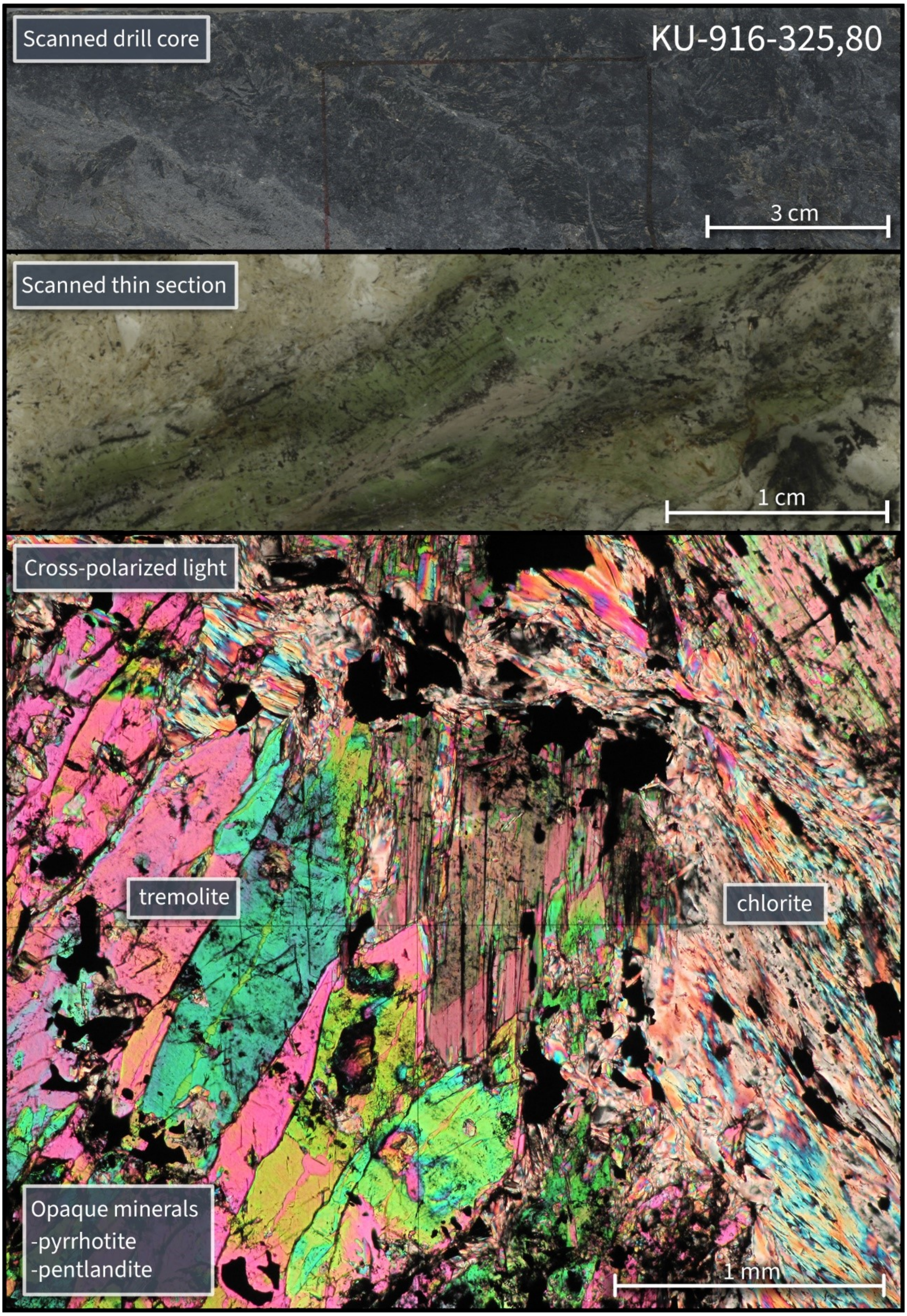

Figure 30. Coarse tremolite and fine chlorite mass, most likely clinochlore.

5.3 EDS data visualized

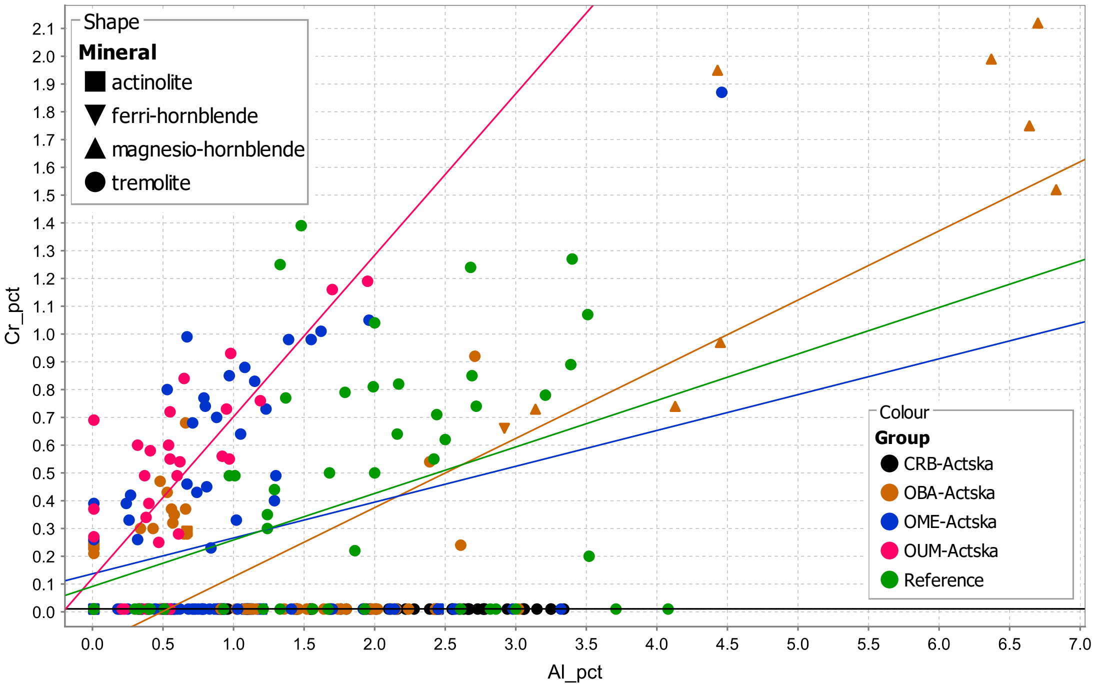

Figure 31. Cr and Al content of all amphiboles measured with EDS. Lines represent Ordinary Least Squares. Some samples have no chromium in them.

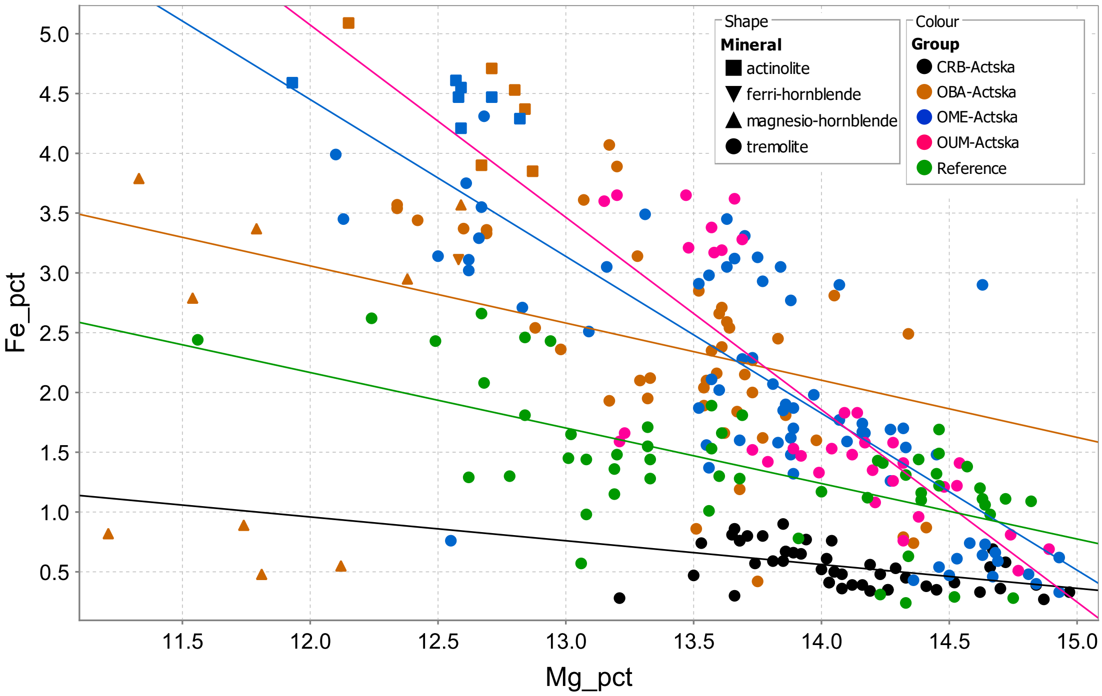

Figure 32. Fe and Mg content of all amphiboles measured with EDS. Lines represent Ordinary Least Squares.

6. SUMMARY AND DISCUSSION

Although the appearance of amphibole in hand samples shows significant variance, the amphibole mineralogy is overall very simple in Kylylahti: Almost all amphiboles are tremolite despite of their colour or crystal habits. The dark or even black tremolite crystals get their colour from still unidentified pigment that is very fine grained. In some cases, the pigment can be identified as sulphides or graphite, but not usually. Darkening by the pigment has caused the past misclassification of tremolite into usually darker actinolite. Asko Kontinen in his personal comment (2023) suggests that the unknown pigmenting matter is most likely very fine, dust-like graphite that does not polish well when polishing the thin section. Microanalyzer (EPMA) could be used to confirm this and track down the pigmenting matter.

These results are well in line with Boliden Kylylahti's geometallurgy research program (2018, not published) about certain disseminated zone ore mineralogy. The study was done at GTK Mintec laboratories using MLA (mineral liberation analysis) and EPMA (microanalyzer). In that study, selected samples contained less than 1% of actinolite and less than 1% hornblende compared to tremolite content.

In few EDS-measured amphiboles, EDS returns actinolite composition, but on closer inspection these measured spots were just large tremolite crystal's internal compositional variation. Other measurements from different spots of the same crystal returned tremolite composition. The only exception to this is explained in section 6.3.

Uranium content in all Outokumpu Assemblage rocks is high compared to primitive mantle (Sun and McDonough, 1989) (Fig. 24). In Geomex report, Kontinen at al. (2006) explain it by mildly oxidizing environment for the primary carbonate-silica alteration.

In most of the OAA samples, the Eu anomaly is negative (Fig. 25), which could be explained by the original depleted mantle source.

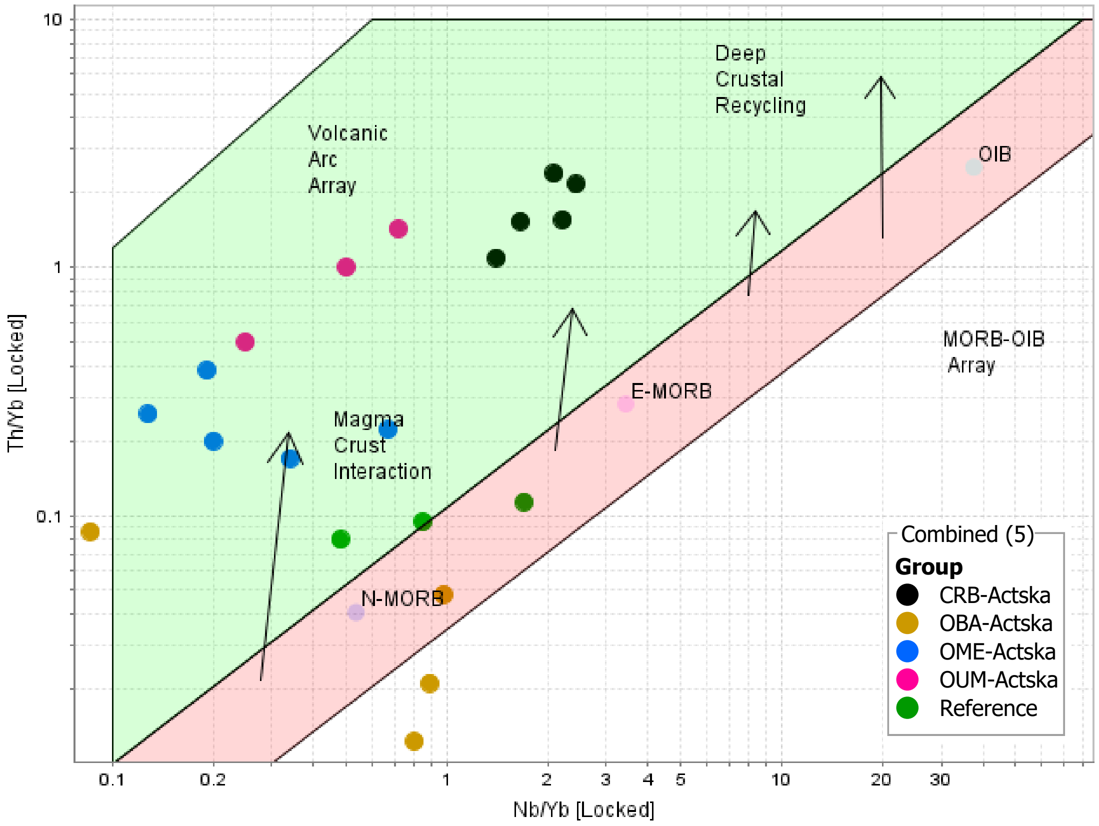

Figure 33. Basalt classification diagram by Pearce (2008). N-MORB = Normal MORB, E-MORB = Enriched MORB.

Diagram in figure 33 depicts magma-crust interaction and crustal recycling (green area) from the red mid-ocean ridge basalt (MORB). The Th/Yb – Nb/Yb diagram can be used to distinguish supra-subduction zone ophiolites from MOR ophiolites (Pearce, 2014). The amount of crustal contamination and magma fractionation increases towards top right corner. Although Th, Nb and Yb are usually considered immobile elements, it needs to be noted, that the samples represent highly altered ophiolite-derived rocks and therefore this diagram should be interpreted with caution. OBA-Actska and reference sample groups are closest to unaltered MOR-basalts.

6.1 Reference samples

Sample KU-681-102,78 (kwc-07, kag-07), that was chosen to represent pure tremolite skarn, turned out to be a metabasitic skarnoid rock. Main minerals were quartz, tremolite, micas, calcite, chlorite and plagioclase with sulphides and Ti minerals. However, on the C1 Chondrite normalized REE-diagram (Fig. 25), it fits roughly on the same level with other reference samples rather than with OBA-Actska samples.

Thin section KU-916-194,85A and B are possibly from different phases of hydrothermal alteration, none of the A sample's tremolite crystals contain Cr (Table 12.) while sample B has tremolite phase than contains Cr up to 1.27%.

Group	Sample	Mineral	O	Na	Mg	Al	Si	Ca	V	Cr	Fe
Ref.	KU-916-194,85B	tremolite	45.2	0.43	12.8	3.4	25.4	9.83	0.35	1.27	1.3
Ref.	KU-916-194,85B	tremolite	45	0.33	13.2	2.42	25.5	9.85	0.23	0.55	1.15
Ref.	KU-916-194,85B	tremolite	44.8	0.52	13.1	3.21	25.8	9.94	0.42	0.78	1.44
Ref.	KU-916-194,85B	tremolite	44.9	0.44	12.6	3.39	24.8	9.62	0.28	0.89	1.29
Ref.	KU-916-194,85B	tremolite	45.2	0	13.6	0.01	25.9	9.86	0	0.01	1.01
Ref.	KU-916-194,85B	tremolite	46.8	0	14.4	0.3	27.6	9.85	0	0.01	1.1
Ref.	KU-916-194,85B	tremolite	46.6	0	14.2	0.93	27.2	10	0	0.01	1.12
Ref.	KU-916-194,85B	tremolite	46	0	14	1.21	26.9	9.83	0	0.01	1.17
Ref.	KU-916-194,85B	tremolite	45.9	0	14.5	0.01	27.6	10.1	0	0.01	1.22
Ref.	KU-916-194,85A	tremolite	47.1	0	14.5	0.01	27.4	9.8	0	0.01	1.32
Ref.	KU-916-194,85A	tremolite	46.5	0	14.6	0.01	27.8	9.99	0	0.01	1.11
Ref.	KU-916-194,85A	tremolite	46.4	0	14.6	0.01	27.7	10.2	0	0.01	1.06
Ref.	KU-916-194,85A	tremolite	46.4	0	14.6	0.01	27.8	10	0	0.01	1.2
Ref.	KU-916-194,85A	tremolite	46.5	0	14.4	0.01	27.9	10.1	0	0.01	1.16
Ref.	KU-916-194,85A	tremolite	46.2	0	14.6	0.01	27.8	9.98	0	0.01	1.38
Ref.	KU-916-194,85A	tremolite	45.8	0	14.5	0.01	28	10.1	0	0.01	1.69
Ref.	KU-916-194,85A	tremolite	47.1	0	14.7	0.01	27.5	9.8	0	0.01	0.98
Ref.	KU-916-194,85A	tremolite	46.2	0	14.8	0.01	27.9	9.99	0	0.01	1.09
Ref.	KU-916-194,85A	tremolite	46.8	0	14.7	0.01	27.7	9.7	0	0.01	1.11
Ref.	KU-916-194,85A	tremolite	46.8	0	14.3	0.33	27.5	9.74	0	0.01	1.31
Ref.	KU-916-194,85A	tremolite	46.7	0	14.2	0.4	27.5	9.82	0	0.01	1.43
Ref.	KU-916-194,85A	tremolite	46.1	0	14.4	0.41	27.8	9.91	0	0.01	1.44
Ref.	KU-916-194,85A	tremolite	46.7	0	14.2	0.51	27.2	9.99	0	0.01	1.41
Ref.	KU-916-194,85A	tremolite	46.3	0	14.5	0.01	27.6	10.2	0	0.01	1.49

Table 12. EDS results of tremolite from sample KU-916-194,85, thin sections A and B.

6.2 CRB-Actska

CRB-Actska has typical sedimentary LREE enrichment, which is shown by the negative slope in C1 Chondrite normalized REE-diagram (Fig. 25). This group forms a tight cluster in figure 33 reflecting their different, sedimentary origin from OAA groups. Average nickel content of this group, 1106 ppm (table 11), is distinctly higher than average Outokumpu black schist Ni content, which is 390 ppm (Kontinen et al. 2006). This could be proof of metal transfer from OAA rocks or from massive – semi massive ores to Upper Kaleva sedimentary carbonate rocks. Another evidence for this is the chalcopyrite, sphalerite and pentlandite occurrences in some of the CRB-Actska samples. The relationship of this rock unit and Outokumpu black schists is explained and discussed in chapter 2.1.3.

6.3 OME-Actska

Actinolite was found only in one sample KU-916-242,82 which was part of the OME-Actska group. The confirmed rock type was tremolite skarn, but at least one crystal of actinolite was found in the sample. Sample KU-916-242,82 EDS-measured tremolites had higher Al and Fe content than observed in other samples. However, the whole rock analyses do not show elevated Al or Fe content compared to other samples of the group. Reason for this is unknown. The Fe content measured by EDS in OME-Actska tremolites is higher than in tremolites belonging to reference sample group (Fig. 32). Maybe this could explain the overall colour difference of OME-Actskas and other “pure” tremolite skarns.

In figure 33, this group has the lowest Nb/Yb ratio, possibly representing lower crustal contamination than the other groups.

6.4 OUM-Actska

In this soap stone sample group, the overall level in the primitive mantle normalized spider diagram (Fig. 24) is the lowest of all sample groups. The high Th/Yb ratio is a result of the low ytterbium content (Fig. 33) rather than enrichment of thorium. Overall, the REE values in this sample group are close to C1 chondrites (Fig. 25).

OUM-Actska EDS measurements from tremolites show them to be Mg rich. This is well in line with the sample’s whole rock MgO content, which is also the highest of all groups (Fig. 34).

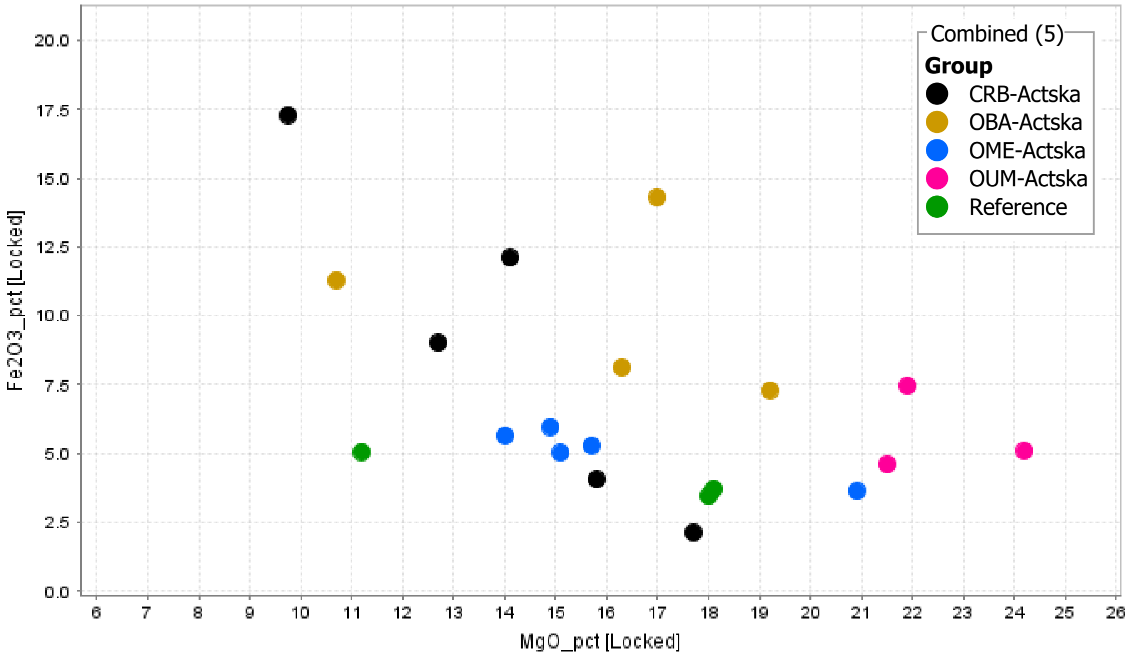

Figure 34. Whole rock assay Fe^2O^3 vs. MgO diagram of all analysed samples.

6.5 OBA-Actska

Two samples in the OBA-Actska group contained Mg-hornblende, which have been identified by Kontinen et al. (2006) as the main amphibole mineral in Kylylahti meta-gabbroic amphibolites. This is further evidence of correct classification of OBA-Actskas: They indeed are tremolite skarns where the proximity of metabasitic sills or dykes have affected their composition and mineral assemblage.

Another proof for the close relation of OBA-Actska group to metabasites is the enrichment in incompatible elements (Fig. 24). This is most likely a result of the basitic sills being originally partial melts of the mantle, with higher incompatible element contents than in the residual mantle.

7. CONCLUSIONS AND SUGGESTIONS FOR THE COMPANY

Actinolite skarn should not be used as a valid rock type in Kylylahti or in exploration projects in vicinity.

Tremolite skarns could be divided to better reflect their geochemistry in them or based on their colour, such as TRESKA-OBA meaning tremolite skarn with metabasitic overprint or TRESKA-DARK to comment the appearance.

Also, statistics study could be done by Boliden personnel to compare the metal contents of disseminated zone regular skarns to disseminated zone darker skarns that were core logged as some type of actinolite skarn. This would be to find out if the darker colour of the skarn itself or its amphiboles correlates with elevated metal contents, such as Au, for example. If there is no correlation, the discussion concerning “actinolite skarns” or the colour of the skarns in general in Kylylahti is pointless and should not be continued. Upper Kaleva sedimentary originated “actinolite skarns” should not be included in this statistics study.

Samples representing group OUM-Actska should not be called skarns at all but rather soapstones with amphiboles.

Although technically correct, skarns or any calc-silicates in the Upper Kaleva metasediments should be named something that clearly separates them from Outokumpu Alteration Assemblage even though logging sheets and database allows the separation to be done via geological unit.

8. ACKNOWLEDGEMENTS

Thanks go to all following persons and organisations: University professors Shenghong Yang and Holger Paulick who were the supervisors of the thesis. Boliden Kylylahti and Boliden FinnEx (now Boliden Kevitsa Mining) for funding the thesis. Asko Kontinen for general Outokumpu geology guidance, sample selection and reviewing the thesis. Hannu Makkonen for general tips and tricks regarding the work and for review. Jari Juurela, who at the time was Boliden Kylylahti's supervisor in thesis work and suggested the drill core profile. Boliden Kylylahti superb technical personnel Ville Hyvärinen, Timo Yletyinen and Eeva Pajarinen for their help at core preparation and general assistance at core logging. Riitta Kontio from Uni. Oulu for sample prep guidance and Sari Forss for thin section preparation. Arttu Taipale, Anssi Kangas, Aleksi Salo and rest of the Savonian Tennis Club for support. Sanna Rötsä from Boliden for her help with data management. Markus Malmberg for digging into old production numbers. Jarkko Lamminen and Holger Oksanen for discussion and tips. Janne Kinnunen for his shared QGIS software knowledge and Juuso Laatio for his master class help with photographs and pictures. Marko Moilanen for his vast mineralogy knowledge and help. Leena Palmu and Pasi Juntunen from Centre for Material Analysis (CMA) at Uni. Oulu. Pasi Jokinen for general, undefined mental support.

Pekka Tuisku, Eero Hanski, Wolfgang Maier, Aulis Kärki, Vesa Peuraniemi, Juha-Pekka Lunkka and rest of the teachers and lecturers at Uni. Oulu for all the classes taught. Tiina Eskola and Minna Haataja for the administrative help.

Nikoli Ry – Oulun yliopiston geologinen kerho, for being part of something that matters. Institutions, faculties, departments, and personnel change as the wind blows and water flows, but like crystalline bedrock, Nikoli Ry remains.

My parents for housing me during the final weeks of the work. Finally, Päivi Rummukainen and my daughter Eevi Kekki for years of patience for the unfinished work.

9. REFERENCES

Background Map of Finland 1:320 000. Digital map layer. National Land Survey of Finland. Referred 21.11.2022.

Bedrock of Finland 1:200 000. Digital map database. Geological Survey of Finland. Referred 23.11.2022. Version 2.3.

Bedrock of Finland 1:5 000 000. Digital map database. Geological Survey of Finland. Referred 23.11.2022.

Claesson, S., Huhma, H., Kinny, P.D., and Williams, I.S. 1993. Svecofennian detrital zircons ages – implications for the Precambrian evolution of the Baltic Shield. Precambrian Research 64, 109-130.

Einaudi, M.T., Meinert, L.D., and Newberry, R.J., 1981, Skarn deposits: Econ. Geol., 75th Anniv. Vol., p. 317-391.

Gaál, G., Koistinen, T., Mattila, E., 1975. Tectonics and stratigraphy of the vicinity of Outokumpu, North Karelia, Finland: including a structural analysis of the Outokumpu ore deposit. Geological Survey of Finland, Bulletin 271, 67 p.

Hawthorne, F. C., Oberti, R., Harlow, G. E., Maresch, W. V., Martin, R. F., Schumacher, J. C., & Welch, M. D. (2012). Nomenclature of the amphibole supergroup. American Mineralogist, 97(11–12), 2031-2048.

Leake, B. E., Woolley, A. R., Arps, C. E., Birch, W. D., Gilbert, M. C., Grice, J. D., ... & Youzhi, G. 1997. Nomenclature of amphiboles; report of the Subcommittee on Amphiboles of the International Mineralogical Association Commission on new minerals and mineral names. Mineralogical magazine, 61(405), 295–310.

Locock, A.. (2014). An Excel spreadsheet to classify chemical analyses of amphiboles following the IMA 2012 recommendations. Computers & Geosciences. 62, 1–11.

Loukola-Ruskeeniemi, K., 1991. Geochemical evidence for the hydrothermal origin of sulphur, base metals and gold in Proterozoic metamorphosed black shales, Kainuu and Outokumpu areas, Finland. Mineralium Deposita 26, 152-164.

Loukola-Ruskeeniemi, K., 1999. Origin of black shales and the serpentinite-associated Cu-Zn-Co ores at Outokumpu, Finland. In: Gize, A.P. (ed.) A special issue on organic matter and ore deposits: interactions, applications, and case studies. Economic Geology 94, 1007-1028.

McDonough, W. F. & Sun, S., 1995. The composition of the Earth. Chemical Geology, Volume 120, Issues 3–4, 223 – 253.

Meinert, L.D., Dipple, G.M., Nicolescu, S., 2005. World Skarn Deposits. In: Hedenquist, J.W., et al. One Hundredth Anniversary Volume, Economic Geology, 299-337.

Meinert, L.D. 1992. Skarns and skarn deposits. Geoscience Canada, Vol.19 Number 4.

Meinert, L.D. 2022 https://www.science.smith.edu/geosciences/skarn/aboutskarn.html

Mineral Deposits of Finland. Digital map database. Geological Survey of Finland. Referred 23.11.2022.

Huhma, H., 1986. Sm-Nd, U-Pb and Pb-Pb isotopic evidence for the origin of the early proterotsoic Svecokarelian crust in Finland. Geological Survey of Finland Bulletin 337, 1-40.

Kohonen, J., Marmo, J. 1992. Proterozoic lithostratigraphy and sedimentation of Sariola and Jatuli-type rocks in the Nunnanlahti-Koli-Kaltimo area, eastern Finland; implications for regional basin evolution models. Geological Survey of Finland Bulletin 364, 67 p.

Koistinen, T.J. 1981. Structural evolution of an early Proterozoic stratabound Cu-Co-Zn deposit, Outokumpu, Finland. Transactions of the Royal Society of Edinburgh, Earth Sciences 72, 115-158.

Kontinen, A. 1987. An early Proterozoic ophiolite – the Jormua mafic-ultramafic complex, northern Finland. Precambrian Research 35, 313-341.

Kontinen, A., Peltonen, P., Huhma, H. 2006. Description and genetic modelling of the outokumpu-type rock assemblage and associated sulphide deposits. Final Technical Report for GEOMEX J.V. Workpackage “Geology”, 378 p.

Kuisma, M. 1985. Outokumpu 1910–1985 – Kuparikaivoksesta suuryhtiöksi. Outokumpu Oy.

Pearce, J.A., 2008. Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust. Lithos. Vol.100, 14-48.

Pearce, J.A., 2014. Immobile Element Fingerprinting of Ophiolites. Elements Vol.10 (2), 101–108.

Peltonen, P., Kontinen, A., Huhma, H. 1996. Petrology and geochemistry of metabasalts from the 1.95 Ga Jormua Ophiolite, northeastern Finland. Journal of Petrology 37, 1359–1383.

Peltonen, P. 2005. Ophiolites. In: Lehtinen, M., Nurmi, P.A., Rämö, O. T. (toim.) Precambrian Geology of Finland – Key to the Evolution of the Fennoscandian Shield. Developments in Precambrian Geology 14. Elsevier, Amsterdam, 237–278.

Peltonen, P., Kontinen, A., Huhma, H., Kuronen, U. 2008. Outokumpu revisited: New mineral deposit model for the mantle peridotite-associated Cu-Co-Zn-Ni-Ag-Au sulphide deposit. Ore Geology Reviews 33, 559-617.

Sun, S. and McDonough, W. F., 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. Geological Society, London, Special Publications, Volume 42, 313 – 345.

Säntti, J., Kontinen, A., Sorjonen-Ward, P., Johanson, B., Pakkanen, L. 2006. Metamorphism and chromite in serpentinized and carbonate-silica-altered peridotites of the Paleoproterozoic Outokumpu-Jormua ophiolite belt, eastern Finland. International Geology Review 48, 494-546.

APPENDIX 1: WHOLE ROCK ASSAY DETECTION LIMITS

XF700	Detect. limit		Upper limit		Milled in
SiO_2	0.01	%	100	%	W Carbide
Al_2O_3	0.01	%	100	%	W Carbide
Fe_2O_3	0.01	%	100	%	W Carbide
CaO	0.01	%	100	%	W Carbide
MgO	0.01	%	100	%	W Carbide
Na_2O	0.01	%	15	%	W Carbide
K_2O	0.01	%	15	%	W Carbide
MnO	0.01	%	50	%	W Carbide
TiO_2	0.01	%	40	%	W Carbide
P_2O_5	0.01	%	40	%	W Carbide
Cr_2O_3	0.01	%	10	%	W Carbide
Ba	0.01	%	58.8	%	W Carbide
LOI	0.1	%	100	%	W Carbide
SO_3	0.002	%	10	%	W Carbide
Sr	0.002	%	1.5	%	W Carbide

LF100-EXT	Detect. limit		Upper limit		Milled in
Ag	0.1	ppm	100	ppm	Agate
As	0.5	ppm	10000	ppm	Agate
Au	0.5	ppb	100000	ppb	Agate
Bi	0.1	ppm	2000	ppm	Agate
Cd	0.1	ppm	2000	ppm	Agate
Cu	0.1	ppm	10000	ppm	Agate
Hg	0.01	ppm	50	ppm	Agate
Mo	0.1	ppm	2000	ppm	Agate
Ni	0.1	ppm	10000	ppm	Agate
Pb	0.1	ppm	10000	ppm	Agate
Sb	0.1	ppm	2000	ppm	Agate
Se	0.5	ppm	100	ppm	Agate
Tl	0.1	ppm	1000	ppm	Agate
Zn	1	ppm	10000	ppm	Agate

LF100	Detect. limit		Upper limit		Milled in
Ba	1	ppm	50000	ppm	Agate
Be	1	ppm	10000	ppm	Agate
Ce	0.1	ppm	50000	ppm	Agate
Co	0.2	ppm	10000	ppm	Agate
Cs	0.1	ppm	1000	ppm	Agate
Dy	0.05	ppm	10000	ppm	Agate
Er	0.03	ppm	10000	ppm	Agate
Eu	0.02	ppm	10000	ppm	Agate
Ga	0.5	ppm	10000	ppm	Agate
Gd	0.05	ppm	10000	ppm	Agate
Hf	0.1	ppm	10000	ppm	Agate
Ho	0.02	ppm	10000	ppm	Agate
La	0.1	ppm	50000	ppm	Agate
Lu	0.01	ppm	10000	ppm	Agate
Nb	0.1	ppm	1000	ppm	Agate
Nd	0.3	ppm	10000	ppm	Agate
Pr	0.02	ppm	10000	ppm	Agate
Rb	0.1	ppm	1000	ppm	Agate
Sm	0.05	ppm	10000	ppm	Agate
Sn	1	ppm	10000	ppm	Agate
Sr	0.5	ppm	50000	ppm	Agate
Ta	0.1	ppm	1000	ppm	Agate
Tb	0.01	ppm	10000	ppm	Agate
Th	0.2	ppm	10000	ppm	Agate
Tm	0.01	ppm	10000	ppm	Agate
U	0.1	ppm	10000	ppm	Agate
V	8	ppm	10000	ppm	Agate
W	0.5	ppm	10000	ppm	Agate
Y	0.1	ppm	50000	ppm	Agate
Yb	0.05	ppm	10000	ppm	Agate
Zr	0.1	ppm	50000	ppm	Agate

TC003	Detect. limit		Upper limit		Milled
total C	0.02	%	100	%	Agate
total S	0.02	%	50	%	Agate

TC005	Detect. limit		Upper limit		Milled
Graphite	0.02	%	20	%	Agate

APPENDIX 2. THIN SECTION REPORTS

Appendix 2.1 Reference samples

Sample number	KU-681-102,78 (kwc-07, kag-07)
Sample description	Non-aligned sample with quartz vein cutting through tremolite crystals
Main minerals	**Textures, comments, observations**
quartz	Recrystallized, mostly very fine with 120-degree angles on grain boundaries.
tremolite	
mica	
calcite	Coexists on top of the section with Quartz
clinochlore	
plagioclase	Partially altered
Accessory minerals	
chalcopyrite	
pyrite	Very fine, forms bands and clusters
titanite	
rutile	
pyrrhotite	
pentlandite	

Sample number	KU-917-243,65 (kwc-08, kwc-08)
Sample description	Non-aligned, coarse sample. Figure 26.
Main minerals	**Textures, comments, observations**
tremolite	Porphyroblastic, subhedral, very coarse. Very fine inclusions of pyrite and pyrrhotite. Minor alteration on some crystal edges. Cr content on average (EDS, n18) 6500ppm
calcite	Relatively coarse. Recrystallized with perfect 120-degree grain boundary angles
Accessory minerals	
pyrite	
Co-pentlandite	
pentlandite	
pyrrhotite	
chalcopyrite	
gersdorffite?	Or the unnamed Ni-As mineral found in Kylylahti
magnetite	Trace

Sample number	KU-916-194,85B (kwc-11, kag-11)
Sample description	Presumably the older part of the sample that was intruded with younger veins reported in next table, sample KU-916-194,85A. Thin section is missing the bottom part due to poor quality preparation.
Main minerals	**Textures, comments, observations**
dolomite	Very fine, forms the matrix with assumed pyrrhotite companion in micron scale. Some recrystallization of smaller carbonates next to big vein.
carbonates in veins	Contains less inclusions, clearer crystals. Calcite is dominant. Crystals elongated perpendicular to vein walls; it seems they have grown from sides towards middle.
Accessory minerals	
tremolite	One big crystal has partially dissolved into carbonate vein. Al poor tremolite.
magnesio-hornblende	Might be tremolite but with internal elemental variation in crystal.
pyrrhotite	
graphite	Very fine graphite is assumed to be present. Samples stain hands.
plagioclase	
pentlandite	
pyrite	
gersdorffite	
quartz	
uraninite	one grain

Sample number	KU-916-194,85A (kwc-11, kag-11)
Sample description	Fine grained carbonate matrix with at least 2 different carbonate veins. At least 2 new separate carbonation cycles are visible. Mildly strained that caused mechanical bending of tremolite crystals.
Main minerals	**Textures, comments, observations**
dolomite	Matrix is very fine. Old veins have significantly larger grainsize but are filled with fine inclusions to make them appear messy. Inclusions are too fine to determine their composition
calcite	
tremolite	Very coarse, bent and broken. Contains no chromium.
Accessory minerals	
pyrrhotite	Disseminated in the presumably older, finer parts of the carbonate rock. Fine, anhedral crystals forming larger clusters. Also, in very fine particles inside carbonates.
pyrite	Sometimes with pyrrhotite. No cobalt in crystal lattice.
phlogopite	
chlorite	Contains Cr
quartz	Undulating extinction. Only one small tremolite crystal at the contact of carbonate and quartz. Seems that the latest carbonation happened in conditions where skarn minerals no longer form.
plagioclase	An80 on average
graphite	very fine

Appendix 2.2 CRB-Actska

Sample number	OKU-1000-253,42 (kwc-01, kag-01)
Sample description	Fine-grained dark grey carbonate rock showing slaty cleavage with relatively smooth cleavage domains. With 10-20% slightly oriented sulphides. Graphite rich. Roughly 50% of the thin section is opaque.
Main minerals	**Textures, comments, observations**
calcite	Fine, messy look due to pigment.
calcite (vein)	Fluid inclusions parallel to crystal edges. Opaque staining/inclusions.
pyrite	Medium grainsize, up to 5mm. Eroded, contains sphalerite and magnetite or chromite as inclusions.
tremolite	Rotated, deformed, medium to coarse. Large, coarse crystals are bent and as bending proceeds, it shows undulation extinction. Also joints crosscutting the crystals. Fold/fault structure that has broken the tremolite crystals, also visible on macro scale.
Accessory minerals	
phlogopite	
apatite	
titanite	
chlorite	
sphalerite	

Sample number	KU-681-90,44 (kwc-02, kag-02)
Sample description	Fine grained, sheared, oriented dark carbonates with contact to massive copper ore in the upper part of the section. Section is cut half by carbonate cemented joint.
Main minerals	**Textures, comments, observations**
carbonates	Both calcite and dolomite. Grainsize is coarser and less oriented near the ore contact. Also, same effect near amphibole crystals.
tremolite	Upper end of the section is the contact of the rather massive Cu-ore, which is surrounding the amphibole crystals. This would speak of the hydrothermal sulphides came at the same time or after the crystallization of amphibole. At bottom, tremolite crystals are surrounded with coarser carbonates and Ti-minerals, this speaks of some sort of proto-vein where the big tremolite crystals occur.
pyrite	Fine, subhedral grains disseminated mostly everywhere. Colours the whole section dark as there is very little graphite in this sample. Also, in coarser grains with cpy here and there.
pyrrhotite	Disseminated in the matrix, generally coarser than pyrite.
quartz	few grains
chalcopyrite	especially in the upper part of the section
Accessory minerals	
pentlandite	
titanite	
rutile	as inclusions in titanite crystals
phlogopite	trace amounts in matrix
clinochlore	
halite	as inclusion in tremolite

Sample number	KU-656-153,39 (kwc-03, kag-03)
Sample description	Fine, foliated, and sheared carbonate rock with fine sulphides and coarse tremolite. Carbonate veins and some folding, too. Highly opaque, yet not many sulphides or visible graphite.
Main minerals	**Textures, comments, observations**
carbonates	Both calcite and dolomite. Generally, very fine, but coarser at tremolite porphyroblasts' strain shadow.
tremolite	Coarse. Rotated in the shear, shows signs of strain. Messy look, lots of inclusions or alteration.
phlogopite	Fine single crystals here and there.
Accessory minerals	
pyrite	
magnetite	Replaces pyrite.
hematite	
rutile	
pyrrhotite	
pentlandite (?)	

Sample number	KU-656-82,66 (kwc-04, kag-04)
Sample description	Sample rich with opaque minerals, both alone and as inclusions. Fine carbonate-dominated matrix with coarse tremolite and disseminated pyrrhotite. Most likely quartz and feldspars in matrix, too. Some kinematic indicators both in ductile and brittle regime. Lower in Ca and Mg, richer in Si and Fe than other samples of this group.
Main minerals	**Textures, comments, observations**
carbonates	Very fine as matrix, coarser in veins and around tremolite crystals
tremolite	Prismatic, coarse, messy look due to alteration and carbonate inclusions. Possibly graphite and sulphides, too.
pyrrhotite	Fine to medium grains.
plagioclase	An91 anorthite (n=2)
quartz	Possibly in very fine matrix, too.
phlogopite	
Accessory minerals	
rutile	
unknown	Isotropic, opaque. Has internal reflections.
chalcopyrite	
muscovite	

Sample number	KU-917-225,41 (kwc-05, kag-05)
Sample description	Foliated, fine grained, dark grey carbonate rock with fine sulphide grains forming undulating bands. Few coarse, black, zonal amphiboles that are not oriented. Some mica in matrix. Figure 27.
Main minerals	**Textures, comments, observations**
carbonate	Calcite and dolomite. Slightly elongated grains. Fine, euhedral.
tremolite	Medium to coarse, zonal. Altered to carbonates on outer rim. Also, magnetite at rims.
pyrite	Round, anhedral blebs. Forms bands. Very fine, but coarser in veins.
phlogopite	Medium size
Accessory minerals	
talc?	No confirmation via EDS
pyrrhotite	Fine, anhedral
pentlandite	Fine, anhedral
chalcopyrite	Fine, anhedral
magnetite	Fine, subhedral

Appendix 2.3 OME-Actska

Sample number	KU-681-19,66 (kwc-18, kag-18)
Sample description	Non-oriented, pale-green carbonate-tremolite rock with some disseminated sulphides. Very fine inclusions in both carbonates and tremolite. Some inclusions are sulphides, some unidentified due to their small size.
Main minerals	**Textures, comments, observations**
carbonates	Dolomite and calcite. Anhedral, most likely recrystallized.
tremolite	Coarse, up to several cm. Cr content 0.2% to 1%.
Accessory minerals	
pyrrhotite	
pentlandite	
chromite (+Zn)	With 1.5% Zn and Eu

Sample number	KU-934-90,34 (kwc-19, kag-19)
Sample description	Mostly non-oriented, light-green carbonate-tremolite rock with some disseminated sulphides and Ti-minerals that occur in vein-like or fold hinge shape. Also, right bottom corner of the sample has tremolite crystals slightly aligned.
Main minerals	**Textures, comments, observations**
tremolite	Cr 0.4 - 0.8 %
carbonates	Calcite and dolomite. Grainsize everything from 0.1mm to 3mm.
chlorite	Cr 2.6 %
Accessory minerals	
pyrrhotite	When with tremolite, filling the gaps between crystals together with Ti-minerals. Also, microcrystalline po filling gaps between tremolite.
pentlandite	
titanite	In fold hinge or similar proto vein.
rutile	
chalcopyrite	

Sample number	OKU-1000-140,44 (kwc-20, kag-20)
Sample description	Sheared, veined sample. Carbonate veins also transported the sulphides, cannot say which was first. Inclusions in minerals are the reason for the dark colour of this sample. One inclusion with 30% F.
Main minerals	**Textures, comments, observations**
tremolite	coarse
carbonates	In matrix and veins. Dolomite and calcite.
quartz	Some quartz grains form the core for carbonate crystals.
Accessory minerals	
pyrrhotite	Very fine staining everywhere. Also disseminated in coarser grains.
graphite	Fine
chromite (+Zn)	6-7% Zn
pentlandite	Typical flame inclusions in po.
chalcopyrite	Fine, trace

Sample number	KU-916-242,82 (kwc-21, kag-21)
Sample description	Unoriented sample. Amphibole-carbonate skarn with lots of inclusions making the carbonates messy-looking.
Main minerals	**Textures, comments, observations**
tremolite	Al elevated compared to typical Kylylahti tremolites, up to 2.4 %
carbonates	
actinolite	Al rich. The only sample containing actual actinolite. One orthorhombic crystal was found in the thin section, but EDS confirmed it to be actinolite.
biotite	Not phlogopite
Accessory minerals	
pyrrhotite	
graphite	
pentlandite	
titanite	
rutile	
chlorite	
apatite	

Sample number	KU-917-478,95 (kwc-22, kag-22)
Sample description	Unaligned sample rich in amphiboles
Main minerals	**Textures, comments, observations**
tremolite	Coarse, unaligned.
calcite	
dolomite	
Accessory minerals	
pyrite	
rutile	
chromite	

Appendix 2.4 OUM-Actska

Sample number	KU-681-21,19 (kwc-24, kag-24)
Sample description	Very dark grey talc-carbonate rock with amphibole and unknown opaque, dark material staining everything.
Main minerals	**Textures, comments, observations**
carbonates	Dolomite and calcite. Very fine in matrix, coarser in veins.
talc	In matrix.
tremolite	Smaller crystals show signs of ductile deformation and largest ones also brittle fractures. Alteration and inclusions present.
Accessory minerals	
pyrrhotite	
pentlandite	
Zn-chromite	

Sample number	OKU-1000-192,42 (kwc-25, kag-25)
Sample description	Talc-carbonate rock with undulating foliation planes. Opaque pigment staining.
Main minerals	**Textures, comments, observations**
talc	
carbonates	Dolomite and calcite
tremolite	Prismatic, partially altered/dissolved
Accessory minerals	
pyrrhotite	
pentlandite	
phlogopite	just one crystal
chromite	

Sample number	KU-917-430,70 (kwc-26, kag-26)
Sample description	More coarse talc-carbonate rock with spectacular coarse, most likely tremolite pseudomorph shapes that are now talc and carbonate. Opaque pigment staining. Figure 29.
Main minerals	**Textures, comments, observations**
dolomite	
talc	
tremolite	Partially altered to carbonate.
Accessory minerals	
chromite	Abundant in veinlets.
pyrrhotite	
pentlandite	
rutile	
serpentine	
pyrite	
gold?	Not confirmed, tiny, bright yellow bleb.

Appendix 2.5 OBA-Actska

Sample number	KU-681-66,68 (kwc-27, kag-27)
Sample description	Coarse sample where sulphides are interstitial with amphiboles
Main minerals	**Textures, comments, observations**
tremolite	
carbonates	Enclosed in sulphides, not in contact with tremolite.
pyrrhotite	Crystallized after tremolite.
Accessory minerals	
phlogopite	
clinochlore	
pentlandite	As flame inclusions in pyrrhotite. Also, in subhedral, larger form.
magnetite/chromite?	

Sample number	KU-681-118,30 (kwc-28, kag-28)
Sample description	Sheared sample of fine grained, mostly transparent minerals with banded sulphides and Ti-minerals. Bands of coarser quartz and plagioclase crosscut finer qtz matrix. Lots of micas and some relatively altered, broken amphibole. Lots of chalcopyrite and lesser amount pyrrhotite and pentlandite.
Main minerals	**Textures, comments, observations**
quartz	fine, granoblastic, anhedral, undulating extinction
phlogopite	bent flakes
tremolite	possibly edenite, too. Mechanically broken crystals, also alteration into quartz and possibly into carbonates, too.
magnesio-hornblende	Another different amphibole, yet composition is very close to tremolite.
rutile	
plagioclase	On shear bands. Grain size from microcrystalline to fine. From euhedral to anhedral. Big compositional variation, everything from labradorite to anorthite.
Accessory minerals	
chalcopyrite	
carbonates	Undefined
pyrrhotite	
talc	
titanite	
pentlandite	
clinochlore	
apatite	
allanite?	REE-mineral
unknown REE-miner.	REE-mineral
pyrite?	

Sample number	KU-916-325,80 (kwc-29, kag-29)
Sample description	Partially sheared sample of dark, carbonate - chlorite - amphibole rock. Figure 30.
Main minerals	**Textures, comments, observations**
tremolite	
magnesio-hornblende	Could also be internal variation of tremolite crystals
carbonates	Mostly calcite, at least in EDS samples
phlogopite	
clinochlore	Cr up to 1%
Accessory minerals	
quartz	
pyrrhotite	Sulphides filling the gaps between amphibole crystals.
pentlandite	
apatite	

Sample number	KU-917-304,05 (kwc-30, kag-30)
Sample description	Sheared dark grey carbonate-amphibole rock
Main minerals	**Textures, comments, observations**
carbonates	Calcite and dolomite. Very fine in shear bands, otherwise larger grain size. Stained with pyrrhotite.
tremolite	Partially broken crystals, brittle environment.
actinolite	Internal composition variation of the same crystal that also yields tremolite values in EDS
Accessory minerals	
pyrrhotite	As staining or pigmenting carbonates. Also replacing tremolite.
phlogopite	
undefined mica	Most likely chlorite.
pentlandite	Flame and flaky inclusions in pyrrhotite.
chalcopyrite	trace