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A Petrological Investigation of the Host Rocks for the Kuj-Kiirunavaara Ore

En petrologisk studie av värdberget för Kuj-Kiirunavaara-malmen

Holger Sandberg

DEPARTMENT OF EARTH SCIENCES
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Sammanfattning

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Holger Sandberg

Kiirunavaara-gruvan är belägen vid en av världens största mineraliseringar av apatit-järnmalm. Denna malmkropp har stått i fokus för både omfattande gruvdrift samt genomgripande forskning. Malmkroppen är belägen mellan den syenitiska liggväggen och den ryodacitiska hängväggen, som består av varierande mineralogi och karaktär. Båda av dessa bergmassor innehåller intrusiv gångporfyr med distinkt karaktär. Målet med denna studie var att analysera 31 prover, främst i form av tunnsliper, och bestämma dess mineralogi samt att identifiera eventuella mikrostrukturer. Detta genomfördes genom användning av optisk mineralogi och EDS/WDS-analys vid det nationella mikrosondslaboratioriet vid Uppsala Universitet.

Liggväggen består av syenitporfyr och domineras av fältspat i både mellanmassa och som fenokrister. Karaktäristiskt för syenitporfyren är de rundade nodulerna, innehållandes aktinolit, titanit, magnetit och klorit. Hängväggen definieras som kvartsförande porfyr. Det är en ryodacitisk bergart med stora mängder fältspat, gröna silikater, kvarts, titanit och kalcit. Gångporfyren delar många likheter med den kvartsförande porfyren, men består av en finare mellanmassa med större mängd klinopyroxen, samt innehåller mindre mängder kvarts, magnetit och titanit. Hydrotermal omvandling är allmänt förekommande i alla bergarter i Kiirunavaara. Omvandlingsmineral så som aktinolit, biotit och klorit är väldigt vanliga hos Kiirunavaara-bergarterna. Den kvartsförande porfyren uppvisar den mest omfattande exponeringen av hydrotermala vätskor. De hydrotermala vätskorna har penetrerat ett antal prover och därigenom omvandlat mineral, med liten mängd äldre mineral kvar. Den kvartsförande porfyren innehåller de mest prominenta deformationsstrukturer, av olika omfattning och magnitud. Magmatiska flytstrukturer kan observeras i mellanmassan som parallell orientering av fältspat- och silikatkorn. Tecken av fastfasdeformation förekommer främst i form av tryckskuggor runt fältspatsfenokrister.

Nyckelord: Kiirunavaara, optisk mineralogi, hydrotermal omvandling, elektron-mikrosond

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Abstract

A Petrological Investigation of the Host Rocks for the Kuj-Kiirunavaara Ore
Holger Sandberg

The Kiirunavaara mine hosts one of the world's largest apatite-iron ore mineralisations. This ore body has been subject to large amounts of research as well as extensive mining. The ore body is situated between the syenitic foot wall and the rhyodacitic hanging wall, of which consists of differing mineralogy and characteristics. Both these rock masses contain intrusive porphyry dykes, with distinct characteristics of it own. The aim of this study was to analyse 31 samples, mainly in the form of thin sections, and determine the mineralogy and identify eventual microstructures. This was done through the use of optical mineralogy as well as EDS/WDS analysis at the National Microprobe Lab at Uppsala University.

The foot wall consists of syenite-porphyry and is dominated by feldspar in both groundmass as well as phenocrysts. Characteristic for the syenite-porphyry is the rounded nodules containing actinolite, titanite, magnetite and chlorite. The hanging wall is defined as quartz-bearing porphyry. It is a rhyodacitic rock with large amounts of feldspar along with green silicates, quartz, titanite and calcite. The intrusive porphyry dyke-rocks share many similarities with the quartz-bearing porphyry, but contain a finer groundmass with larger amounts of clinopyroxene, as well as lower amounts of quartz, magnetite and titanite. Hydrothermal alteration is prevalent in all the types of rock. Alteration minerals such as actinolite, biotite and chlorite are very common within the Kiirunavaara-rocks. The quartz-bearing porphyry displays the most extensive exposure to hydrothermal fluids. The hydrothermal fluids have penetrated several samples, replacing minerals and leaving very few remnant, older minerals. The quartz-bearing porphyry contains the most prominent deformation structures, of varying extent and magnitude. Magmatic flow structures can be seen in the groundmass, as parallel alignment of feldspar and silicate grains. Evidence of solid-state deformation most commonly occurs as pressure shadows around feldspar phenocrysts.

Keywords: Kiirunavaara, optical mineralogy, hydrothermal alteration, electron microprobe

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The whole document is available at www.diva-portal.org

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1. Introduction

Located in the most northern part of Sweden, the Kiruna mine has long been an important source of iron ore. The Kiirunavaara ore body is the largest known magnetite-apatite iron ore deposit in Sweden. The mining operation has been managed by LKAB (Luossavaara Kiirunavaara Aktiebolag) since 1898 (Kuchta et al. 2004). Mining activity on industrial scale dates back to 1900 (Bergman et al. 2001). The main Kiirunavaara ore body has an approximate length of four kilometers, average width of 80 meters and a known depth of at least 1900 meters (Bergman et al. 2001; Kuchta et al. 2004; Niiranen 2006; Andersson & Rutanen 2016). The smaller ore body of Luossavaara, located in close proximity to the Kiirunavaara ore body, consists of similar apatite-rich iron ore.

The Kiruna area and the local apatite iron ore have long been a focal point in research regarding the controversial formation of magnetite-apatite deposits (e.g. Geijer 1931; Parak 1975; Nyström 1985; Westhues et al. 2017). Examination of rock samples is an essential part of the mining industry. To be able to find iron ore of satisfactory quality and quantity, acquiring knowledge and understanding of the surrounding rocks is very important. LKAB's main objective is to survey iron ore, mine it and then process the ore. Analysis of rock samples from potential mining sites can function as a guiding principle to making productive and worthwhile decisions in mining the iron ore.

The purpose of this study is to determine the petrology of samples from the Kiirunavaara mine, mainly concerning altered country rocks and unknown minerals. These are the approaches during this study.

1. Microscopic examination of the samples and document the mineralogical composition and texture.
2. Determine the alteration minerals present and their chemistry.

2. Background

2.1 Regional Geology

The geology of Norrbotten consists of a slice of the Fennoskandian shield, with an Archean basement consisting mainly of strongly metamorphosed and migmatized metagranitoids. The age of the basement is between 2.83 to 2.68 Ga (Martinsson 2004). This cratonic basement was subjected to rifting approximately 2.45 to 2.1 Ga and a passive margin was formed (Gaál & Gorbatschev 1987; Lahtinen et al. 2005). Later, during the Palaeoproterzoic, they were intruded by mafic to felsic intrusions (Witschard 1984; Bergman et al. 2005).

This basement is covered by a series of dominantly metasedimentary and metavolcanic groups; the Kovo group, the Greenstone group, the Kurravaara conglomerate, the Porphyry group and the Hauki Quartzite (Martinsson 2004). With an age of 2.5-2.3 Ga, the Kovo group is the oldest. It is composed of products formed during the rifting of the Archean cratons, mainly clastic metasedimentary rocks and andesitic to basaltic volcanic rocks (Bergman et al. 2001). In the vicinity of Kiruna, this group overlies the basement in an unconformable fashion. The Greenstone group consists primarily basaltic volcanic rocks, carbonate rocks and graphitic schist. The upper part of the group is predominantly MORB-type pillow lava. The origin of the Greenstone group can be traced back to a second rift-event dating to approximately 2.1 Ga. The rocks present indicate a shallow aquatic setting. This environment underwent change to a deeper marine environment, suggested by the overlying MORB-type pillow lava (Martinsson 2004).

Unconformably overlying the Greenstone group in the Kiruna area is the Kurravaara conglomerate. A rock consisting of pebbles primarily of intermediate metavolcanic rocks. The Kurravaara conglomerate most likely originates from a wave-dominated shallow-marine environment made up of a fan delta (Bergman et al. 2001). The event that followed was the formation of a juvenile arc system through subduction of the oceanic crust approximately 1.94 Ga. The subduction magmatism generated the lavas and associated sediments making up the Porphyrite group (Martinsson et al. 2016; Storey et al. 2007). Rock types in the Porphyrite group are among others metamorphosed andesites and basalts (Bergman et al. 2001). The layer above is the Porphyry group, consists of metamorphosed basalt, rhyodacite-rhyolite and trachyandesite, dating to c. 1.91-1.88 Ga (e.g. Bergman et al. 2001; Westhues et al. 2016; figure 1). The commercially valuable iron ore are found within this group. Compared to the Porphyrite group, the Porphyry group rocks has higher contents of titanium and zirconium. Studies advocate that the Porphyry group rocks were developed in an environment of extensional tectonics (Bergman et al. 2001). The area was later, c. 1.86 Ga, exposed to uplift and consecutive erosion, generating the last component of the Svecofennian sequence, the Hauki Quartzite (Martinsson et al. 1999; Martinsson 2004).

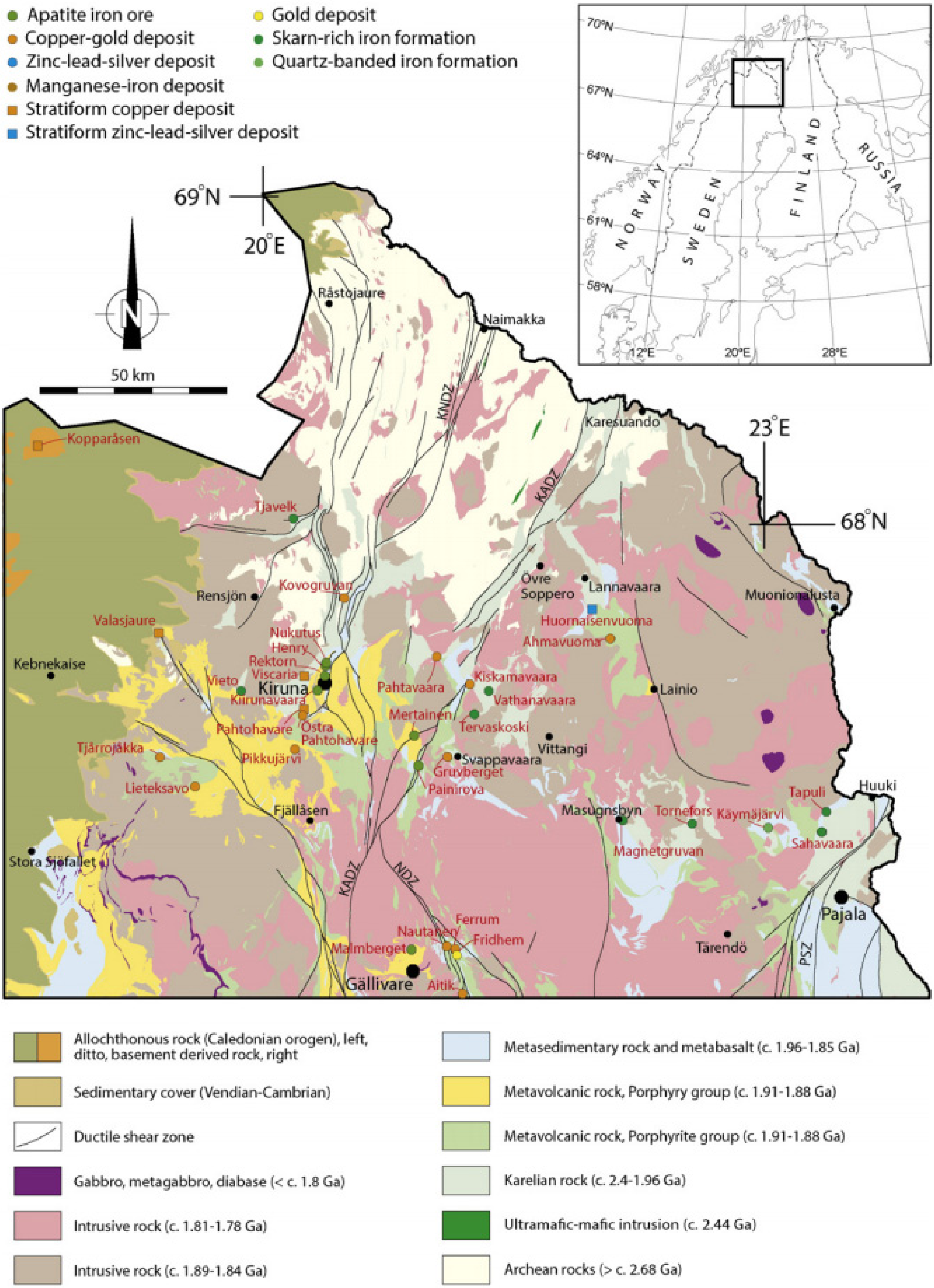

Figure 1. Geological map over Norrbotten, displaying geological groups and mineral deposits (Hellström & Jönsson 2014).

2.2 Local Geology

The Kiirunavaara ore body is situated along the contact of a series of characteristic syenite porphyry-lavas and adjacent pyroclastic rhyodacites (Geijer 1910; Bergman et al. 2001). With an overall tabular shape, the ore body spans approximately 4 kilometres in length and 80 meters in width, with a known depth of 1900 meters (Niiranen 2006; Andersson & Rutanen 2016). The syenite porphyry lava sequence, also typically of trachyandesitic composition, is comprised of a series of lava flows and dykes cutting the ore. Wall rock breccias, as well as alteration assemblages consisting dominantly of magnetite and actinolite can be found in both the foot wall and the hanging wall in connection with the ore body. The ore has a bimodal distribution (<0.05 % P or >1.0 % P) of phosphorus content (Bergman et al. 2001). The section of the ore with low P-content is usually found in vicinity of the foot wall and consists of an apatite-poor, mostly fine-grained magnetite formation. Iron ore with high content of phosphorus is generally located closer to the hanging wall, although irregular occurrences in the foot wall contact exists as well. Alteration is most extensive in the foot wall, with apparent albitisation and occurrence of secondary forms of magnetite, titanite and actinolite. Especially actinolite is a prevalent alteration mineral in the foot wall as well as the hanging wall (Bergman et al. 2001).

2.3 The apatite iron ore

The geology of the Kiruna area accommodates large volumes of apatite iron ore. These iron ore deposits are hosted by the volcanic rocks of the Porphyry group or the subjacent Porphyrite group (Martinsson, 2004, Martinsson et al. 2004). Magnetite and hematite are the main ore minerals, consisting also of considerable amounts of apatite and other light rare earth element-bearing minerals (Harlov et al. 2002). There is considerable variation within the apatite-iron ore in terms of host rock lithology, alteration and phosphorus content. Two groups can be discerned, the iron ore with breccia character and the iron ore with stratiform-stratabound character. The breccia type iron ore are found in the Porphyrite and lower parts of the Porphyry group. Intermediate to mafic volcanic rocks in these groups often contain brecciated iron ore (Bergman et al. 2001). Common minerals in the Porphyrite and Porphyry group are amphibole, which is ubiquitously present, and smaller amounts of pyrite, chalcopyrite and titanite. Magnetite is the dominant iron oxide. The occurrence of host rock alteration is not frequent in the breccia type iron ores, although albite and scapolite are often present, with small amounts of epidote, sericite and tourmaline. The breccia type iron ore display low phosphorus content, 0.05-0.3% (Bergman et al. 2001; Martinsson, 2004). The stratiform-stratabound type of deposits are generally positioned in the upper parts of the Porphyry group. Apatite, quartz and carbonate are the major minerals, with amphibole absent. Alteration of the host rocks is typical with alteration-products such as sericite, biotite and carbonate, with prevalent silicification of rocks in the hanging wall. The dominant iron oxide is magnetite with varying amounts of hematite. The phosphorus-content of the stratiform-stratabound type deposits is 1-4.5%, higher than the breccia type deposits (Martinsson, 2004).

The origin of the apatite-iron ores is not fully determined, with different genetic models in discussion. The theory with the most backing currently is the magmatic model, presented earliest by Geijer (1910). Over time the proposed magmatic model changed, from extrusive origin of the iron ores to intrusive sills (Geijer 1910, 1967). Findings of columnar and dendritic magnetite inside the iron ores supported the magmatic model, when compared to samples from the El Laco-complex in Chile (Nyström & Hernandez, 1994). An alternative theory, developed and presented by Parák (1975), suggested exhalative-sedimentary deposits from hydrothermal processes. Direct deposition from circulating infracrustal hydrothermal fluids is also favoured by some (Westhues et al. 2016).

2.4 The foot wall-rocks

The foot wall consists mainly of syenite and syenite porphyry rocks (Geijer 1910). These feldspar-dominated rocks may vary in composition, from equigranular syenite to porphyritic syenite-porphyry. A type of syenite with prominent nodules of primarily amphibole, titanite, mica, apatite and magnetite are present as well, by the name of nodular syenite-porphyry. These rocks were examined and described by Geijer (1910) and Palm (2015) to great extent.

The syenite, along with the syenite porphyry and nodular syenite-porphyry has, according to Geijer (1910), a groundmass dominated by feldspar. The colour of the groundmass may vary from grey to red. The feldspar grains in the groundmass are usually uniform in size within each thin section, with lengths from hundredths of a millimetre to 0.2 mm. Green silicates such as amphibole, pyroxene and biotite may be present in the groundmass, as well as titanite. Magnetite is almost always present in the groundmass. Larger grains are often enclosed in other minerals as aggregates or single anhedral crystals. Quartz occurs sparingly, most commonly intergrown with feldspar. The syenite rocks contain the most coarse groundmass of the three types (Geijer 1910).

Geijer (1910) writes that the phenocrysts in the syenite porphyry consist chiefly of perthitic feldspar. The size and quantity of these feldspar phenocryst can vary significantly, making up to one-third of a thin section at most. Their average size is about 1-2 mm, although they can stretch up to 1 cm. Tabular crystal habit is the most common. Plagioclase crystals with polysynthetic twinning make up some of the phenocrysts. Carlsbad twinning also occurs. Megacrysts of amphibole and pyroxene are less numerous and often smaller than the feldspar phenocrysts. They are mostly idiomorphic. The pyroxene crystals appear to be primary, and signs indicate that all the amphibole is secondary, except primary hornblende in nodules (Geijer 1910). Titanite is common in all types of syenite. According to Geijer (1910), the titanite most frequently appears as allotriomorphic grains branching out in irregular formations, its shape determined by other, surrounding minerals. Biotite can occur sparsely in many slides, although ample in other slides as the dominant green silicate. It appears as tiny plates, and Geijer (1910) first interprets the biotite as primary, but as they appear along cleavage cracks of feldspar and amphibole, he argues that the biotite may be of secondary origin as well.

The nodular syenite-porphyry contain conspicuous rounded nodules. These nodules consist primarily of amphibole, titanite, magnetite and feldspar, with minor amounts of apatite and biotite (Geijer 1910). They have a dark green colour and are frequently oriented in a pattern indicating compaction or flow. The nodules commonly occur close to the ore body (Andersson 2013).

Geijer (1910) describes the most prevalent alteration minerals in the foot wall rocks being titanite, uralite and chlorite. Uralite, a light-green coloured amphibole as a pseudomorph-product of clinopyroxene, is according to Geijer (1910) the most common alteration product of clinopyroxene. There are no by-products of the uralisation, practically making it paramorphose. It is more frequent in syenite porphyry than in syenite. Epidote and muscovite are present as alteration products in feldspar phenocrysts, but epidote is more common. Alteration through albitization and scapolitization occurs frequently throughout Northern Norrbotten, including the syenite-type rocks of Kiirunavaara (Frietsch et al. 1997).

2.5 The hanging wall-rocks

The rocks belonging to the hanging wall are generally referred to as quartz-bearing porphyries. These rocks are of rhyodacitic-rhyolitic composition with phenocrysts of perthitic alkali-feldspar and plagioclase (Geijer 1910; Bergman et al. 2010). These phenocrysts are rounded, with a diameter of up to 1 cm, and have a red colour (Geijer 1968). A granophyric structure with intergrowths of feldspar and quartz is present in some samples.

Inclusions of magnetite and hornblende, occur sparingly. Likewise for secondary products such as calcite, titanite and muscovite. Geijer (1910) finds that zircon is fairly common, as thick prismatic and pyramidal crystals frequently surrounded by a small spread of red pigment. Phenocrysts of pyroxene (augite) occur, similar to the ones present in the syenite porphyry of the foot wall. The phenocrysts are approximately 1 mm in length. Smaller grains are present as well. Large parts are altered into hornblende (Geijer 1910).

The groundmass, light-red to dark-red in colour, consists of alkali-feldspar, quartz and magnetite. as well as magnetite. The feldspar and quartz occur in similar proportions. Groundmass with blue-grey colour caused by fine-grained magnetite occurs rarely (Geijer 1968). In some samples a groundmass with differing texture and composition is observed, positioned alongside areas of the usual groundmass. These areas of different, coarser groundmass rarely appear as round, but is instead fluidally aligned. Quartz is the predominant mineral, with magnetite, biotite and feldspar also occurring. The majority of minerals in these coarser groundmass streaks are primary according to Geijer (1910). There are no nodules present in the hanging wall, only the syenite porphyries of the foot wall. The foot wall contains porphyry dykes (see below) with the compositions close to that of the hanging wall-rocks. These dyke porphyries, in some cases passing through the ore, have been proposed as feeders for the hanging wall magmatism (Andersson 2013).

2.6 Syenite-porphyry dykes

The syenite-porphyry dykes have a porphyritic texture, often with large amounts of perthitic feldspar phenocrysts, 2-10 mm in diameter. Plagioclase displaying polysynthetic twinning is the most common feldspar. Intergrowths of rectangular feldspar phenocrysts rarely occur, as is typical of the foot wall porphyries (Geijer 1910). The phenocrysts present in the syenite-porphyry dykes are instead rounded. Inclusions of magnetite, augite, actinolitic hornblende and titanite occur (Geijer 1967). Augite and uralite occur as phenocrysts in the form of thick prisms, some as inclusions in feldspar phenocrysts (Geijer 1910).

The major constituents of the groundmass are feldspar, augite and hornblende. Feldspar is most frequent, with augite and hornblende making up one third of the groundmass in some samples. The groundmass is very fine-grained, more so than the older rocks of the foot wall and hanging wall. A lack of nodules in the syenite-porphyry dykes is apparent (Geijer 1910). Quartz occurs as small grains, although rarely. This also applies to magnetite and titanite, as they occur less in the syenite-porphyry dykes than the older, volcanic rocks. Biotite on the other hand can occur in large amounts, some positioned around feldspar phenocrysts or in the groundmass. Calcite is, according to Geijer (1910), seen in almost all the samples examined, as irregular grains of magmatic origin.

2.7 Hydrothermal alteration

Hydrothermal alteration is a type of alteration occurring when the rock interacts with heated aqueous fluids, changing its mineralogy and sometimes the chemistry of the system. The temperature and composition of the fluid have large effect on the rock system. Other significant factors are the water-rock ratio and pressure conditions. The hydrothermal fluids may consist of different types of metals, salts and gases. The fluid can have different sources; seawater, near surface groundwater or exsolved water from magmatic rocks. These fluids circulate through rocks along fractures and faults as well as penetrative through permeable rock (Lagat 2009).

3. Method

The selection of 31 thin section was done by LKAB. The samples originated from the underground parts of Kiirunavaara, and includes samples from both the foot wall and hanging wall, as well as some from the ore. The selection was done for the purpose of characterization of various rock types and to identify unknown minerals. The use of microscopy to determine the mineralogy and structure of rock samples is an established method in petrology. It is based on the principle of utilizing the optical properties of minerals to identify and study their interrelations. This is most often done by cutting extremely thin slices (30 µm) of rock samples and observing how the minerals behave in contact with a light source. Pictures of the thin sections found in this study were taken using a Nikon microscope with mounted camera, in either polarized or reflected light. The thin sections were supplied by LKAB. The process of thin section examination began with thorough use of polarized light microscopy and reflected light microscopy. Later, electron micro probe analysis was used to further examine the minerals and their composition.

The hand sample of thin section 40 was examined with 0.1 M HCl, to see if it contained calcite or dolomite. The criteria for determining the character and type of deformation present in some thin sections were taken from Vernon (2000). Vernon lists evidence used to distinguish magmatic flow structures from solid-state deformations.

Transmitted light microscopy

The polarization microscope with light transmitted through the thin section sample, also known as a petrographic microscope, was used to examine the minerals of the thin sections. By letting light through minerals in the thin section, differences in interference colour, birefractive index and texture can be observed. Character and mineralogy of the individual components were investigated, together with texture, alteration and possible fracture-fill. The distribution of minerals in the thin sections were estimated by area ratio, and presented as percentages in table 1.

Reflective light microscopy

Reflected light microscopy model was used to identify opaque minerals in the thin sections. This group of minerals appear black in transmitted light, no matter in which direction the sample is turned. These minerals are easily identified in light reflecting from the surface of minerals.

Electron micro probe analysis (EMPA)

10 thin sections were chosen to be analysed with the electron micro probe, due to their complex mineralogy. This method was used to identify unknown minerals and confirm the identification of minerals commonly occurring in the samples. Multiple minerals in each of the 10 thin sections underwent EDS and WDS analysis.

EDS analysis (Energy-dispersive X-ray spectroscopy) was used to determine chemical composition of minerals, regarding specific elements. The chemical analysis is obtained through bombarding the thin section with a focused beam of electrons. Through this process, an X-ray spectrum is emitted from the thin section and quantitative and qualitative analysis can be produced. A limitation of EDS analysis is its incapability to detect very light elements, those lighter than Na. Energy peaks of different elements also tend to overlap, resulting in uncertainties regarding what element energy peaks represent.

WDS analysis (Wavelength-dispersive X-ray spectroscopy) also utilizes the principle of electron-beam interaction generating X-rays and derivative electrons. By isolating the characteristic X-rays generated by distinctive elements the WDS can do quantitative analyses, down to levels of trace elements.

The field emission source used was the JEOL JXA-8530F Hyperprobe at CEMPEG (Centre for Experimental Mineralogy, Petrology and Geochemistry), Uppsala University, Sweden. The run conditions were 15 kV accelerating voltage and 10 nA probe current with 10 s on peak and 5 s on lower and upper background. The thin sections were covered by a layer of carbon before the analysis. This was to increase the electrical conductivity and therefore avoid build-up of static electricity during the analysis.

4. Results

The samples were provisionally labeled according to a suggested rock type by LKAB geologists, with some comments and questions. The samples were then subdivided into four main groups for the purpose of clarity. These were syenite porphyry of the foot wall, quartz-bearing porphyries of the hanging wall, porphyry dyke rocks, and others. The latter group consists of samples that do not fit in any of the other groups. The samples are either from a different type of rock, e.g. ore (sample 40), dolerite dyke or (sample 47), or differ greatly from samples of the same origin. Detailed microscopic descriptions are found in the Appendix.

4.1 Syenite porphyry/Trachyandesite (Foot wall)

The nodules consisting primarily of green amphiboles and titanite described by Geijer (1910), Andersson (2013) and Palm (2015) are present in roughly half of the observed samples of syenite porphyry. Magnetite, chlorite, biotite, clinopyroxene and epidote occur in nodules in lesser amounts. The nodules are either rounded, which is the most common shape, or irregular. Their size varies from 0.2 mm to 10 mm in the presently studied samples. Quartz lines the nodules in a few samples. The syenite porphyry are characterized by low amounts or absence of quartz, and smaller feldspar phenocrysts/glomerocrysts compared to the quartz-bearing porphyry and porphyry dykes.

The syenite-porphyry rocks are generally dominated by feldspar, as a major component in the groundmass, as well as phenocrysts of varying sizes. These feldspar phenocrysts are what makes up a large portion of the porphyritic texture present in the syenite porphyry-rocks. The feldspar phenocrysts usually have tabular habit with euhedral to subhedral shape. Perthitic texture is common, as well as sericite and epidote alteration. The rims of the phenocrysts are sometimes lined with aggregates of anhedral quartz. Sample 33 contains large secondary K-feldspar crystals, with a probable metasomatic origin. These are classified as megacrysts.

Amphibole occurs as separate megacrysts, outside of nodules. The shape varies, with a rounded shape being most common. The borders of the amphibole megacrysts often display acicular structures. Uralite, pseudomorphs of clinopyroxene altered to amphibole, are observed in a small number of samples. These pseudomorphs have largely retained the shape of the clinopyroxene, and in some cases contain an inner core of unaltered clinopyroxene. Uralite may in some samples contain a noticeable amount of fine-grained magnetite inclusions. Phenocrysts of clinopyroxene, rounded, crystalline without the bladed habit of the amphiboles appear in a few samples. Clinopyroxene may also appear as constituents in nodules alongside titanite, chlorite and amphibole. Chlorite occurs as a common alteration mineral, as a product after amphibole, biotite and clinopyroxene. Small amounts of the chlorite occur as alteration lamellae within biotite grains.

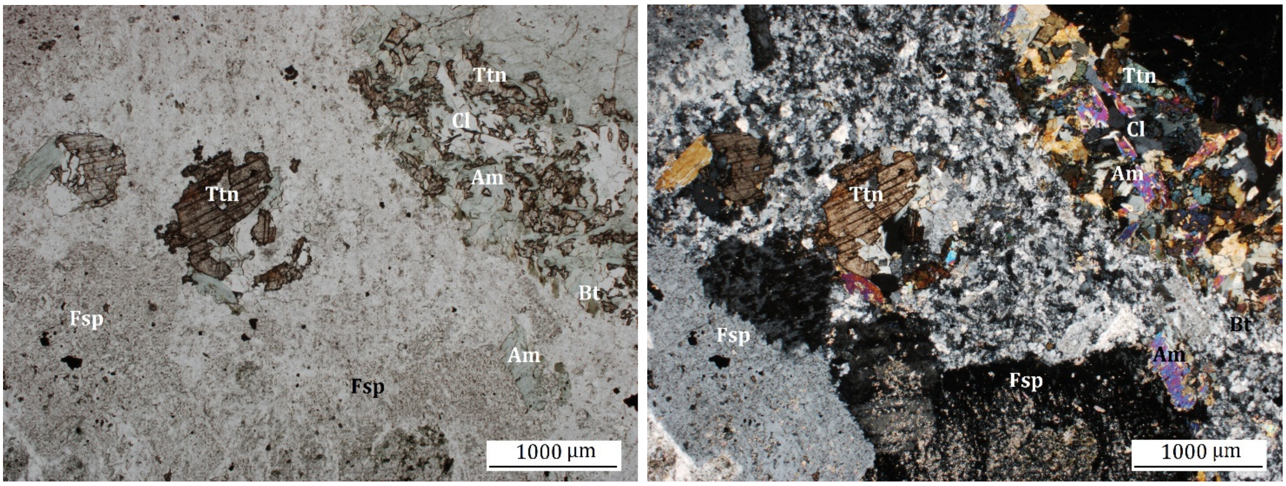

Figure 2. Left: plane-polarized light. Right: cross-polarized light. In the upper right is the edge of a rounded nodule consisting of amphibole (Am), titanite (Ttn) and chlorite (Cl). Feldspar (Fsp) phenocryst with epidote-alteration in lower center. Sample 42.

Megacrysts and grains of irregular, anhedral titanite are common in the syenite-porphyry rocks. The smaller titanite grains may occur as inclusions in feldspar phenocrysts and megacrysts of biotite and amphibole. The most common size is 0.1-1 mm, although megacrysts up to 8 mm in diameter have been observed (see sample 43). A few samples contain veins filled with titanite and magnetite. Anhedral grains of apatite, displaying moderate relief, noticeably higher than the commonly surrounding feldspar and quartz. Epidote occurs in a few samples, as yellow-green anhedral grains and as granular aggregates. Carbonate is present in low amounts in many samples. It appears as aggregates of anhedral grains, or as vein fill. Anhydrite is a fairly common mineral in the samples. It appears as colourless grains with very high birefringence. Gypsum may occur as colourless anhedral grains with distinctly softer texture than the anhydrite. It appears sometimes surrounded by amphibole and epidote (e.g. sample 41).

Magnetite occurs regularly as inclusions inside other minerals, most often titanite, but also inside feldspar, biotite and uralite. It appears as anhedral grains up to 1 mm in diameter. Magnetite grains may contain anhedral inclusions of fine titanite. Sample 33 display long streaks of fine-grained magnetite, clearly visible in hand sample as darker areas.

Ilmenite is the second most common oxide mineral, appearing almost exclusively as anhedral grains positioned in the center of large titanite grains. Hematite is the most common alteration mineral of magnetite, occurring in the samples as a product of martitization. Pyrite occurs in most of the syenite-porphyry samples, but in very minor amounts. The very small, <0.1 mm, euhedral to subhedral cubical grains cover less than 1% of the samples. Chalcopyrite is observed in sample 47, as yellow anhedral grains generally positioned along outer rims of magnetite/hematite grains.

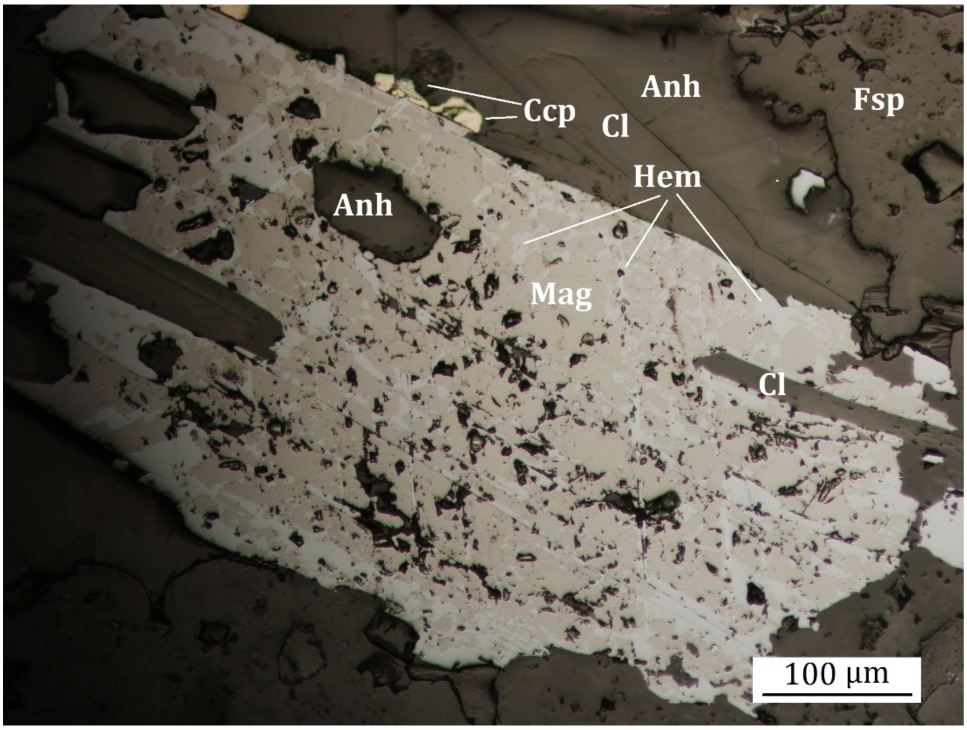

Figure 3. Large grain of magnetite (Mag) with hematite (Hem) alteration. Small grains of chalcopyrite (Ccp) positioned along the outer top rim. Proximate anhydrite (Anh), chlorite and feldspar. Sample 47. Crossed polarized light in reflected light microscope.

The groundmass is fine-grained, sometimes aphanitic, and consists mainly of feldspar, amphibole, magnetite and biotite. Plagioclase, albite and K-feldspar are present in the groundmass in varying proportions. Some of the groundmass is made up of equal proportions of irregular grains of albite and K-feldspar, such as sample 43. Amphibole, when present in the groundmass, appears mostly as pale green bladed grains, constituting up to a third of the groundmass. Biotite occurs as more anhedral green grains, and never makes up more than a fifth of the groundmass at most. Magnetite is present in the groundmass in almost all samples of syenite-porphyry, though never in large amount. Small amounts of carbonate, anhydrite and epidote may appear in the groundmass.

4.2 Quartz-bearing porphyry/Rhyodacite (Hanging wall)

The occurrence of feldspar phenocrysts is common within all samples from the hanging wall. These phenocrysts usually have euhedral to subhedral tabular habit, and are up to 13 mm in diameter. Glomerocrysts, where multiple feldspar phenocrysts are intergrown, are present in a moderate number of samples. The glomerocrysts may contain lesser amounts of amphibole, quartz, biotite, titanite and carbonate. These minerals may also occur as inclusions in feldspar phenocrysts. Sericite, albite and epidote alteration occur to varying degree in the feldspar phenocrysts. Polysynthetic twinning can be seen in some phenocrysts. Fractures in feldspar phenocrysts are in some cases filled with carbonate.

Amphibole is only present in a few of the samples of quartz-bearing porphyry. When occurring, it is as fine bladed grains in the groundmass (sample 34) or as aggregates of subhedral bladed grains (sample 50). Amphibole is also present as vein fill in sample 34. The same sample contain amphibole megacrysts positioned alongside titanite and magnetite. Apatite occurs very sparingly, as colourless grains with low birefringence and moderate relief and may occur surrounded by anhydrite or titanite. Anhydrite and gypsum occur sparingly, sometimes positioned in calcite aggregates and in the groundmass. Tourmaline appears in a single sample, as green columnar prisms.

Magnetite occurs in low amounts, generally as relatively small euhedral grains, but larger grains occur as well. The smaller grains may occur in the groundmass or as inclusions in minerals such as feldspar, titanite, amphibole and carbonate. Hematite can be seen in some magnetite grains, generally along the edges or as anhedral inclusions. The hematite is most probably a product of martitization. Ilmenite also appears as inclusions in magnetite, although most frequently appears as anhedral grains in the center of large titanite grains. Very small amounts of pyrite occur, appearing as fine cubic grains.

The groundmass has an aphanitic texture with a generally hypidiomorphic fabric. It consists mainly of feldspar, occurring as fine-grained, tabular and round grains, and anhedral quartz. EDS analysis indicate that the groundmass feldspar of at least one sample of quartz-bearing porphyry consists of equal parts alkali feldspar and albite (appendix: table 7). The groundmass contains, in some cases, large amounts of bladed amphibole grains. When present, the bladed amphibole constitutes up to half of the groundmass. In samples exposed to magmatic flow, these amphibole grains can be seen displaying alignment in the direction of the flow (figure 4). This indicates the complete replacement of an original mineral and its alignment by secondary amphibole.

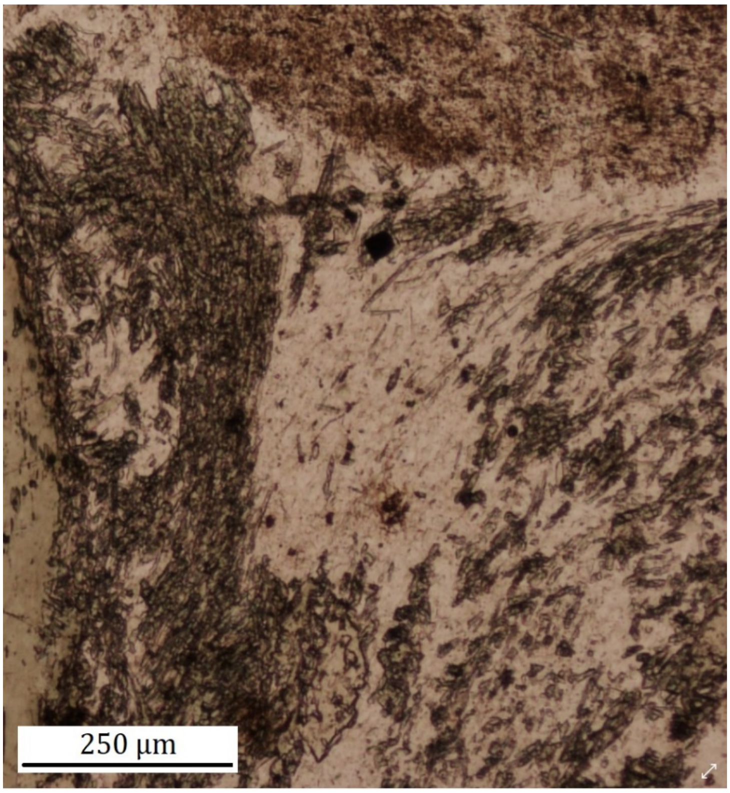

Figure 4. Example of magmatic flow structures. Amphibole, feldspar and quartz grains in the groundmass display parallel alignment. This is most apparent in the right part of the image. Sample 34. Plane-polarized light.

Biotite may occur as small anhedral and subhedral bladed grains in the groundmass, although never as a major constituent of the groundmass. Biotite may also occur as green, bladed grains with a length up to 0.3 mm, positioned in aggregates. These aggregates of biotite often display alignment in a uniform direction. Inclusions of fine-grained radioactive minerals are common in the biotite. These inclusions radiate pleochroic brown halos, making them easily distinguishable from the biotite. Monazite and zircon account for a part of these inclusions.

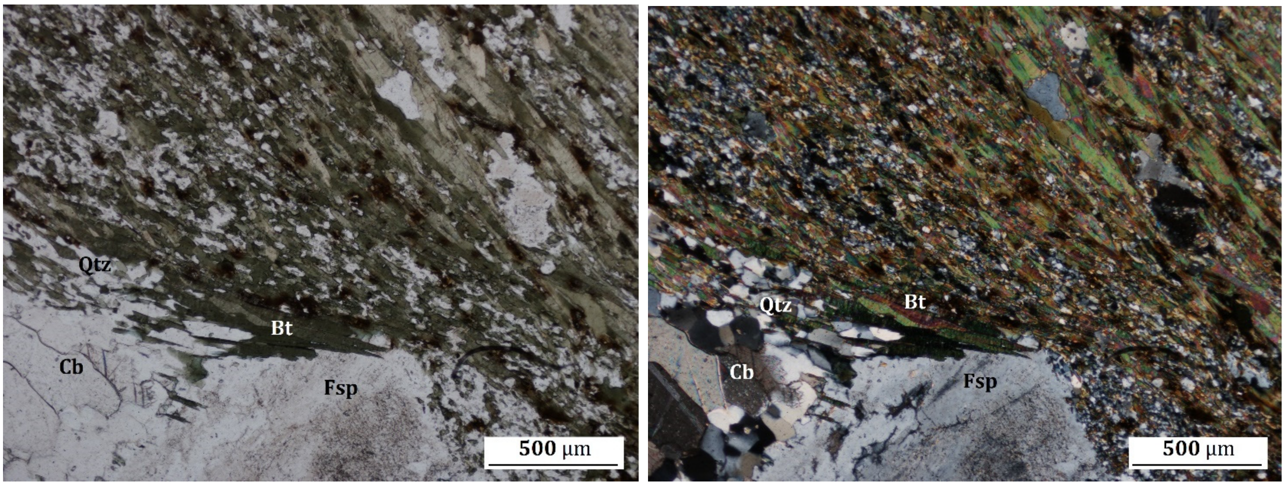

Figure 5. Left: plane-polarized light. Right: cross-polarized light. Example of solid state deformation. Pressure shadow to the left of the feldspar phenocryst, containing aggregates of quartz (Qtz) and carbonate (Cb). Large aggregates of bladed biotite (Bt) surround the feldspar phenocryst. Sample 49.

Practically all the samples containing aggregates of green biotite also contain aggregates of carbonate grains. These carbonate aggregates consist of anhedral grains, up to 0.3 mm in length. In some cases elongated in the direction of foliation. The aggregates are often aligned with anhedral quartz grains, 0.1-0.3 mm in diameter, sometimes making up aggregates. The aggregates of quartz can also be seen lining the biotite aggregates.

Signs indicating both magmatic flow structures and solid-state deformation are fairly common in the quarts-bearing porphyry-rocks. Elongate feldspar and amphibole grains in the groundmass of some samples display alignment in the flow direction. This is interpreted as evidence for magmatic flow structures (Vernon 2004). Other samples display pressure shadows along rims of feldspar phenocrysts. These areas are filled with aggregates of quartz, carbonate and biotite. Elongation of quartz aggregates as well as internal deformation can be seen in feldspar grains positioned in the groundmass in some samples. Both the pressure shadows and internal grain deformation indicates solid-state deformation (Vernon 2004).

Figure 6. Two pressure shadows on each side of a feldspar phenocryst, constituted of aggregates of quartz and biotite. Sample 50. Cross-polarized light.

4.1.3 Syenite-porphyry dykes

Porphyry in the form of porphyry dykes are a group of rocks not belonging exclusively to the hanging wall or the foot wall of Kiirunavaara. The dykes are present as intrusions in both foot wall and the ore, indicating a younger age of the dykes. These dykes partly crosscut the ore and partly interleave and mingle with it (Geijer 1960; Andersson 2013)

The porphyry dyke-rocks share a porphyritic texture and a number of similarities with the quartz-bearing porphyry of the hanging wall. Large feldspar phenocrysts are very common, sometimes appearing as multiple phenocrysts grouped together as glomerocrysts. The individual crystals are most often euhedral and tabular. The crystals in the feldspar glomerocrysts tend to be more rounded, displaying subhedral shapes. Protruding triangular edges of feldspar crystals may appear out of the glomerocrysts. The feldspar phenocrysts are partially altered into K-feldspar and albite. At least one sample contains feldspar phenocrysts with epidote-zoisite alteration.

Clinopyroxene may occur as blocky, rectangular crystals, sometimes forming anhedral grains as well as a common constituent in the groundmass. Titanite occurs in some circumstances together with clinopyroxene. These titanite crystals are present as grains enclosed in clinopyroxene. Amphibole occurs as elongated crystals with a bladed or tabular shape in varying size. Minor amounts of anhydrite occur in at least one sample. The anhydrite appears as blocky, subhedral crystals, often in contact with amphibole and quartz. Biotite is present in some samples of porphyry dyke-rocks, as grains with irregular outline positioned in aggregates. Titanite may occur as inclusions. Sample 49 contains large amounts of tabular and bladed biotite in aggregates, probably indicating the presence of fractures. Small aggregates of carbonate grains occur occasionally. Calcite is the most probable carbonate. The amount of magnetite is very low compared to the older rocks in the foot wall and the hanging wall, also pointed out by Geijer (1910). When magnetite is present it appears as small anhedral grains. Small amounts of epidote are present in some samples, mainly as inclusions inside feldspar phenocrysts. Chlorite is only present in one sample (51), as small crystals positioned near amphibole grains; possibly as alteration minerals of the amphibole. Apatite has been noted in one sample as anhedral crystals in the groundmass.

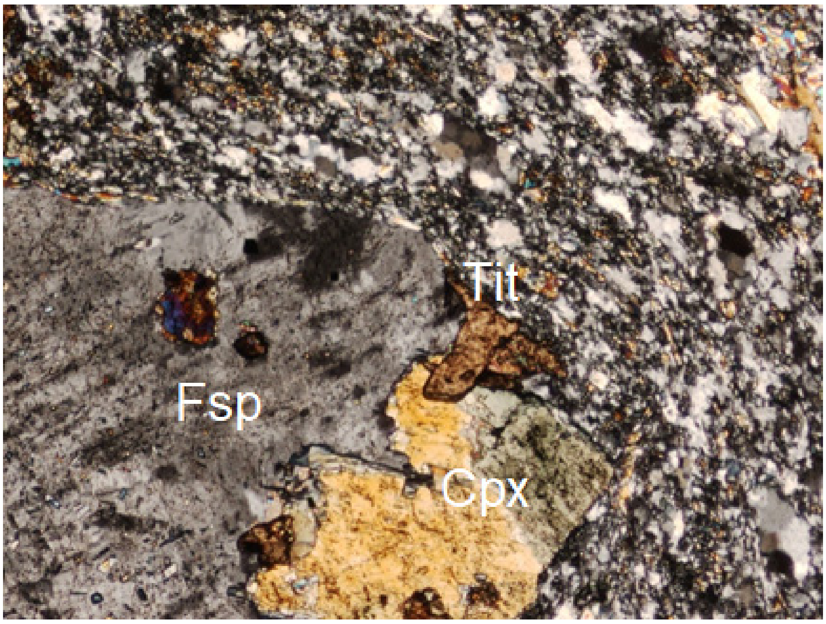

Figure 7. Large feldspar phenocryst with dark alteration mineral (probable K-feldspar). Brown titanite partially enclosed in clinopyroxene (Cpx). Groundmass of feldspar, clinopyroxene and quartz. Sample 35. Cross-polarized light.

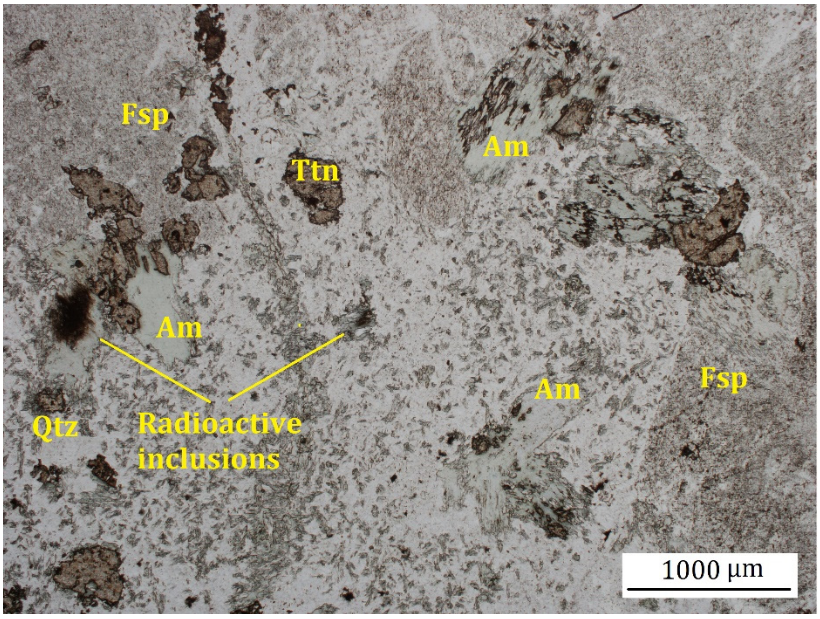

Figure 8. Glomerocrysts of feldspar, amphibole and titanite. Some of the amphibole grains contain radioactive inclusions with brown halos (unknown mineral). Groundmass of feldspar, bladed amphibole and quartz. A vein of acicular amphibole run vertically through the thin section. Sample 51. Plane-polarized light.

The groundmass is generally very fine-grained. In some cases to an extent of making it difficult to distinguish specific minerals. Feldspar is the most common mineral in the groundmass, occurring as subhedral to irregular grains. Green silicates such as clinopyroxene and amphibole are fairly common, and can constitute up to half of the groundmass. Clinopyroxene may occur as fine green anhedral grains, while amphibole occurs as thinner, bladed grains. Quartz is present in the groundmass in varying amounts and grain sizes. Some samples display large amounts of quartz in the groundmass. One porphyry dyke sample displays magmatic flow structures and another one contains veins filled with amphibole, titanite, quartz and carbonate.

As mentioned before, the porphyry dyke rocks share similarities with the hanging wall-rocks, regarding texture and chemical composition. Major distinguishing features of the porphyry dyke-rocks are a finer grained groundmass, consisting of higher amounts of silicate minerals, and lower amounts of magnetite, titanite and quartz.

4.1.4 Others

Sample 39 is taken from a vein inside the quartz-bearing porphyry of the hanging wall. It has a very different composition than the surrounding quartz-bearing porphyry, containing large columnar allanite crystals in a groundmass of anhydrite, carbonate and amphibole. A very similar composition is found in sample 37, with large fractured columnar crystals of allanite. Unlike the previously mentioned sample, sample 37 is taken from a vein in skarn, in the foot wall close to ore contact. Sample 38 is taken from the D3-ore and is composed of a porphyritic texture with large carbonate megacrysts in a groundmass of quartz, biotite and magnetite (figure 9).

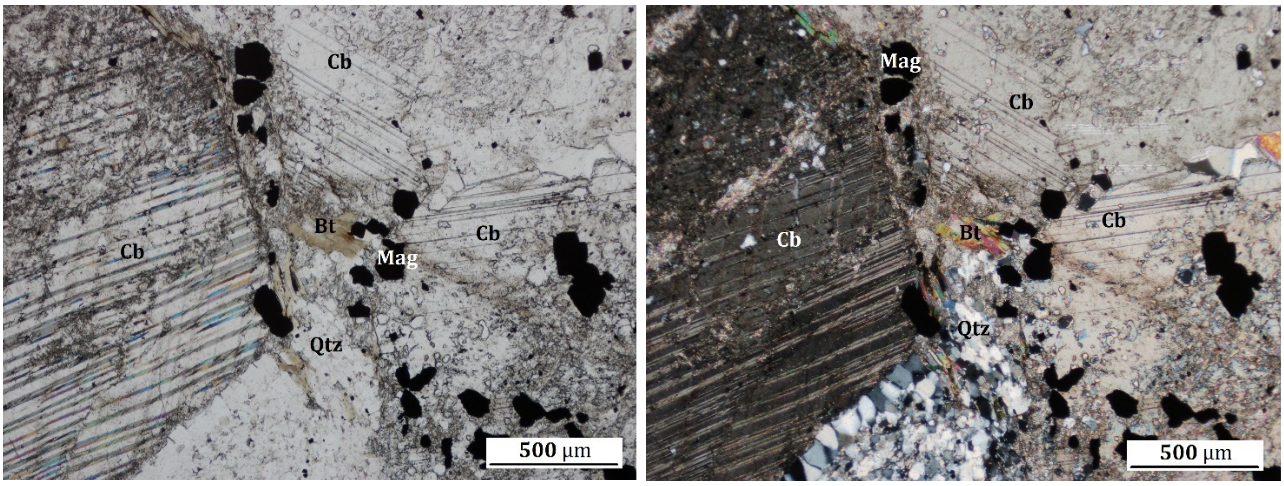

Figure 9. Left: plane-polarized light. Right: cross-polarized light. Fine-grained talc lines some of the carbonate megacrysts. Sample 38.

The D3-ore type is classified as apatite-rich ore. Another ore sample is number 40, belonging to the B2-type of ore. The B2-ore type is classified as a silicate-rich ore. Coarse-grained magnetite is the most prominent mineral. A large mass of biotite cuts through the middle of the sample, with chlorite veins running through both biotite and some of the magnetite. Dolomite acts as vein fill in the magnetite fractures as well. The only sample displaying subophitic texture, characteristic to diabase/dolerite, is sample 46. It is composed of elongated and often irregular plagioclase crystals intergrown with amphibole, clinopyroxene, biotite and magnetite.

4.2 Mineral chemistry

Mineral chemistry from a number of minerals in 10 selected samples are found in the appendix, tables 1-8 (EDS) and 9-18 (WDS). These are partly incomplete but give a general overview of the mineral chemistry, and are given here without further comment, except for amphibole and biotite.

Amphibole

Amphibole is one of the most common silicates of the Kiirunavaara rocks, occurring in both the hanging wall and the foot wall rocks as well as in the porphyry dykes and ore (B2). All the chemically analysed amphibole present in the samples were classified as actinolite according to classification nomenclature by Leake et al. (1997) and a mineral recalculation and classification spreadsheet (Appendix: table 19). Previous studies also classify the amphibole as actinolite (Nordstrand 2012; Aupers 2014; Palm 2015). Actinolite pseudomorphs of clinopyroxene, known as uralite appears in a few samples.

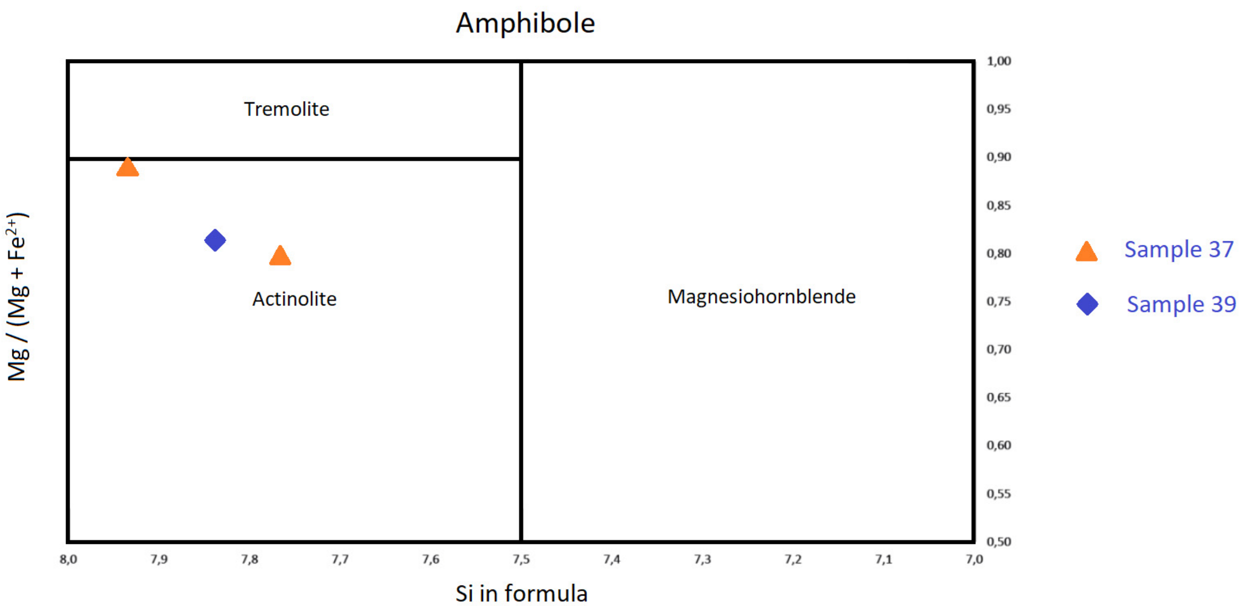

Figure 10. Composition and nomenclature of amphiboles in diagram designed for calcic amphiboles. Modified from (Leake et al. 1997).

Biotite

The biotite present in the samples were classified as phlogopite, although with varying composition (figure 10), according to the nomenclature of Fleet et al. (2006). The most common appearance of biotite in the samples was as green-brown bladed grains. These grains could form large biotite aggregates, most common in the quartz-bearing porphyry.

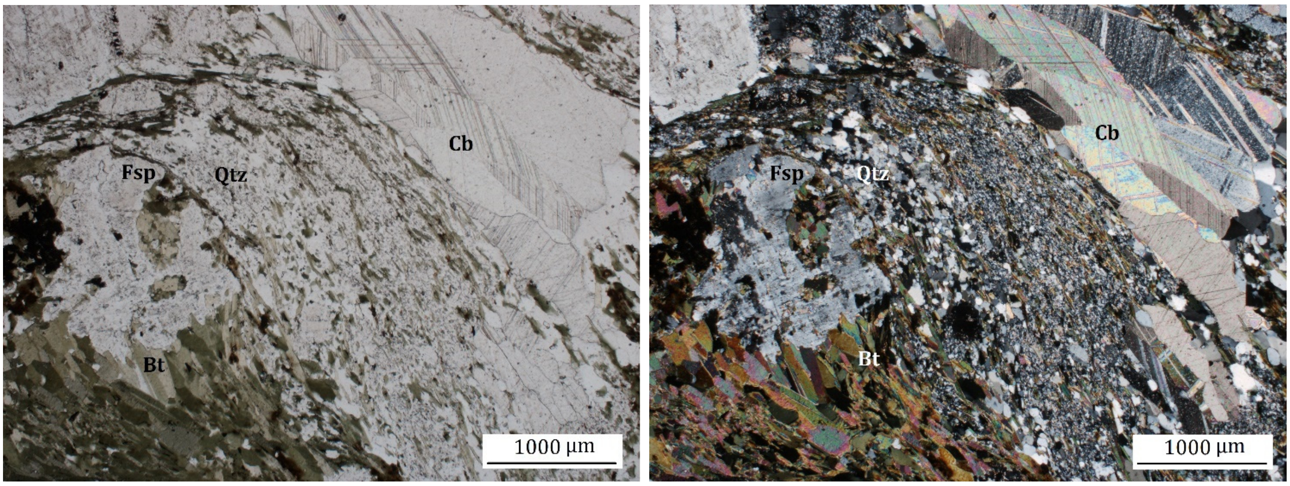

Figure 11. Left: plane-polarized light. Right: cross-polarized light. Example of the presence of hydrothermal fluids. Aggregates of biotite and carbonate with minor amounts of gypsum and anhydrite, both lined with quartz, and aligned in the same uniform direction. Sample 44.

Sample 40 contained distinct pale brown biotite. Despite the different colour, it still classified as phlogopite, and is similar in composition to that of groups 2/3 of Nordstrand (2012). The chemical formulas of biotite were calculated using data from the WDS analysis (Appendix: table 11).

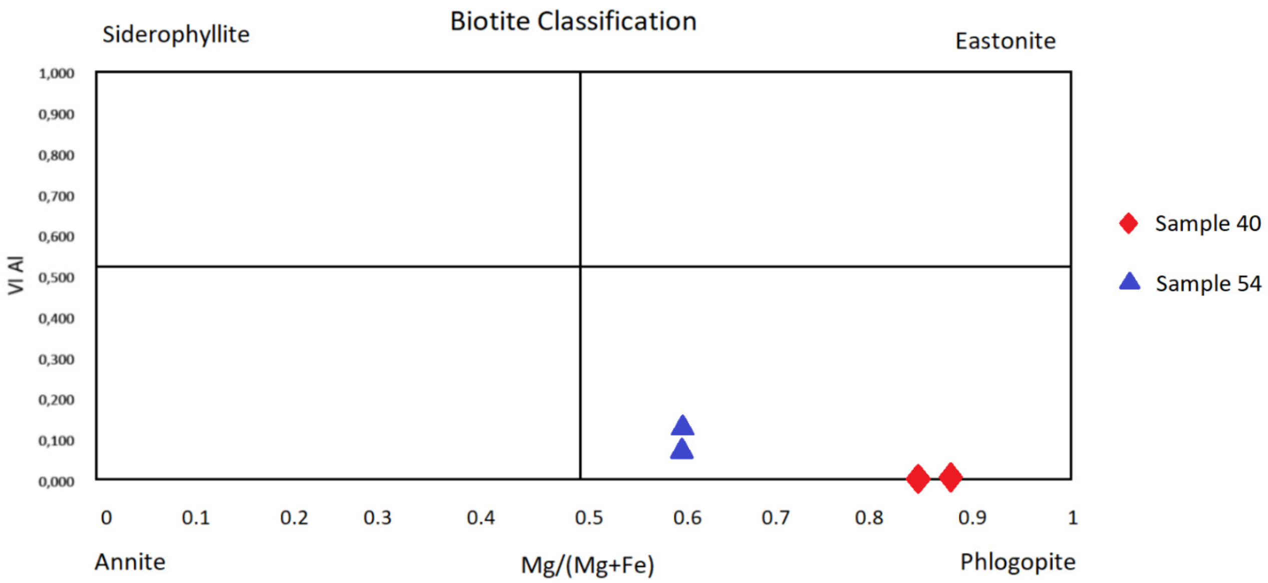

Figure 12. Biotite classification with data from WDS analysis. The red dots represent sample 40. The blue dots represent sample 54. Diagram after (Fleet 2006).

Modal composition

Modal compositions have been estimated for all thin sections by microscopy, and is summarized in table 1 and 2. Abbreviations are found in the appendix.

Table 1. Estimated modal amounts of the most frequently occurring minerals of the thin sections.

Thin section nr.	Fsp	Qtz	Am	Cpx	Bt	Ttn	Ep	Chl	Cb	Anh	Mag	Pyr	Ilm	Hem
32	50-60%	1-5%	10-15%		5-10%	8-15%	1-5%	5-10%		1%	10-20%	<1%		
33	45-55%		20-25%			1-5%	5-10%				10-20%			
34	30-45%	15-30%	20-30%	3-7%		1-5%					1-5%	<1%		1-5%
35	55-65%	10-15%	3-7%	15-25%		1-5%				1-5%	1-3%		1%	
36	50-60%	1-5%	15-25%	10-20%		1-5%			3-7%		<1%			
37			5-10%			10-20%			3-7%	20-25%	1-5%			
38		5-10%			3-7%	1%			25-35%		30-40%			
39		15-25%	5-10%		5-10%			1-3%	10-15%	20-30%				
40					10-20%			10-15%	*		50-60%	1-5%		1-5%
41	55-65%	1-5%	5-10%	3-7%	5-10%	3-7%	3-7%	5-10%			3-7%	1%	1%	
42	60-70%		5-15%		1-5%	1-5%		3-7%	1-5%		5-10%	1-3%		
43	40-50%		15-25%		1-5%	5-10%		1-5%	1%		10-20%	1-5%		1-3%
44	15-20%	25-30%			10-20%				15-25%	1%	1%	<1%		<1%
45	65-75%		10-17%	1-5%	1-5%	1-5%	1%		1-5%		1-3%	<1%		
46	25-35%		10-20%	10-15%	10-15%	5-10%					15-25%	1-5%		
47	50-60%	5-10%			10-20%	1-5%	1%	3-7%	3-7%	5-10%	1-5%		1%	1%
48	65-75%	10-15%			5-15%	1-5%		1-3%	3-7%			1%		
49	15-25%	20-30%			25-35%				5-15%	1-3%		1%	1%	
50	60-65%	10-15%	15-20%		10-15%	1-5%		1-5%	1-5%	1-3%	3-7%		1%	
51	50-60%	3-7%	25-35%			3-7%			1-3%	1-3%		1%	1%	
52	75-85%	5-15%						1-5%	1-5%	1-5%	5-15%			
53	15-25%	20-30%			5-15%	5-15%	1-5%		25-35%	1-3%	10-15%			
54	15-25%	5-10%			10-15%	35-45%			10-20%		5-10%	<1%	10-15%	
55	45-55%		10-20%			10-20%	10-15%	3-7%		3-7%	3-7%		3-7%	3-7%
56	25-35%	1-5%	1-5%		20-30%	15-25%		1-5%	1-5%		3-7%	<1%	3-7%	1-3%
57	10-15%	10-15%	20-30%	3-7%	20-30%			1-5%	5-15%					
58	25-35%	1-5%	15-25%		10-20%	15-25%			1-5%	1-5%	5-10%		1-5%	
59	40-50%	3-7%			5-15%	5-10%		1-5%	15-25%		3-7%		1-3%	
60	20-30%	5-10%			30-35%	5-15%					15-20%		1-5%	
61	5-15%	10-20%			15-25%	10-20%		1-5%	10-20%		10-15%	<1%	3-7%	
62	25-35%		10-20%			15-25%	1-5%				10-20%		5-10%	

Table 2. Estimated modal amounts of more uncommon minerals in the thin sections.

Thin section nr.	Aln	Gp	Talc	Dol	Cal	Rt	Zrn	Ccp	Ap	Mnz	Tur	Uralite	Unknown
37	45-55%												
38			1-5%					1%					
39	20-30%												
40				10-20%	1-5%	1%							
41	1%	1%							1%				
42									1-3%			5-15%	
44	1%	1%											
45		1%										10-17%	
47		1-3%						1%					
48	1%												
49							1%			1-3%			
51									1-5%				
52								<1%	1-3%				
53	1-3%					1%					1%		1-3%
54	1%							1-3%	1-5%				
57	<1%						1-3%					20-30%	
58		1%											
59							1-5%						
60	1-3%												
61							1%						

5. Discussion

Syenite-porphyry/Trachyandesite

The observed mineralogy and texture of the syenite-porphyry-rocks was in general consistent with how the rocks has been described in literature. No scapolite was observed in the samples, in contrast to the wide-spread scapolizitation in northern Norrbotten described by Frietsch et al. (1997). The amount of clinopyroxene observed in the samples was relatively low, compared to what Geijer (1910) describes. He notes that clinopyroxene may appear in the groundmass as well as primary idiomorphic megacrysts. At least one sample displays dark streaks of magnetite and light streaks of feldspar and actinolite (sample 33). The light streaks are products of the rock being penetrated by hydrothermal fluids, altering the mineralogy. The magnetite in the dark areas are therefore the last remnant of the original rock. Similar types of hydrothermal alteration occur in a number of samples, with extensive alteration leaving only small amounts of primary remnants. Feldspar and magnetite appears to be the most common of the primary minerals occurring in this type of samples.

Quartz-bearing porphyry/Rhyodacite

What has been described in the literature about the quartz-bearing porphyry matched well against the observations in this study, albeit a few exceptions. Very low amounts of zircon were observed in the samples, although Geijer (1910) mentions that prismatic and pyramidal zircons are fairly common. The groundmass in some samples contained noticeable amounts of green silicates such as actinolite, biotite and clinopyroxene, which does not correlate with the Geijers (1910) descriptions of the quartz-bearing porphyry. Evidence of hydrothermal alteration was observed in a number of samples, with magmatic flow structures occurring and the influence of penetrating hydrothermal fluids. Some samples displayed late hydrothermal veins of carbonate, anhydrite and gypsum running through the thin sections (figure 11). Indications of solid-state deformation occurred as well, such as pressure shadows. Sample 34 contains actinolite, titanite and magnetite indicating a paragenesis by hydrothermal fluids.

Porphyry dyke-rocks

Geijer (1910) notes the high amount of clinopyroxene and amphibole in the porphyry dykes. This correlates with the observations in the present samples, where clinopyroxene and actinolite occur in ample amounts in the groundmass as well as megacrysts. The feldspar phenocrysts contain inclusions of titanite and clinopyroxene, as is also noted by Geijer (1967). No biotite appeared in the samples, contrary to what Geijer (1910) mentions. The porphyry dyke-rocks contained a significantly higher amount of clinopyroxene, and lower amount of quartz, than the quartz-bearing porphyry of the hanging wall.

Others

The unknown black mineral noted in samples 37 and 39 turned out to be large columnar allanite crystals that displayed a range of colours besides reddish brown. Dark green crystals occurred as well as crystals with a maroon colour. This colour spread is most probably due to chemical variations, but the specific differences are unknown. Sample 38 contained large crystals of dolomite lined with very fine-grained talc, surrounded by a groundmass of quartz (figure 9). The presence of the talc can be explained by the Mg-rich dolomite reacting with the Si-rich quartz, producing the talc. The unknown “white coloured, soft mineral”, referred to in sample 40, turned out to be dolomite. The mineralogy and texture of sample 46 confirms it is a (meta)dolerite.

Actinolite
Actinolite occurs as separate megacrysts, in nodules as well as in veins (i.a. sample 34, 45). The actinolite can be generally be classified as a product of hydrothermal activity, although there is a possibility of crystallization from a water-rich magma. The type of hydrothermal actinolite present actinolite is a frequent alteration mineral in environments with the interaction of magmatic-hydrothermal systems and external fluids (Thompson & Thompson 1996). Lledo & Jenkins (2008) proposes the possibility of an igneous origin of the actinolite, as natural actinolite can precipitate as an igneous phase in Kiirunavaara-type ore deposits. Geijer (1910) notes that uralite is a common alteration mineral in the rocks of the foot wall, the hanging wall as well as the porphyry dykes. The uralite that Geijer describes is possibly the mineral I have to large extent interpreted as actinolite. Pseudomorphic products after clinopyroxene, known as uralite is observed in only three samples, all belonging to the syenite-porphyry of the foot wall. Hornblende is also observed by Geijer (1910) in all three types of rock. All the chemically analysed amphibole in this study falls under the classification of actinolite, and no samples classifies as hornblende.

Biotite
The colour of biotite varied through the samples. A green-brown colour was most common, but biotite with a pale brown colour occurred (sample 40; B2 ore). The variation in colour is most probably a product of the mineral composition. Biotite of hydrothermal origin commonly has a green-brown colour, compared to the more red-brown colour of igneous biotite (Thompson & Thompson 1996). According to studies done by Hayama (1959) and Lalonde & Bernard (1993), the green colour correlates with high Mg and Fe^{3+} content. A high Ti-content correlates with a browner colour (Lalond & Bernard 1993). The pale brown biotite of sample 40 is probably due to low Fe-content and comparably low Al-content (Appendix: table 11). Fleet et al. (2006) and Nordstrand (2012) notes the tendency of Mg-rich biotite (sample 40) to be enriched in F, and Fe-rich biotite (sample 54) to be enriched in Cl. This correlates well with the samples analysed in this study.

Epidote
Epidote can exist both as a replacement mineral as well as in veins. Epidote is most often dependant on the availability Ca or Fe. Alteration of Ca-rich plagioclase therefore commonly results in epidote or zoisite. Epidote is commonly a product of propylitic alteration, along with chlorite and calcite. The presence of epidote within fractures and open spaces indicates a redistribution of some major base elements. Metamorphism at higher temperature often favours generation of epidote over other minerals with similar base elements, such as calcite (Bove et al. 2007).

Fugacity
A significant factor in the composition and stability of iron oxides is oxygen fugacity (fO_2) (Frost, 1991). It indicates the possibility of iron present in silicate or oxide minerals to exist in more reduced or more oxidized states. The presence of magnetite (Fe_3O_4) in the samples indicates a high oxygen fugacity during the formation, as magnetite contains iron both Fe^{2+} and Fe^{3+} valence states. An even higher oxygen fugacity is displayed in the samples containing magnetite oxidizing into hematite (Fe_2O_3). Hematite consists of iron exclusively in Fe^{3+} state (Frost 1991).

Hydrothermal fluids

The source of element-rich fluids and the transportation rate of eventual fluid components is an important variable regarding the final composition of the rock. The transport rate may differentiate through different features and rock textures (Stober et al. 2000). In the case of the crystalline Kiirunavaara rocks, the hydrothermal fluids most probably first penetrated through fracture planes and then along grain boundaries. The presence of high-salinity brines is a key component, providing a source of the high Fe-content and the forming of Na-rich alterations, such as albite (Smith et al. 2013). Magmatic-hydrothermal solutions usually have relatively low salinity (Candela 1989), but can in some environments be highly saline, which is the case of the Kiruna district (Smith et al. 2013). According to Smith et al. (2013), the Cl-enrichment is the result of multiple inclusions and interactions of saline fluids, with different sources and time periods. The origins of the brine fluids may include evaporitic, surface fluids, and crustal melts. The Cl-enrichment does not appear prominently in the minerals present, due to Cl being rejected in favour of F and OH. The presence of Cl in the system is evident by the Cl-content in the biotite (Appendix: table 11). The fluids are also classified as CO_2 and Ca-rich (Smith et al. 2013).

The presence of anhydrite in the rocks may indicate the occurrence of seawater, as the most broadly acknowledged process is, according to Chen et al. (2013), the mixing of Ca-enriched high temperature hydrothermal fluid with sulphate-enriched seawater.

6. Conclusions

I have shown in my study that a combination of optical mineralogy, EDS and WDS analysis is a viable method for determining the mineralogy and texture of the samples. The different types of rocks in Kiirunavaara have their own characteristics and distinct differences. The syenite-porphyry of the foot wall, while dominated by feldspar, contained in some samples the characteristic nodules of actinolite, titanite, magnetite and chlorite. The quartz-bearing porphyry of the hanging wall lacked these nodules, and consisted of a finer groundmass with larger amounts of quartz. Biotite and carbonate occurs in large aggregates with grains aligned in the direction of foliation. The syenite-porphyry dykes displayed finer groundmass with larger amounts of clinopyroxene. Feldspar phenocrysts were common in all three types of rock. These phenocrysts, sometimes forming glomerocrysts, displayed sericite, albite and epidote alteration to varying degrees. Signs indicating deformation structures were present in the rocks of both the foot wall and the hanging wall as well as in the syenite-porphyry dykes. Magmatic flow structures occurred in all three types of rock, while solid state deformation only appeared in the quartz-bearing porphyry of the hanging wall. Analysed biotite was classified as phlogopite, and the amphiboles were classified as actinolite. The products of hydrothermal alteration, through the penetration of hydrothermal fluids, are present in a majority of the thin sections. Remnants of older minerals, unaffected by the hydrothermal fluids appear in some thin sections. Data acquired through further usage of the microprobe could possibly produce more accurate results regarding the mineral chemistry.

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Appendix

Thin section descriptions of Kuj32-Kuj61

This appendix contains the thin section descriptions of 32 samples, Kuj32-Kuj62, all originating from the Kiirunavaara mine. Each thin section description contains at least two pictures, displaying the most frequently occurring mineralogy and textures in each thin section. The pictures to the left display the thin sections in plane-polarized light and the pictures to the right the thin sections in crossed-polarized lights. A few pictures in this appendix are taken with in reflected light, with crossed nicols. These display the opaque mineralogy.

Mineral abbreviations

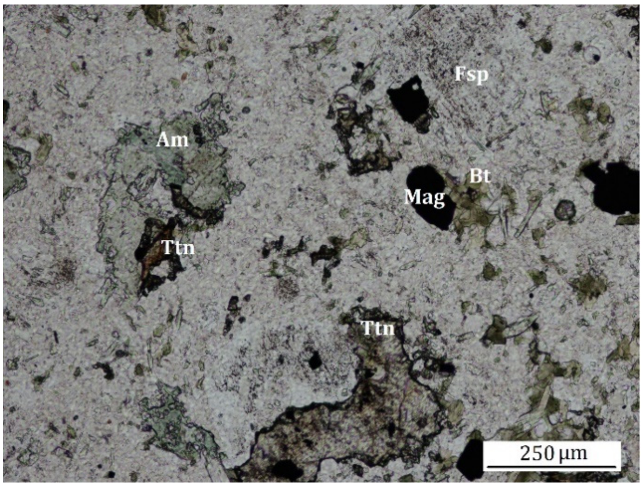
Aln:	Allanite
Am:	Amphibole
Anh:	Anhydrite
Ap:	Apatite
Bt:	Biotite
Cb:	Carbonate
Ccp:	Chalcopyrite
Cal:	Calcite
Cl:	Chlorite
Cpx:	Clinopyroxene
Dol:	Dolomite
Ep:	Epidote
Fsp:	Feldspar
Gp:	Gypsum
Hem:	Hematite
Mag:	Magnetite
Mnz:	Monazite
Ilm:	Ilmenite
Pyr:	Pyrite
Qtz:	Quartz
Rt:	Rutile
Ttn:	Titanite
Zrn:	Zircon

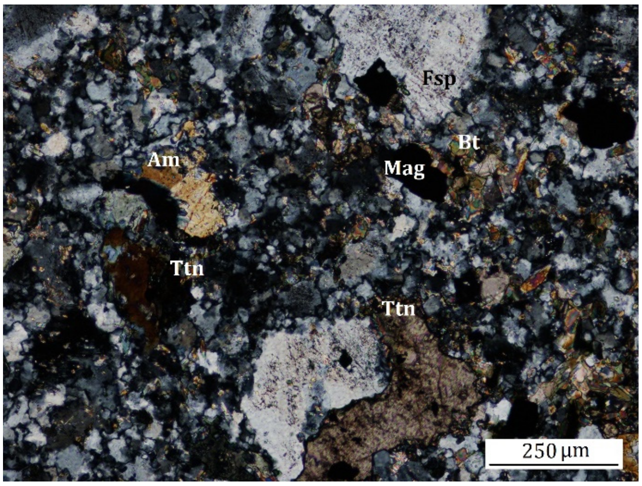
Rock type abbrevations

According to the standard system used by LKAB.

Sp1 – Trachyte.	Qp1 – Rhyodacite, flow structures.
Sp2 – Trachyte, altered, patchy.	Qp2 – Rhyodacite.
Sp3 – Nodular porphyry.	Qp3 – Rhyodacite, Amph/Cl-rich.
Sp4 – Trachyandesite, idiomorph.	Qp4 – Rhyodacite, Ep/Cpx.
Sp5 – Weathered trachyte.	Qp5 – Weathered rhyodacite.
Gp – Porphyry dykes.	

Sample number: 32





Rock type: Sp1
Porphyritic texture with feldspar phenocrysts and biotite, amphibole, titanite and magnetite megacrysts in a groundmass consisting of anhedral grains of feldspar, biotite, magnetite and amphibole. Amphibole is present as individual grains.

Minerals:

Feldspar	50-60%
Quartz	1-5%
Amphibole	5-10%
Biotite	5-10%
Chlorite	5-10%
Anhydrite	1%
Titanite	8-15%
Magnetite	10-20%
Pyrite	<1%

Feldspar: Present as groundmass as well as larger phenocrysts. The phenocrysts are rectangular and contain inclusions of titanite and biotite. They display alteration in the shape of dark, cloudy patches as well as sericitization. The darker alteration is probably albitization. Polysynthetic twinning observed in some grains as well as rare cross-hatched twinning. Anhedral grains in groundmass of varying size. Possible alteration into albite.

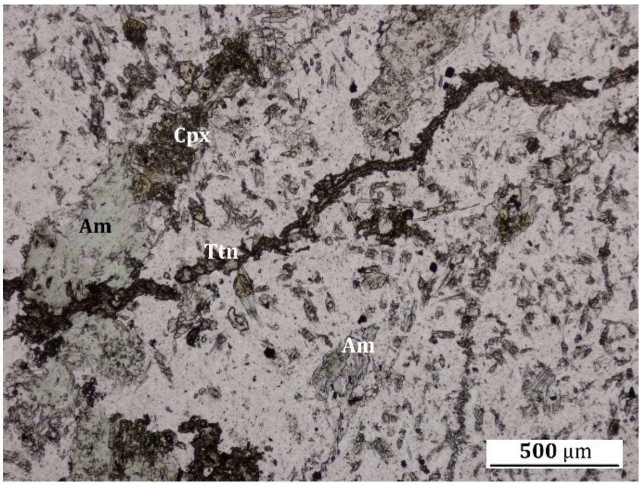
Quartz: Small amount of anhedral grains of varying size, <0.5 mm, in the groundmass. Also occurs as inclusions in amphibole grains.

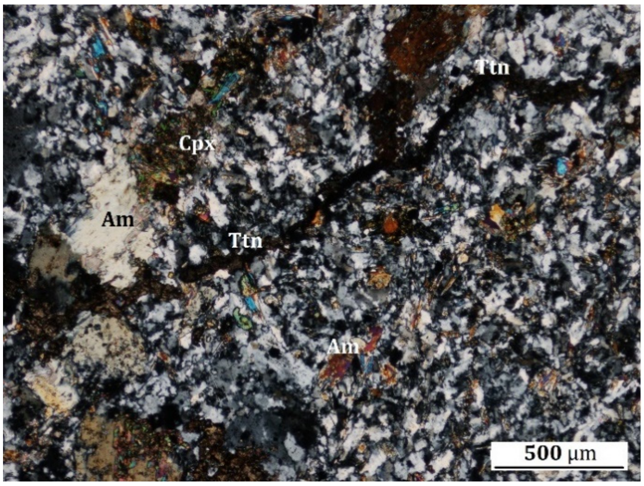
Amphibole: Bladed and columnar megacrysts and grains, up to 0.5 mm, often lined with smaller biotite grains, possibly altering into biotite as well as chlorite. The amphibole is most probably an alteration product of clinopyroxene, as the amphibole grains contain inclusions of quartz. Some amphibole grains appear to alter into biotite.

Biotite: Subhedral, tabular megacrysts. Smaller grains, <0.1 mm, are often positioned on outer borders of amphibole. Larger grains of

	secondary biotite are present as inclusions in feldspar phenocrysts.
Chlorite:	Pale green bladed and columnar megacrysts, with similar habit and colour as amphibole. The chlorite has notably lower interference colours, of the 1st order. Possibly an alteration product of biotite and/or amphibole, retaining the amphibole shape. May also be a product of biotite.
Anhydrite:	Anhedral colourless grains with very high birefringence.
Titanite:	Irregular anhedral megacrysts, 0.1-0.5 mm. Some grains as inclusions in feldspar phenocrysts. Lining some grains of amphibole and biotite.
Magnetite:	Anhedral megacrysts, 0.1-0.6 mm, often as inclusions in titanite or amphibole.
Pyrite:	Rounded grain in the groundmass, single one in the thin section. 0.3 mm in diameter.

Sample number: 33





Rock type: Sp2

Porphyritic texture with feldspar as both phenocrysts and megacrysts. Megacrysts of magnetite. Groundmass consists of feldspar, amphibole, epidote and magnetite. Two thin veins are cutting across the thin section, filled primarily with titanite. Minor amounts of amphibole and epidote are present in the veins. Long streaks of fine magnetite grains stretch through the sample. These dark streaks are very distinct in the hand sample. The lighter areas surrounding these darker magnetite streaks are most probably results of a penetrative fluid, running through the rock. These light areas contain feldspar, amphibole and epidote. The magnetite would therefore be the oldest part of the rock.

Minerals:	Feldspar	45-55%
	Amphibole	20-25%
	Epidote	5-10%
	Titanite	1-5%
	Magnetite	10-20%

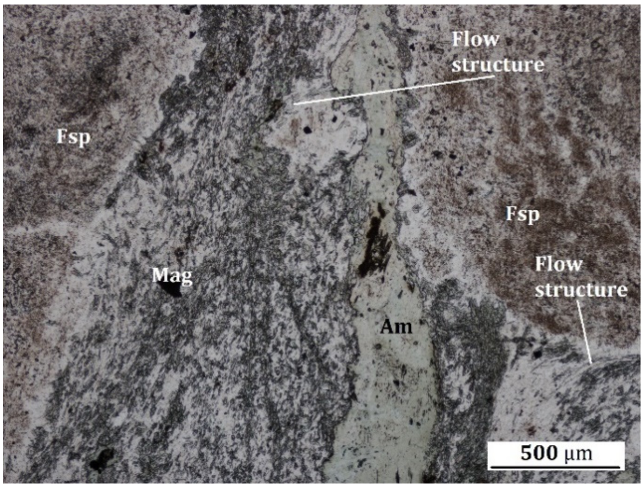
Feldspar: Groundmass consisting of feldspar as well as phenocrysts. The phenocrysts are varying in size, some >1 mm. Euhedral tabular phenocrysts are present as well as subhedral phenocrysts exposed to more extensive albitization. Secondary alkali feldspar megacrysts with cross-hatched twinning, of metasomatic origin. Prismatic feldspar phenocrysts with subhedral faces and contain inclusions of amphibole, titanite, magnetite and epidote, partly as alteration products. Carlsbad twinning is present in a large tabular phenocryst.

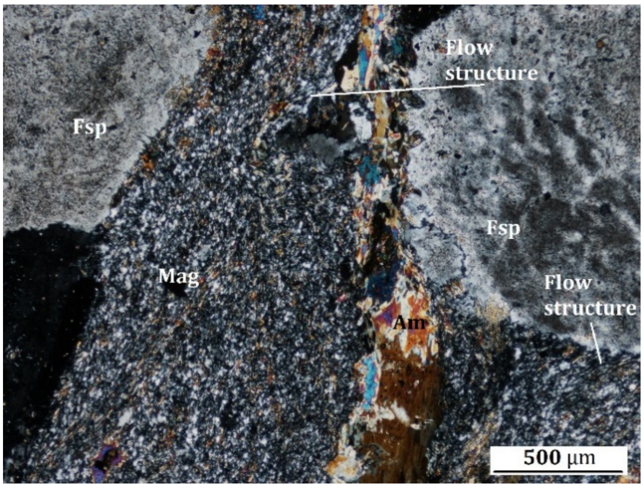
Amphibole: Two types of amphibole, small grains in the groundmass and megacrysts, 0.1-0.7 mm. Both small and big grains have bladed crystal habit

Epidote: Yellow-green epidote as granular aggregates and anhedral grains. The grains are 0.1 mm and aggregates up to 0.4 mm. Amphibole may be altering to epidote.

Titanite:	Appears as vein fill and anhedral grains, often intergrown with amphibole and epidote. Possibly replaces primary feldspar and magnetite.
Magnetite:	Subhedral, rounded grains of varying size, 0.05-0.2 mm. In groundmass and as inclusions in other minerals. Long streaks of fine magnetite grains stretch through the sample. These dark streaks are very distinct in the hand sample.
Hematite:	Anhedral grains as lining and inclusions in the larger magnetite grains. Light grey with moderate reflectance. White and grey polarization colours. Most probable an oxidation product of the magnetite, through martitization.

Sample number: 34





Rock type: Qp3
Porphyritic texture with feldspar phenocrysts and amphibole megacrysts. Magmatic flow structure in groundmass, noticeable in the parallel alignment of fine quartz, amphibole and feldspar grains present in the groundmass. Noticeable vein running through the thin section, filled with amphibole. Titanite, magnetite and hematite are present as small anhedral grains. Clinopyroxene occurs as inclusions in feldspar phenocrysts. The amphibole megacrysts, titanite and magnetite appear to have been formed by hydrothermal fluids at the same stage, and later on surrounded by the flow structures.

Minerals:		
	Feldspar	30-45%
	Quartz	15-30%
	Amphibole	20-30%
	Clinopyroxene	3-7%
	Titanite	1-5%
	Magnetite	1-5%
	Hematite	1-5%
	Pyrite	<1%

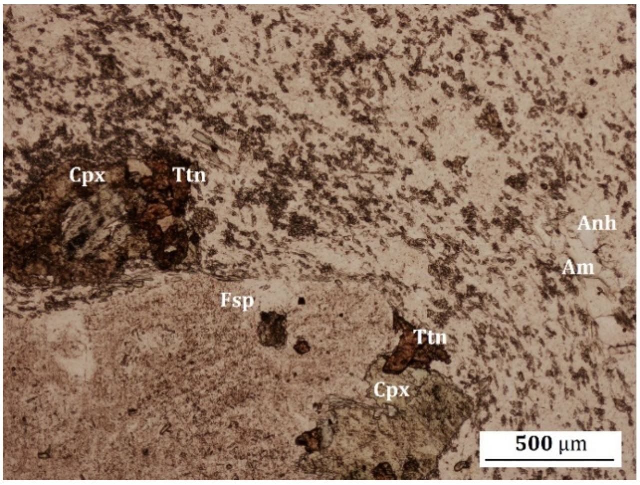
Feldspar: Large feldspar phenocrysts with a size of up to 10 mm. Some are intergrown with each other, making up glomerocrysts. A few phenocrysts with poikilitic texture are present, with inclusions of clinopyroxene. Sericite and epidote alteration are present in most phenocrysts and albite twinning seen in some. The groundmass contains minor amounts of feldspar grains. The groundmass is so very fine grained that further categorization is difficult.

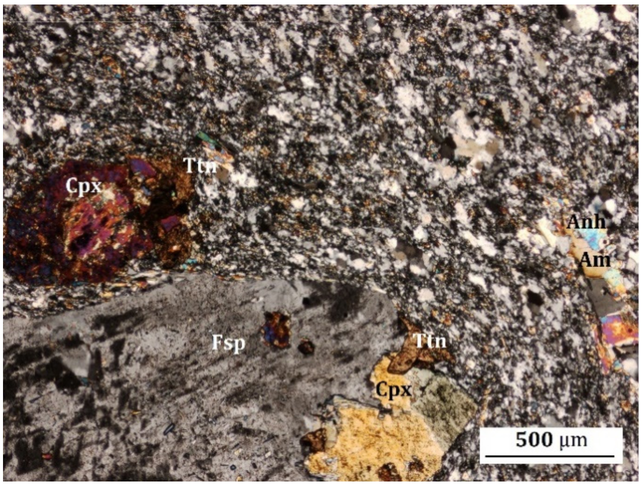
Quartz: Occurs as very fine, anhedral grains in groundmass.

Amphibole: Present as filling in a large vein and several smaller veins. Bladed texture. Small euhedral/subhedral bladed grains in groundmass, generally positioned in a uniform direction, indicating magmatic flow. Larger amphibole megacrysts can be seen in between feldspar phenocrysts. Possibly a product of clinopyroxene. Appears to have been formed in paragenesis with the titanite and the magnetite.

Clinopyroxene:	Subhedral rounded grains and stubby prisms as inclusions in feldspar phenocrysts. <0.2 mm. Have not yet been replaced by amphibole.
Titanite:	Rounded and irregular grains, <0.2 mm. Practically all of the titanite grains are positioned alongside amphibole, indicating paragenesis. This applies to the magnetite as well.
Magnetite:	Rounded subhedral grains and euhedral square-shaped grains. Up to 0.1 mm. Makes up most of the inner parts of the opaque grains. Appears to have been formed in paragenesis with the amphibole and the titanite.
Hematite:	Hematite as martitization-product of magnetite. Makes up most of the rims of the magnetite grains. Most probably product of magnetite.
Pyrite:	Opaque mineral with yellow-golden colour with weak to no pleochroism. Cubic. Moderate reflectance. Weak anisotropy with yellow to pale yellow polarization colours.

Sample number: 35





Rock type: Gp

Porphyritic and glomerophyric texture with large feldspar phenocrysts and smaller phenocrysts of clinopyroxene as well as smaller megacrysts of amphibole. Glomerocrysts consisting of amphibole, titanite and clinopyroxene. The groundmass consists of feldspar, clinopyroxene, quartz and magnetite as well as low amounts of amphibole. Magmatic flow structures are present in the groundmass. Most probably Gp, based on the high amount of clinopyroxene.

Minerals:		
	Feldspar	55-65%
	Quartz	10-15%
	Amphibole	3-7%
	Clinopyroxene	15-25%
	Titanite	1-5%
	Anhydrite	1-5%
	Magnetite	1-3%
	Ilmenite	1%

Feldspar: Appears in groundmass and as phenocrysts. Some of the phenocrysts are >10 mm. Grains of amphibole and titanite are in some cases in contact with the feldspar phenocrysts. These phenocrysts display albite twinning and in some cases cross-hatched twinning. The EDS analysis suggests that the phenocrysts consists of alkali feldspar and albite (table 1). The fine grains in the groundmass display flow structures most prominent along the edges of feldspar phenocrysts, with parallel alignment of elongated crystals.

Quartz: Small rounded grains in groundmass, often positioned in small aggregates in groundmass and in parts of glomerocrysts.

Amphibole: Aggregates of clinopyroxene grains turning into finer grained amphibole are present, sometimes making up glomerocrysts along with titanite and clinopyroxene. A few of the bladed amphibole grains in the glomerocrysts display twinning. This fine-grained amphibole is most probably an alteration product of clinopyroxene. The groundmass contains a small amount of needle-like amphibole grains.

Clinopyroxene: Small rounded grains and stubby prisms in groundmass, roughly the same size as the neighboring feldspars in the groundmass. Some of the grains in the groundmass are aligned in the direction of the foliation. Also appears as larger subhedral phenocrysts. These larger grains, 0.1-0.5 mm, are often in contact with amphibole and titanite.

Titanite: Small anhedral grains most often positioned in contact with larger grains of feldspar, clinopyroxene and amphibole.

Anhydrite: Colourless anhedral grains (<0.2 mm) with very high interference colours and low relief.

Magnetite: Small rounded grains, <0.1 mm, positioned in the groundmass.

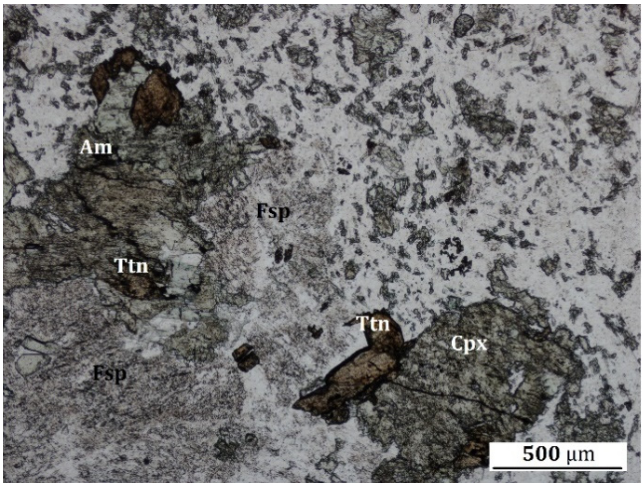
Ilmenite: Anhedral grains as inclusions in magnetite grains, displaying shades of grey as polarization colours.

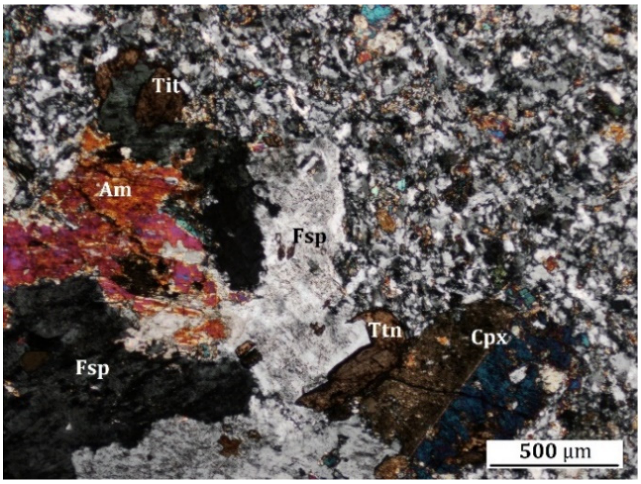
Table 1. EDS-data. Mass percentages and atom percentages of chemical elements.

	Albite		*K-fsp*		*Act*		*Anh*	
Chemical formula	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%
O	45.13	57.97	41.93	55.55	43.95	59.83	42.88	62.91
Al	11.24	8.56	9.74	7.65				
Si	34.16	25	30.6	23.09	28.04	21.74		
K			14.4	7.81				
Na	9.48	8.47						
Mg					12.08	10.82		
Ca					9.1	4.95	32.26	18.89
Fe					6.82	2.66		
S							24.87	18.2
Ti								

	Cpx-1		*Cpx-2*		*Qtz*		*Ttn*	
Chemical formula	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%
O	39.38	56.23	40.68	57	52.11	65.64	39.8	61.51
Al								
Si	27.1	22.04	27.02	21.56	47.89	34.36	14.88	13.1
K								
Na	1.23	1.22	0.81	0.79				
Mg	8.76	8.23	10.23	9.43				
Ca	16.46	9.38	17.02	9.52			20.82	12.84
Fe	7.09	2.9	4.25	1.7			1.3	
S								
Ti							23.2	11.98

Sample number: 36





Rock type: Gp
Porphyritic and glomerophyric texture with large feldspar phenocrysts and smaller phenocrysts of clinopyroxene as well as smaller megacrysts of amphibole. Glomerocrysts of feldspar, amphibole, clinopyroxene and titanite. The groundmass is fine-grained, with feldspar making up half of it and clinopyroxene with lesser amounts amphibole the other half. Carbonate is present as aggregates containing small amounts of quartz.

Minerals:		
	Feldspar	50-60%
	Quartz	1-5%
	Amphibole	15-25%
	Titanite	1-5%
	Clinopyroxene	10-20%
	Carbonate	3-7%
	Magnetite	<1%

Feldspar: Phenocrysts with perthitic texture. May contain minor inclusions of titanite and amphibole. Diameter up to 10 mm. Some albite twinning present as well as possible epidote-zoisite alteration as fine green inclusions. The groundmass contains irregularly shaped grains with no apparent striations. Part of the groundmass may be orthoclase.

Quartz: A few rounded grains in carbonate aggregates.

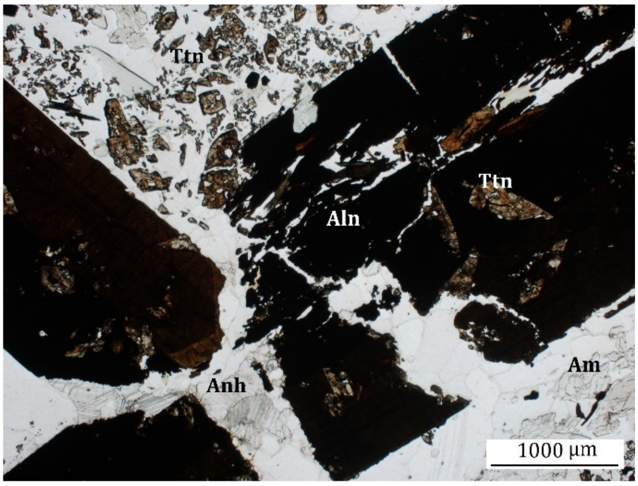
Amphibole: Bladed crystals seen both as small grains in groundmass as well as megacrysts of acicular/fibrous habit. Some amphibole megacryst have a distinct core of clinopyroxene, indicating clinopyroxene altering into amphibole.

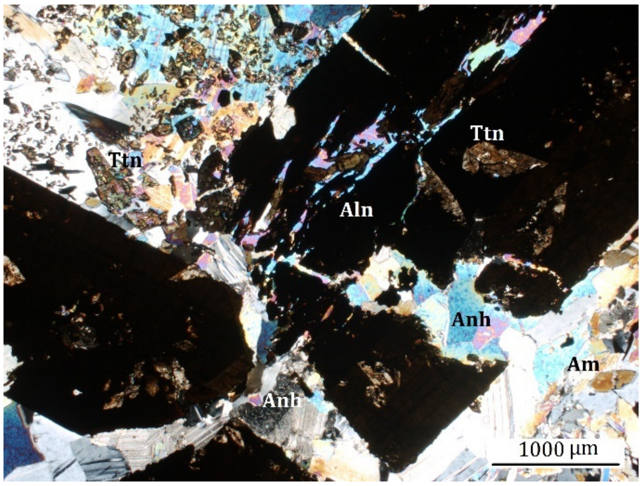
Titanite: Euhedral grains <0.5 mm. Small rounded grains evenly distributed in groundmass, <0.2 mm. Probably related to the clinopyroxene and amphibole via alteration.

Clinopyroxene: Small anhedral grains in groundmass along with similarly sized amphibole grains. Larger crystals of rectangular and prismatic shape (0.5 mm), often in connection with large fibrous amphibole grains. Appears in the center of some amphibole megacrysts, yet to be altered into amphibole.

Carbonate:	Aggregates of anhedral grains. Individual grains can be 0.5 mm. Often occurs in conjunction with amphibole in the sample.

Sample number: 37





Rock type: Vein in skarn, in footwall close to ore contact
Large, partly fractured grains of columnar allanite stretch through the sample. The groundmass consists of anhydrite and carbonate with associated wedge-shaped titanite. Aggregates as well as individual grains of pale green bladed amphibole.

Minerals:	Titanite	10-20%
	Anhydrite	20-25%
	Carbonate	3-7%
	Allanite	45-55%
	Amphibole	5-10%
	Magnetite	1-5%

Titanite: Small euhedral and subhedral grains with wedge-shape cover large parts of the groundmass. Also present as inclusions in the columnar allanite.

Anhydrite: Anhedral grains anhydrite with varying grain size. Very high interference colours. A few grains display lower birefringence. These are possibly barite.

Carbonate: Aggregates of carbonate represents the groundmass in a small part of the sample. Generally smaller grains than the anhydrite and characteristic changing relief when rotated.

Allanite: Large columnar crystals with a width of 1-1.5 mm. Length is 1 cm to >3 cm. Displays zoning. Most of the columnar crystals are broken off in at least two different places. These fractures have irregular boundaries and are broken near mutual contacts. The colour of the crystals varies, from dark tones of red and brown to green and clear red. EDS and WDS analysis indicate allanite (table 2 & 9).

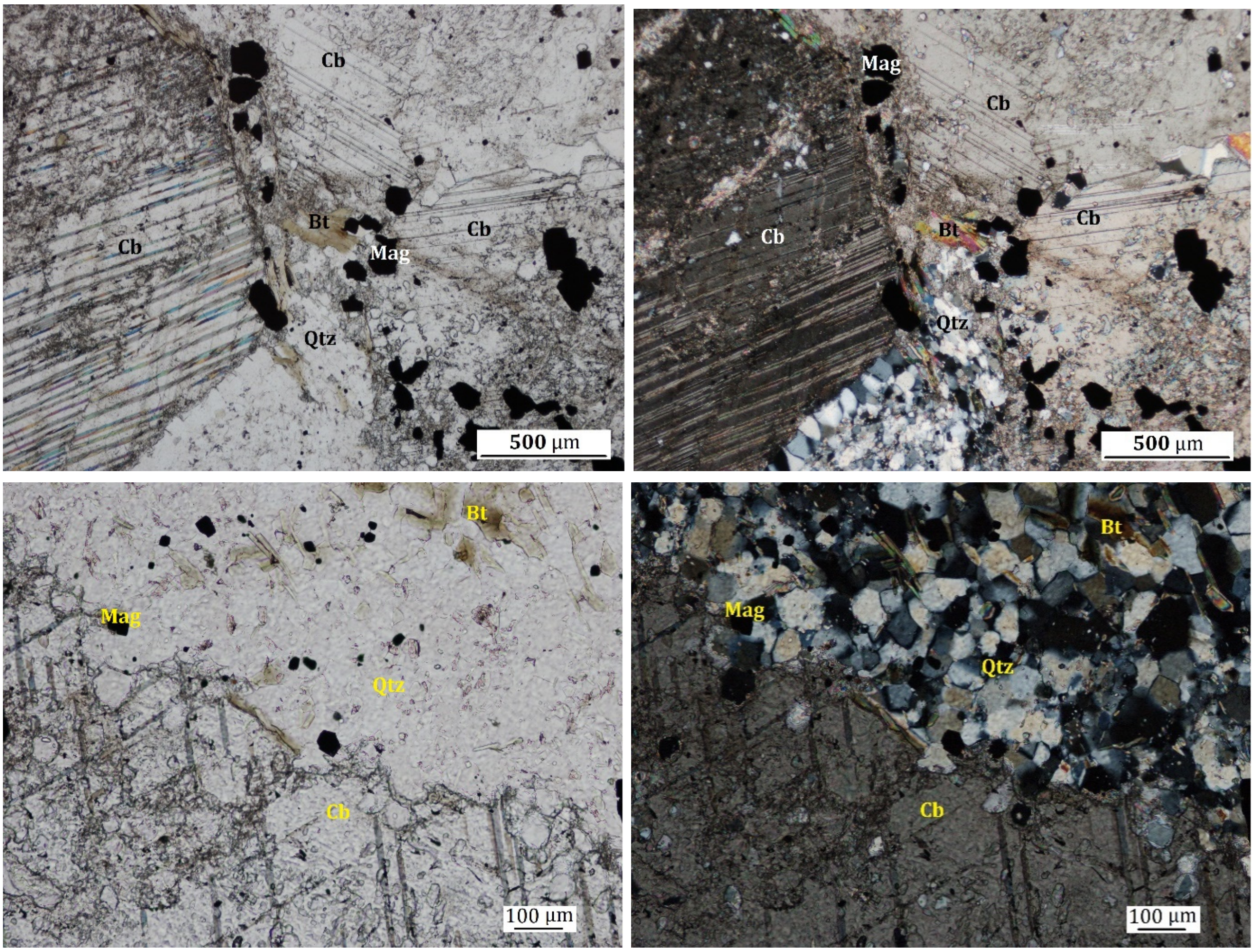
Amphibole: Pale green subhedral bladed and stubby crystals, 0.2-1 mm.

Magnetite: Rounded subhedral grains. <0.5 mm.

Table 2. EDS-data. Mass percentages and atom percentages of chemical elements.

	Aln-Core		*Aln-Rim*		*Anh*		*Act*		*Ttn*	
Chemical formula	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%
O	41.21	62.55	41.18	61.59	37.94	55.06	40.21	55.54	37.16	58.98
Al	4.96	4.46	7.56	6.71			14.39	13.08		
Si	18.17	15.71	18.67	15.91			30.12	23.69	15.23	13.77
K										
Na										
Mg										
Ca	10.37	6.28	10.8	6.45	32.75	18.97	10.55	5.82	21.53	13.64
Fe	25.29	11	21.78	9.34			4.73	1.87	2.83	1.28
S					25.4	18.39				
Ti									23.25	12.32

Sample number: 38



Rock type: D3-ore

Porphyritic texture with dolomite and calcite megacrysts. Groundmass consists of quartz, biotite and magnetite. Magnetite grains cover groundmass and parts of the carbonate megacrysts.

Minerals:	Carbonate	25-35%
	Quartz	5-10%
	Biotite	3-7%
	Talc	1-5%
	Titanite	1%
	Magnetite	30-40%
	Chalcopyrite	1%

Carbonate: Anhedral to subhedral megacrysts, 0.2-5 mm. Exposed to varying amounts of silicification, with quartz “eating” away on edges as well as inclusions. Some megacrysts are lined with fine-grained talc. Eds analysis indicate the presence of both calcite and dolomite (table 3). The dolomite megacrysts are lined with very fine-grained talc and have a more distinct white colour in the hand sample.

Quartz: Groundmass consisting of anhedral grains with undulatory extinction. Grains are generally larger in contact with the carbonate. Also present as inclusions in carbonate megacrysts.

Biotite: Subhedral to anhedral grains, 0.05-0.5 mm. Distributed in the groundmass and near edges of carbonate megacrysts.

Talc: Very fine-grained talc lining the boundaries of the dolomite megacrysts. The talc is most probably a product of the reaction of the dolomite with the surrounding quartz.

Titanite: Euhedral wedge-shaped crystal. 0.4 mm.

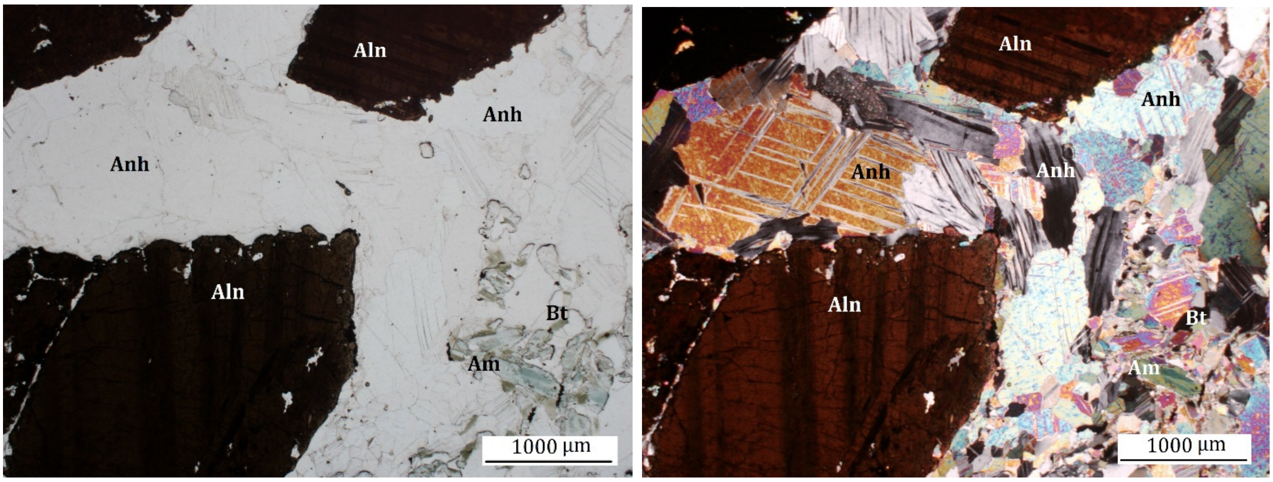
Magnetite: Anhedral grains, 0.2-0.4 mm. Tends to be more widespread in the quartz groundmass than in the carbonate megacrysts. The magnetite is primary and most probably the oldest mineral in the sample.

Chalcopyrite: Distinctive yellow, irregular grains.

Table 3. EDS-data. Mass percentages and atom percentages of chemical elements.

	Dol		*Cal*		*Mag*	
Chemical formula	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%
O	47.88	61.55	40.54	58.88	21.7	49.17
Ca	26.85	13.78	52.72	30.56		
Fe	5.62	2.07			78.3	50.83
Mg	12.74	10.78				
Mn			1.63	0.69		

Sample number: 39



Rock type: Vein in Qp1
Groundmass consists of anhydrite and lesser amounts of carbonate. The groundmass changes to consisting of quartz and lesser amounts of biotite in a part of the sample. Aggregates and separate grains of amphibole, green biotite and chlorite aligned in direction of foliation. Large brown, columnar allanite crystals with prismatic ends cover a quarter of the thin section.

Minerals:		
	Anhydrite	20-30%
	Carbonate	10-15%
	Quartz	15-25%
	Biotite	5-10%
	Chlorite	1-3%
	Allanite	15-25%
	Amphibole	5-10%

Anhydrate: Anhedral grains, 0.1-0.8 mm in diameter, make up the groundmass.

Carbonate: Subhedral to anhedral grains in aggregate. Relief changes when sample is turned. 0.5 mm in diameter. Positioned in a wide (1.5 mm) allanite fracture. Small amounts of anhydrate are present in this fracture.

Quartz: Anhedral grains, 0.1-0.3 mm. Makes up the groundmass in a part of the sample.

Biotite: Euhedral and subhedral grains, 0.1-0.3 mm, with tabular and bladed habit. Green colour. Grains are generally aligned along the foliation.

Chlorite: Subhedral grains with light green colour pleochroism and low interference colours. Generally larger than most of the biotite grains. Approximately 0.5 mm in diameter. Probably an alteration product of biotite.

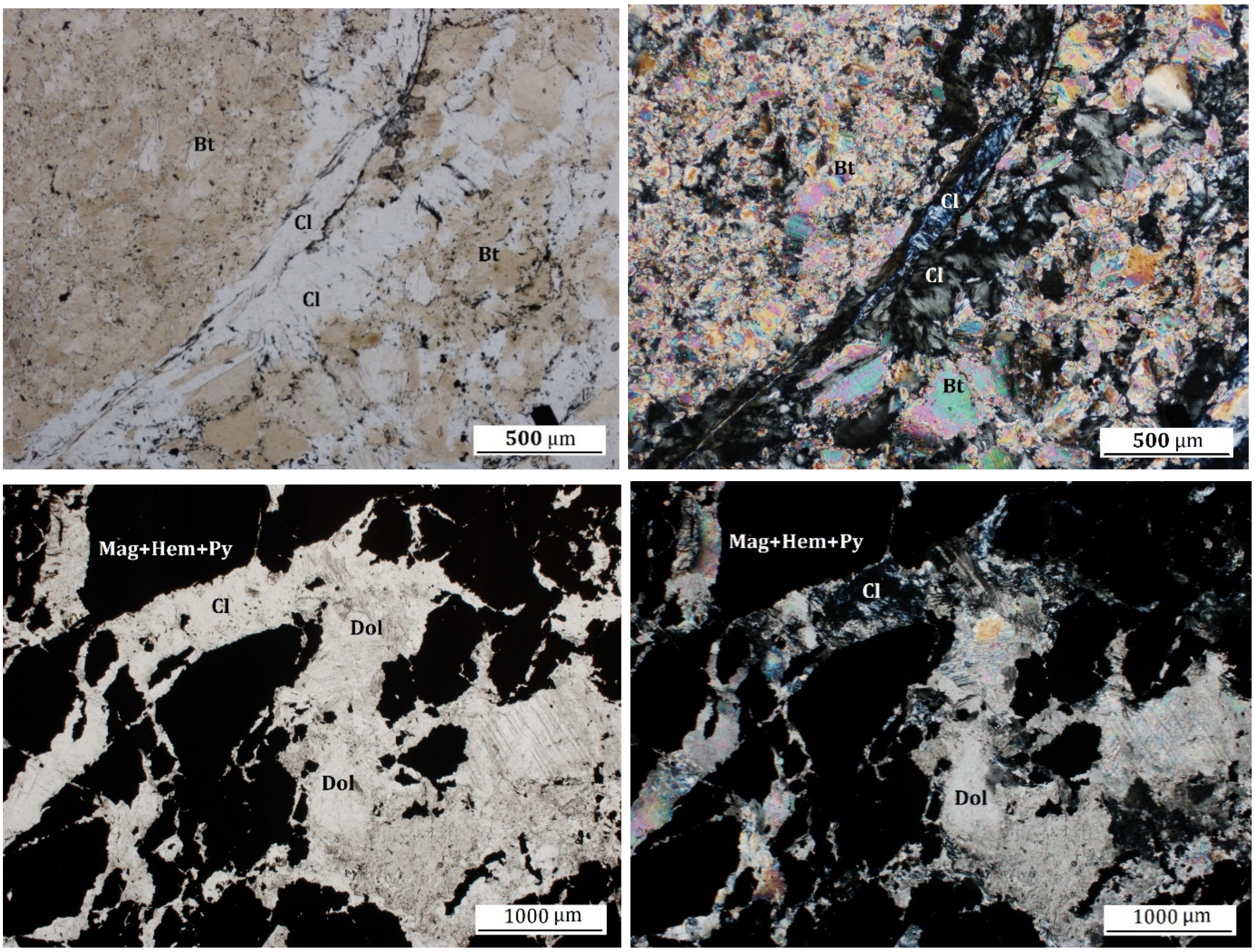
Allanite: Large columnar allanite crystals with prismatic ends. Diameter of 1.5-4 mm. Extensive fractures with anhydrite as filling mineral. Brown-burgundy pleochroism and zoning. EDS and WDS analysis indicate allanite (table 4 and 9).

Amphibole: Subhedral grains, 0.1-0.4 mm. Majority of grains are bladed, but more blocky grains are present as well. It is possible that two different generations of amphibole are present, with variations in colour and shape.

Table 4. EDS-data. Mass percentages and atom percentages of chemical elements.

	Act		*Aln*		*Anh*		*Pyr*		*Qtz*	
Chemical formula	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%
O	41.26	56.85	42.05	63.45	39.81	57.99			48.33	62.15
Al			4.53	4.06						
Si	29.33	23.02	17.96	15.44					51.67	37.85
K										
Na										
Mg	13.45	12.19								
Ca	10.49	5.77	10.16	6.12	32.09	18.66				
Fe	5.48	2.16	25.29	10.93			44.21	28.77		
S					25.69	18.67	51.56	58.43		

Sample number: 40



Rock type: B2-ore

Large-grained magnetite is the most prominent mineral. A large mass of biotite cuts through the middle of the sample, with chlorite veins running through both biotite and some of the magnetite. Dolomite acts as vein fill in the magnetite fractures as well. Thin veins running through the chlorite are filled with calcite.

Minerals:	Biotite	10-20%
	Chlorite	10-15%
	Calcite	1-5%
	Dolomite	10-20%
	Rutile	1%
	Magnetite	50-60%
	Pyrite	1-5%
	Hematite	1-5%

Biotite: Light-brown grains with weak pleochroism. Anhedral with fibrous texture. 0.05-0.1 mm in diameter. Intersected by veins of chlorite. It is probable that the biotite is altering into chlorite. The light-brown colour is probably a result of the biotite's high Mg-content and low Fe-content.

Chlorite: Two different kinds of chlorite present. Both act as vein fill, but with different interference colours. The most prevalent has low

first order interference colours, colourless to dark grey. It located as vein fill in proximity to the biotite and in magnetite fractures; typically with a fibrous texture. It appears to be an alteration product of the surrounding biotite.
The second type has higher first order colours, blue to colourless. It is not as frequent as the first type of chlorite, and can be found as thin streaks inside the first chlorite, as vein fill. It has fibrous and radiant texture internally, with regular external boundaries.

Calcite: Present as grey coloured filling in thin veins running through the chlorite.

Dolomite: Aggregates of light-brown anhedral grains with varying size, 0.1-1 mm. Found in large fractures of magnetite. Possibly stained by iron oxides. A more prominent white dolomite is located in a corner of the sample, displaying fine grains and extensive alteration. The mineral does not react with HCl in hand sample, indicating it is dolomite. EDS and WDS analysis confirm the presence of dolomite and calcite (table 5 & 12).

Magnetite: Anhedral, isotropic with low-moderate reflectance. Cover large parts of the sample. Displays extensive fractures. A few anhedral grains positioned in a chlorite vein consists mainly of magnetite and hematite, with inclusions of rutile.

Rutile: Anhedral, grey inclusions a few larger magnetite-ilmenite grains.

Pyrite: Subhedral, cubical crystals. Yellow-white in reflected microscope with higher reflectance than the magnetite. <0.1 mm in diameter.

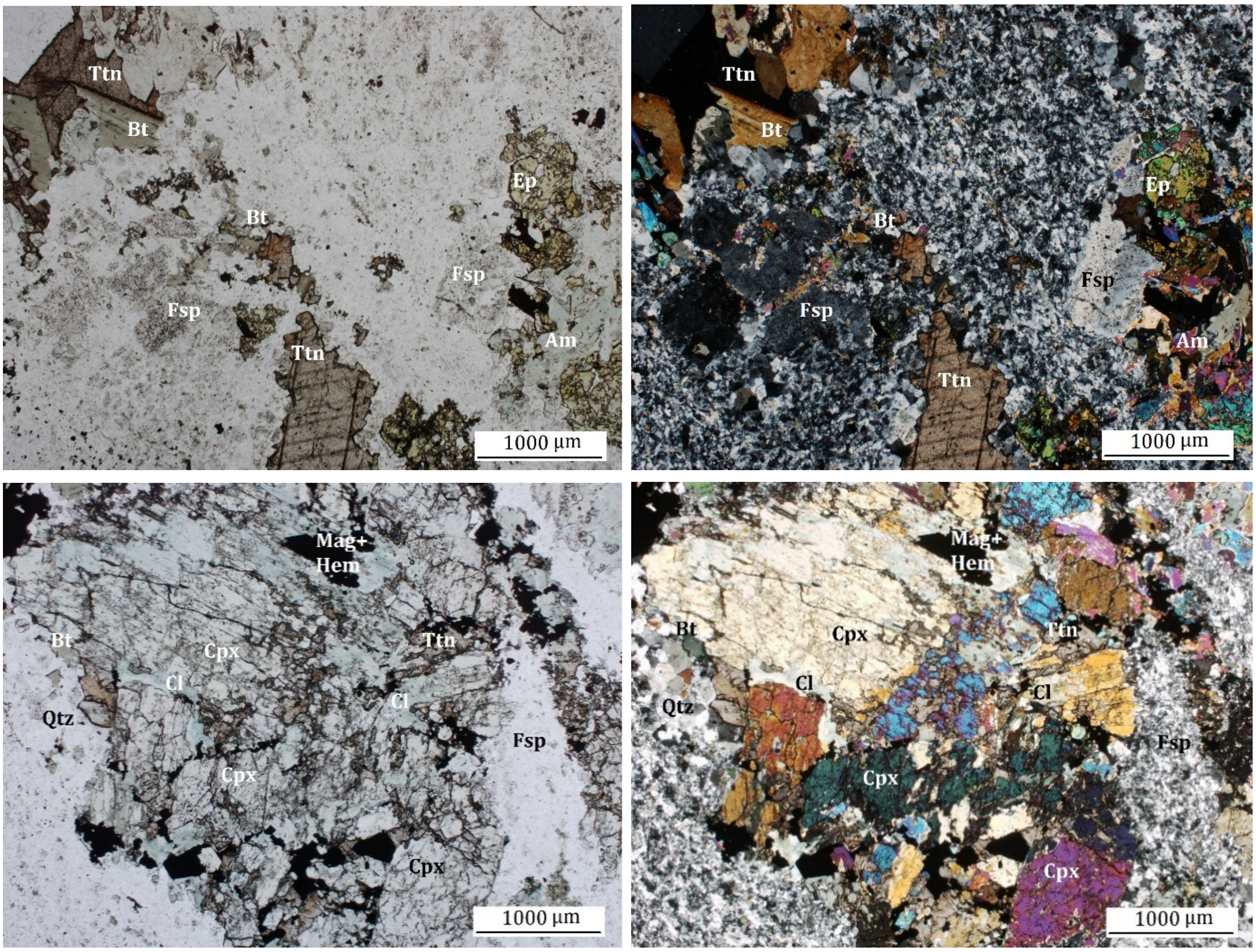
Hematite: Fine anhedral grains as inclusions in magnetite. Anisotropic with grey-blue colour and moderate reflectance. <0.1 mm in diameter. Often found in connection to pyrite. Possible alteration-relationship. Hematite is also found in the grains positioned in a chlorite vein, alongside magnetite and rutile.

Table 5. EDS-data. Mass percentages and atom percentages of chemical elements.

	Dol		*Cal*		*Bt*		*Cl*	
Chemical formula	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%
O	49.4	61.93	37.84	57.38	37.45	50.97	45.37	58.42
Al					6.66	5.38	7.8	5.96
Si					21.3	16.52	20.46	15.01
K					8.94	4.98		
F					5.18	5.94		
Mg	13.65	11.26			16.26	14.57	22.76	19.28
Ca	27.03	13.52	52.79	31.95				
Fe	2.49	0.9			4.21	1.64	3.61	1.33
Mn			5.23	2.31				

	Rutile		*Iron oxide*	
Chemical formula	Mass%	Atom%	Mass%	Atom%
O	36.32	63.07	26.2	54.9
Mg				
Fe			65.78	39.49
Mn				
Ti	63.68	36.93	8.02	5.61

Sample number: 41



Rock type: Sp3/Sp4

Porphyritic and nodular texture with phenocrysts of feldspar and nodules of amphibole, titanite, feldspar, biotite, chlorite, magnetite and epidote. Groundmass of feldspar, magnetite and biotite. It displays characters of both Sp3 (nodules) and Sp4 (feldspar phenocrysts).

Minerals:	Feldspar	55-65%
	Quartz	1-5%
	Biotite	5-10%
	Amphibole	5-10%
	Clinopyroxene	3-7%
	Chlorite	5-10%
	Epidote	3-7%
	Apatite:	1%
	Titanite	3-7%
	Gypsum	1%
	Magnetite	3-7%
	Pyrite	1%
	Hematite	1%

Feldspar: Phenocrysts and nodules as well as groundmass. The phenocrysts can be up to 10 mm in diameter. These perthitic phenocrysts have inclusions of titanite, biotite and magnetite. The feldspar in the groundmass is partly epidote-altered.

Quartz: Anhedral grains, 0.1-0.3 mm, lining some of the nodules.

Biotite: Subhedral grains and megacrysts, 0.2-1 mm. Each grain with one or two well-defined boundaries. Positioned in nodules together with amphibole, titanite and epidote. Very fine anhedral grains are present in the groundmass.

Amphibole: Present as megacrysts inside nodules. The nodules have a width of 0.5-1 mm and length of up to 6 mm. The shape of the amphibole varies from elongated to rounded, blocky grains. The amphibole is one of the products of clinopyroxene, along with chlorite.

Clinopyroxene: Appears as pale green subhedral and anhedral prismatic grains in nodules alongside titanite and chlorite. Also present as subhedral tabular megacrysts with pyramidal ends. Alters into amphibole and chlorite.

Chlorite: Subhedral blocky or prismatic grains. Approximately 0.2 mm in diameter. Present in nodules along with clinopyroxene as pale green grains with 1st order interference colours. The clinopyroxene alters into amphibole and chlorite.

Epidote: Yellow-green anhedral grains, some as granular aggregates. Present in some nodules. Looks to be an alteration product of amphibole. 0.5-1 mm in diameter.

Apatite: Colourless anhedral grains with higher relief than feldspar and quartz. 0.1-0.2 mm. Sometimes surrounded by a thin layer of titanite.

Titanite: Anhedral grains often enclosed within other minerals, such as amphibole, biotite and feldspar. 0.1-1.5 mm.

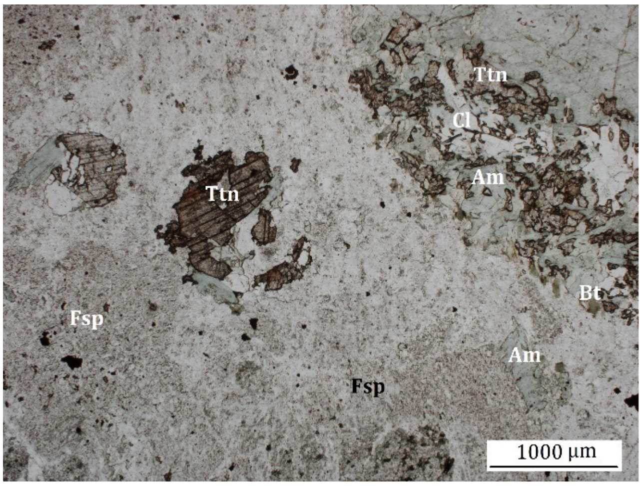
Gypsum: Colourless anhedral grains with distinct soft plastic texture. Sometimes surrounded by amphibole and epidote.

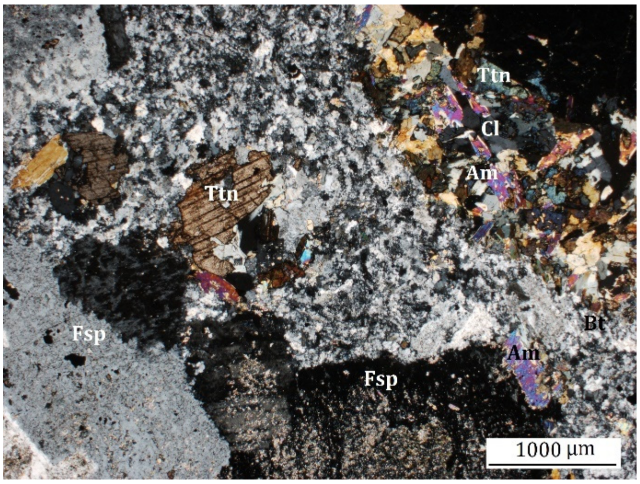
Magnetite: Anhedral grains, 0.05-1 mm. Larger grains are enclosed in other minerals. Smaller grains in groundmass.

Pyrite: Anhedral rectangular grains with yellowish white colour and high reflectance.

Hematite: White-grey anisotropic hematite inside magnetite grains. Most probably replaces magnetite through martitization.

Sample number: 42





Rock type: Sp3 with nodules
Nodular texture with rounded nodules of titanite, uralitic amphibole, chlorite, biotite and apatite. Feldspar phenocrysts exposed to alteration. Groundmass consists of feldspar, amphibole, biotite and magnetite. It contains feldspar phenocrysts, characteristic for Sp4.

Minerals:

Feldspar	60-70%
Amphibole/Uralite	5-15%
Chlorite	3-7%
Biotite	1-5%
Titanite	1-5%
Carbonate	1-5%
Apatite	1-3%
Magnetite	5-10%
Pyrite	1-3%

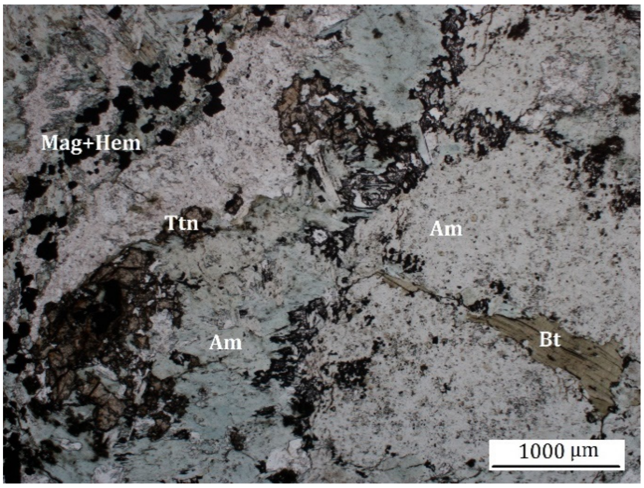
Feldspar: Phenocrysts of albite and K-feldspar, displaying polysynthetic twinning. Diameter up to 20 mm. Inclusions of magnetite, biotite and titanite. Extensive sericite alteration in some of the phenocrysts. Smaller blocky phenocrysts, 0.5-1 mm, display Carlsbad twinning, possibly indicating orthoclase. Feldspar phenocrysts, partly zoisite-altered, are present in a few nodules along with titanite, amphibole, chlorite and biotite. This is out of the normal, as feldspar usually does not appear in nodules.

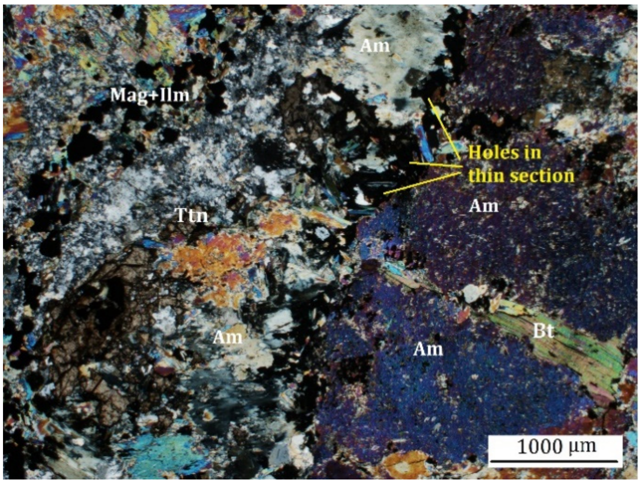
Amphibole: Subhedral prismatic megacrysts, 0.2-10 mm. Majority of the grains are positioned in nodules along with titanite, biotite and chlorite. Small anhedral and subhedral grains of amphibole in the groundmass. All the observed in the sample can be classified as uralite, the pseudomorph-product of clinopyroxene. These uralite grains have retained the original shape of the clinopyroxene crystals.

Chlorite: Pale green tabular crystals found in nodules and aggregates along with amphibole, biotite and titanite. Low interference colours

	of the first order. 0.1-0.4 mm. The chlorite is possibly replacing the amphibole and biotite.
Biotite:	Subhedral and anhedral tabular/bladed grains, 0.2 mm. Small grains are lining some of the rounded nodules. Some smaller anhedral grains are scattered in groundmass.
Titanite:	Subhedral wedge shaped grains and anhedral masses mostly present as inclusions in feldspar megacrysts or in aggregates of amphibole and biotite.
Carbonate:	Anhedral crystals with highly irregular shapes. Colourless, negative relief compared to surrounding minerals, and high interference colours.
Apatite:	Colourless subhedral crystals with interference colours of the 1st order. High relief. Positioned in some of the nodules. Contains fine inclusions of unknown colourless minerals.
Magnetite:	Anhedral grains, 0.05–0.2 mm. Present mostly in the groundmass, but can also be found enclosed in larger grains. Especially titanite regularly contains magnetite inclusions. Fine-grained magnetite inclusions are present in uralite.
Pyrite:	Cubical white-yellow grains with high reflectance.

Sample number: 43





Rock type: Sp
Porphyritic and nodular texture. Phenocrysts of feldspar, megacrysts amphibole and nodules of amphibole along with biotite and magnetite. The middle part of the thin section is occupied by a thick vein of amphibole, titanite, chlorite and magnetite. The reported "unknown grey mineral" appear to be amphibole in this case.

Minerals:		
	Feldspar	40-50%
	Amphibole	15-25%
	Biotite	1-5%
	Chlorite	1-5%
	Titanite	5-10%
	Carbonate	1%
	Magnetite	10-20%
	Hematite	1-3%
	Pyrite	1-5%

Feldspar: Present as groundmass and phenocrysts. EDS analysis indicate that the groundmass consists of irregular grains of albite and K-feldspar with the distribution roughly being 50/50 (table 6). Subhedral rectangular and tabular phenocrysts, 0.5-2 mm. The phenocrysts display some albite and minor Carlsbad twinning.

Amphibole: Anhedral to subhedral grains, 0.1-0.8 mm. Anhedral and subhedral grains with sometimes fibrous texture positioned in aggregates and rounded nodules with grains of varying size along with biotite, chlorite and magnetite. It indicates the possibility that the titanite is replacing amphibole and biotite. Smaller grains are present as inclusions in feldspar phenocrysts.

Biotite: Subhedral and anhedral grains, 0.1-1 mm. Small anhedral grains often positioned along small fractures or outer boundaries of the amphibole. Inclusions in feldspar phenocrysts also present. The biotite is an alteration product of amphibole, as the biotite crystals cuts through some of the amphibole grains.

Chlorite: Pale green bladed grains in aggregates of amphibole. Possible product of alteration.

Titanite: Irregular grains and megacrysts, 0.1-8 mm. The middle part of the sample consists large masses of titanite with enclosed magnetite. The titanite is most probably replacing the magnetite. Smaller grains are present as inclusions in feldspar and amphibole megacrysts. The inner regions of some titanite grains display a different texture and colour. These areas, with a generally darker colour and more granular texture may be a combination of rutile and titanite, or the remains of an older generation titanite crystal lying on top of the younger titanite.

Carbonate: Aggregate of anhedral grains, <0.5 mm, on the edge of the thin section.

Magnetite: Anhedral grains mostly found as inclusions titanite, but amphibole as well. Smaller grains are present in the groundmass. Alters into titanite.

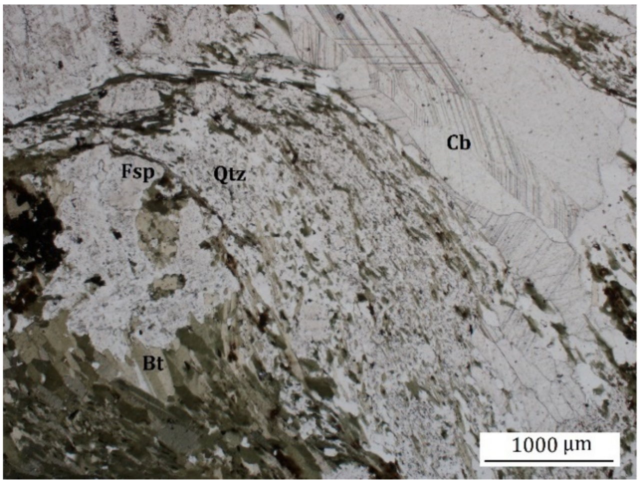
Ilmenite: Anisotropic grains found on the outer borders of magnetite and as lath-like inclusions.

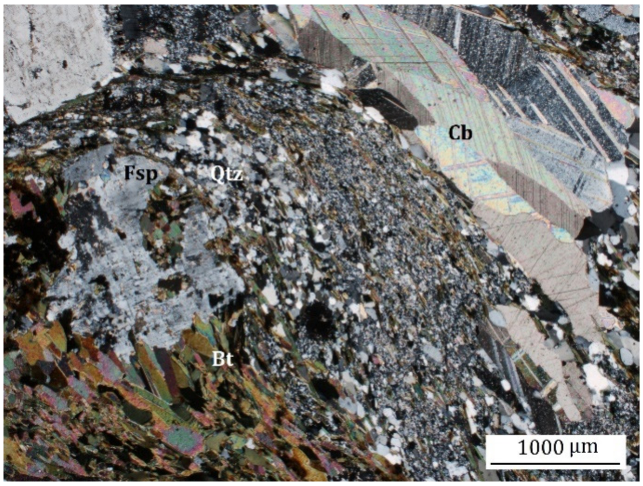
Pyrite: Subhedral grains with white colour and high reflectance.

Table 6. EDS-data. Mass percentages and atom percentages of chemical elements.

	Albite		*K-fsp*		*Bt*	
Chemical formula	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%
O	43.74	56.66	40.81	56.53	39.15	55.54
Al	11.34	8.71	10.39	8.53	7.72	6.49
Si	35.83	26.44	32.72	25.82	20.55	16.6
K			16.08	9.12	9.61	5.58
Na	9.09	8.19				
Mg					12.24	11.42
Ca						
Fe					10.74	4.37

Sample number: 44





Rock type: Qp
Porphyritic texture with feldspar phenocrysts and phenocrysts grouped together as glomerocrysts. The groundmass consists of feldspar, quartz and biotite. Aggregates of carbonate and biotite, both often lined with quartz, are aligned in the same uniform direction, indicating thin section exposure to hydrothermal effects. Evidence for magmatic flow structures can be observed in the groundmass, as part of the feldspar grains are aligned in uniform directions. Younger hydrothermal veins of carbonate cuts through the structures of the older minerals, including the magmatic flow structures. Determined as Qp primarily based on the large amount of quartz.

Minerals:		
	Feldspar	15-20%
	Quartz	25-30%
	Biotite	10-20%
	Calcite	15-25%
	Anhydrite	1%
	Gypsum	1%
	Epidote-allanite	1%
	Magnetite	1%
	Hematite	<1%
	Pyrite	<1%

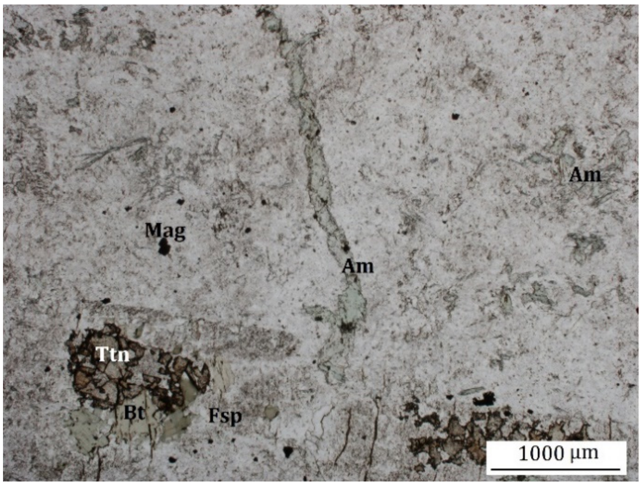
Feldspar: Tabular phenocrysts with sericite alteration. 0.3-8 mm. Some phenocrysts are joined together, forming glomerocrysts. K-feldspar are present, as some phenocrysts display cross-hatched twinning. Feldspar crystals in the groundmass display parallel to sub-parallel alignment, indicating magmatic flow structures.

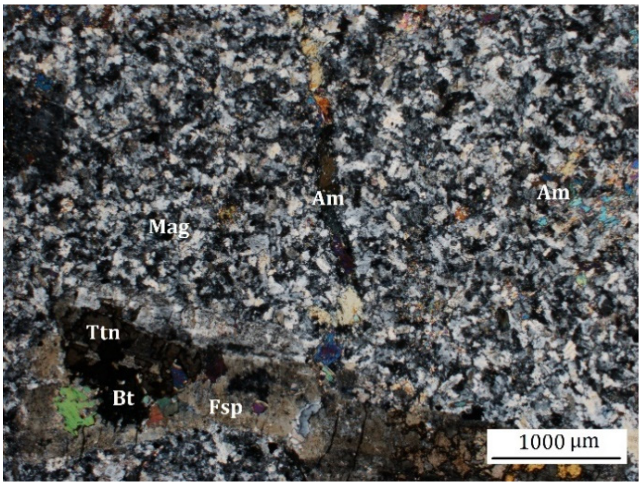
Quartz: Fine-grained quartz in groundmass. Larger anhedral grains, 0.1-0.3 mm, are positioned in small aggregates, often on the boundaries of carbonates.

Biotite: Fine anhedral grains in groundmass aligned in direction of foliation. Larger grains, 0.1-0.4 mm with bladed habit are positioned in aggregates aligned in foliation direction and alongside outer boundaries of carbonate and feldspar. Most probably result of hydrothermal activity. Some of the biotite grains

	contain radioactive inclusions. These brown inclusions display pleochroic halos. Possibly monazite.
Calcite:	Anhedral grains, 0.2-1.2 mm. Often elongated in direction of foliation. Also present in thin veins as fine-grained carbonate, sometimes along with biotite.
Anhydrite:	Minor amounts of anhedral colourless grains positioned in calcite aggregates. Distinct high birefringence.
Gypsum:	Minor amounts of anhedral colourless grains positioned in calcite aggregates. Displays very soft texture and contains depressions.
Epidote-allanite:	Brown-green anhedral grains of possible epidote-allanite positioned in the groundmass. Subhedral with good cleavage in one direction.
Magnetite:	Anhedral elongated grains positioned in veins of biotite and carbonate.
Hematite:	Anhedral grains making up the outer boundaries of some magnetite grains. Product of martitization.
Pyrite:	White-yellow cubic or rounded grains with high reflectance. Isotropic.

Sample number: 45





Rock type: Sp5
Nodular texture with nodules of feldspar, amphibole and clinopyroxene.
Feldspar phenocrysts with inclusions of biotite and titanite. Veins are running through the thin section filled with amphibole, titanite and magnetite and carbonate. The groundmass consists of feldspar, amphibole and magnetite.

Minerals:	Feldspar	65-75%
	Amphibole/Uralite	10-17%
	Biotite	1-5%
	Titanite	1-5%
	Carbonate	1-5%
	Anhydrite	1%
	Gypsum	1%
	Epidote	1%
	Magnetite	1-3%
	Pyrite	<1%

Feldspar: Subhedral phenocrysts with tabular habit. 0.4-1.2 mm. Inclusions of biotite, magnetite and titanite. Carlsbad twinning and polysynthetic twinning are present as well as some perthitic texture. The groundmass contains anhedral feldspar with irregular, uneven texture. A red colour is apparent through macroscopic analysis. This red colour may be a product of fine-grained hematite or limonite in the feldspar.

Amphibole: Present as filling in veins, approximately 0.2-0.4 mm thick. Megacrysts are often part of larger nodules, with tabular shape and irregular boundaries. The amphibole megacrysts may be pseudomorphs of clinopyroxene, as their shape is similar to the stubby prismatic shape of the clinopyroxene. This would classify the megacrysts as uralite.

Biotite: Irregular secondary grains, 0.1-0.3 mm as inclusions in feldspar phenocrysts,often in proximity to titanite. A few grains in centers of amphibole megacrysts.

Titanite: Anhedral and subhedral fractured grains. Some grains with subhedral wedge-shape. 0.2-0.4 mm. Positioned as inclusions in feldspar phenocrysts and small amounts at boundaries of veins filled with amphibole.

Anhydrite: Colourless subhedral grains with very high birefringence. Most of the anhydrite grains display good cleavage on one edge of the grain. Noticeably harder than the gypsum grains. Positioned in the groundmass.

Gypsum: Colourless anhedral grains with distinct soft texture. Positioned in the groundmass.

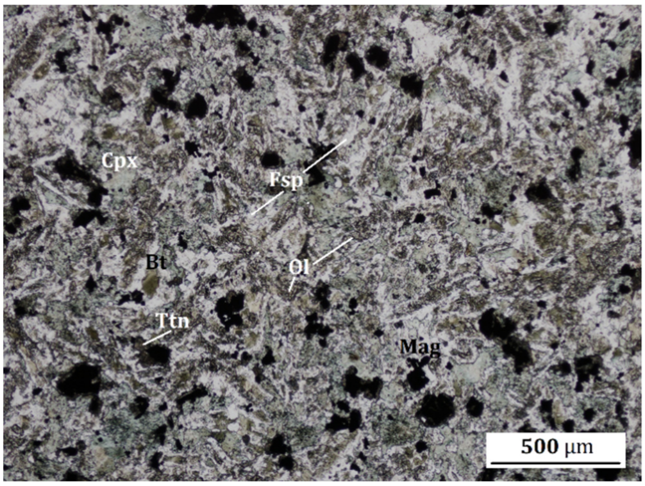
Epidote: Fine, yellow grains with high relief and high interference colours. Round shape. Occurs as inclusions in amphibole. <0.1 mm.

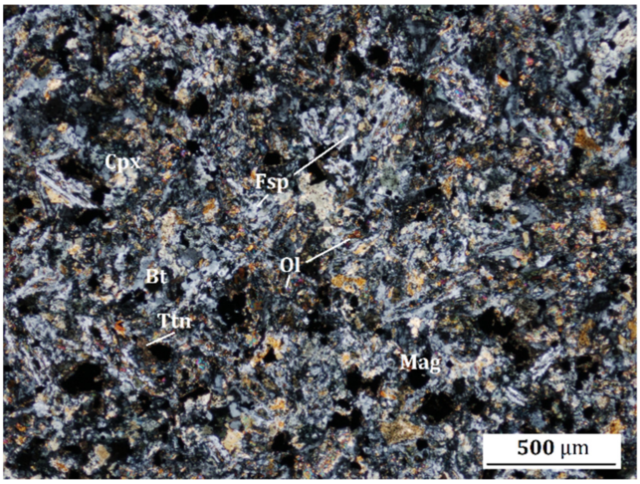
Carbonate: Small anhedral grains, <0.1 mm, in veins along with amphibole.

Magnetite: Small anhedral grains in the groundmass and in veins, as inclusions in amphibole.

Pyrite: White-yellow mineral on outer edges of some magnetite grains.

Sample number: 46





Rock type: Diabase/Dolerite
Subophitic, altered texture with elongated and often irregular plagioclase grains intergrown with amphibole, clinopyroxene, biotite and magnetite rimmed with titanite.

Minerals:	Plagioclase	25-35%
	Amphibole	10-20%
	Clinopyroxene	10-15%
	Biotite	10-15%
	Titanite	5-10%
	Magnetite	15-25%
	Pyrite	1-5%

Feldspar: Plagioclase grains display sharp twinning on some grains. Most of the grains are anhedral, with inclusions of olivine, biotite and clinopyroxene.

Olivine: Rounded and anhedral grains, <0.1 mm. Present as both small aggregates of grains and separate grains.

Amphibole: Pale green subhedral and anhedral grains with bladed habit. 0.05-0.3 mm. The larger amphibole grains contain fine-grained magnetite inclusions.

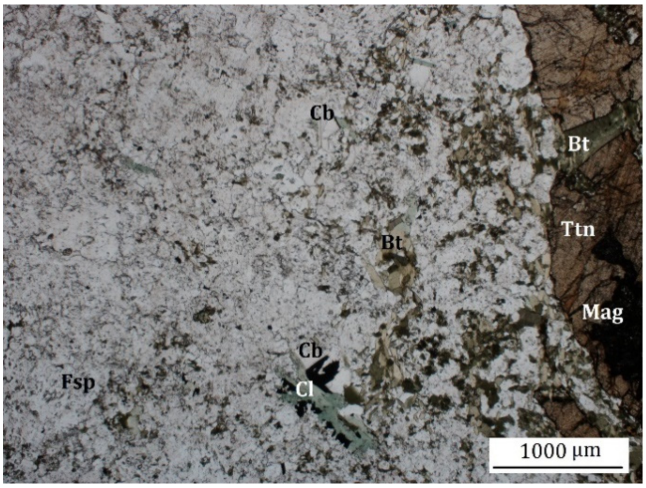
Clinopyroxene: Subhedral tabular green grains, 0.05-0.1 mm. The relief of the clinopyroxene grains are slightly higher than the relief of the amphibole grains.

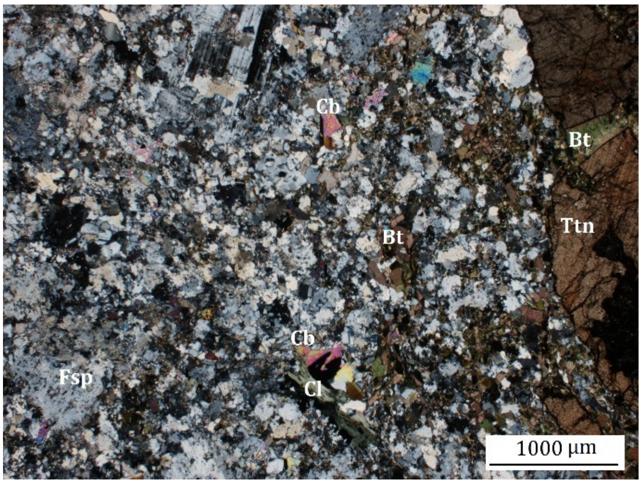
Biotite: Subhedral bladed grains and anhedral irregular grains. 0.05-0.2 mm.

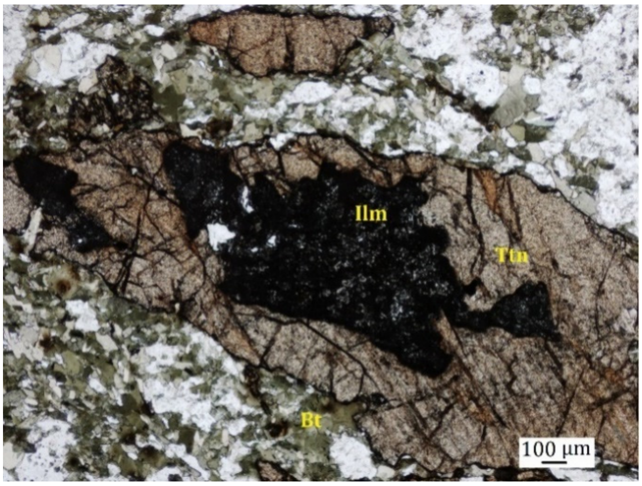
Titanite: Anhedral grains, almost exclusively found in contact with opaque minerals. The titanite makes up the outer borders of the magnetite grains, possibly indicating titanite as a reaction product between the magnetite and primarily feldspar.

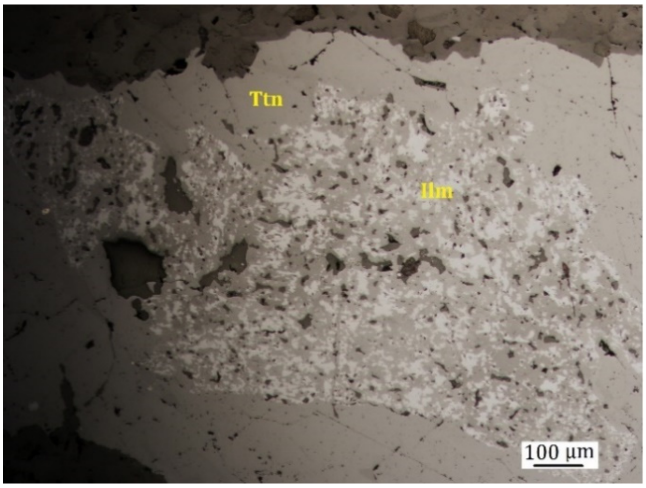
Magnetite:	Rounded anhedral grains, 0.05-0.2 mm. Possibly alters into titanite.
Pyrite:	White-yellow mineral with high reflectance and no apparent anisotropy. Positioned along magnetite rims, possibly replacing it.

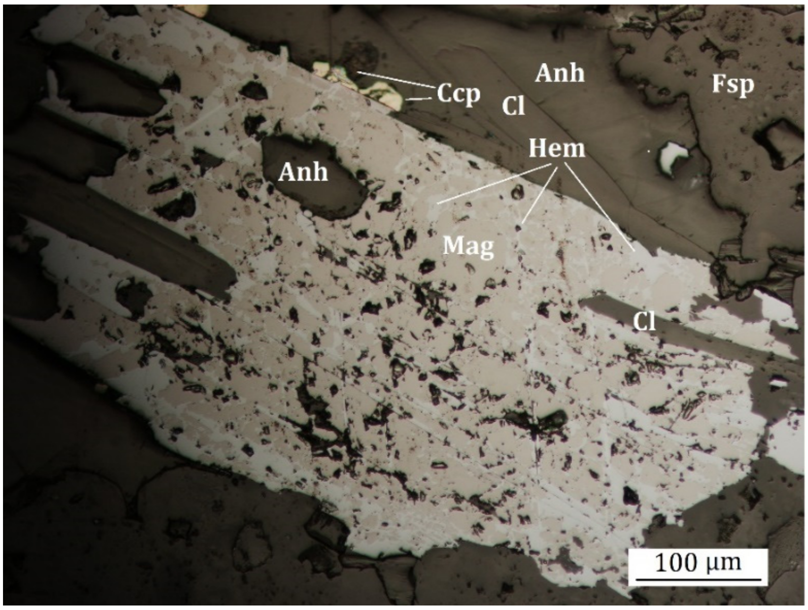
Sample number: 47











Rock type: Sp5

Porphyritic texture with megacrysts of titanite and phenocrysts of feldspar. Groundmass of feldspar, biotite and carbonate. Large aggregates of biotite, some intergrown with titanite megacrysts. Magnetite and hematite appears combined in megacrysts. Ilmenite occurs as megacrysts in centers of large titanite megacrysts. The reported “unknown light beige mineral” appear to titanite.

Minerals:		
	Feldspar	50-60%
	Quartz	3-7%
	Biotite	10-20%
	Chlorite	3-7%
	Carbonate	3-7%
	Anhydrite	5-10%
	Gypsum	1-3%
	Epidote	1-2%
	Titanite	1-5%
	Magnetite	1-5%
	Hematite	1%
	Ilmenite	1-3%
	Chalcopyrite	1%

Feldspar: Subhedral phenocrysts of possible plagioclase. Some have poikilitic texture, with large amounts of biotite, chlorite and carbonate inclusions. Polysynthetic twinning. 0.8-2 mm in diameter.

Quartz: Anhedral grains in aggregates often positioned along borders of feldspar phenocrysts. 0.1–0.2 mm. Occurs most often in conjunction with anhydrite.

Biotite: Bladed and tabular grains, 0.1-0.2 mm. Present as aggregates and as separate grains in groundmass. Looks to be altering into chlorite.

Chlorite: Subhedral and anhedral grains with bladed or tabular habit. Pale green colour and interference colours of the first order. Some grains containing inclusions of magnetite. Possible alteration product of biotite.

Carbonate: Anhedral grains in aggregates and often in contact with biotite. Grains are 0.05-0.3 mm in diameter. Fine irregular grains in groundmass.

Anhydrite: Anhedral, colourless grains with high interference colours. Often positioned along with carbonate. 0.01-0.2 mm.

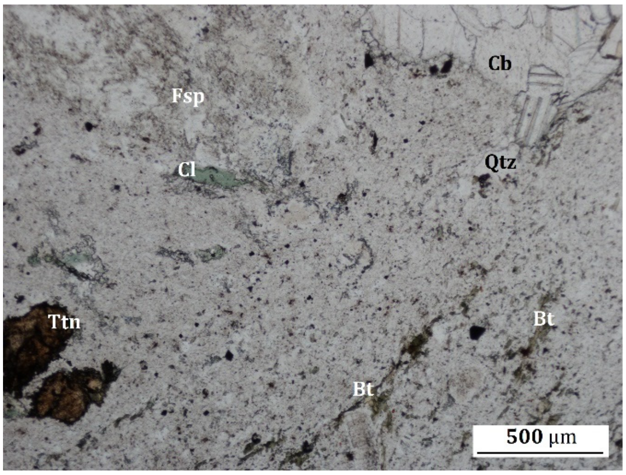
Gypsum: Colourless anhedral grains with distinct soft texture. Lower birefringence than the anhydrite. Positioned in aggregates of carbonate and anhydrite as well as in the groundmass.

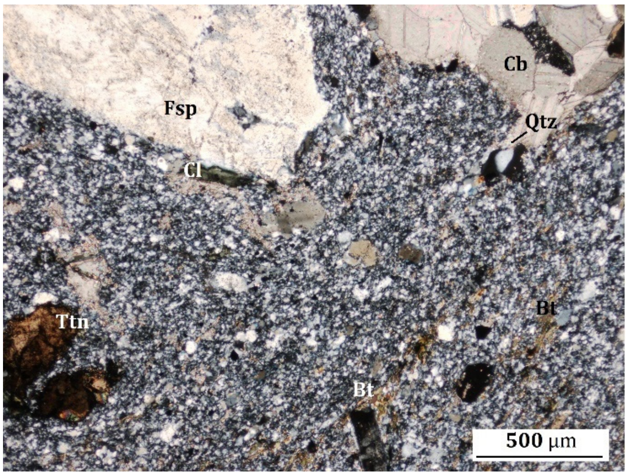
Epidote: Anhedral rounded grains with pale green pleochroism. Moderate to high relief. High birefringence. Appears as small single grains positioned in carbonate aggregates as well as in the groundmass.

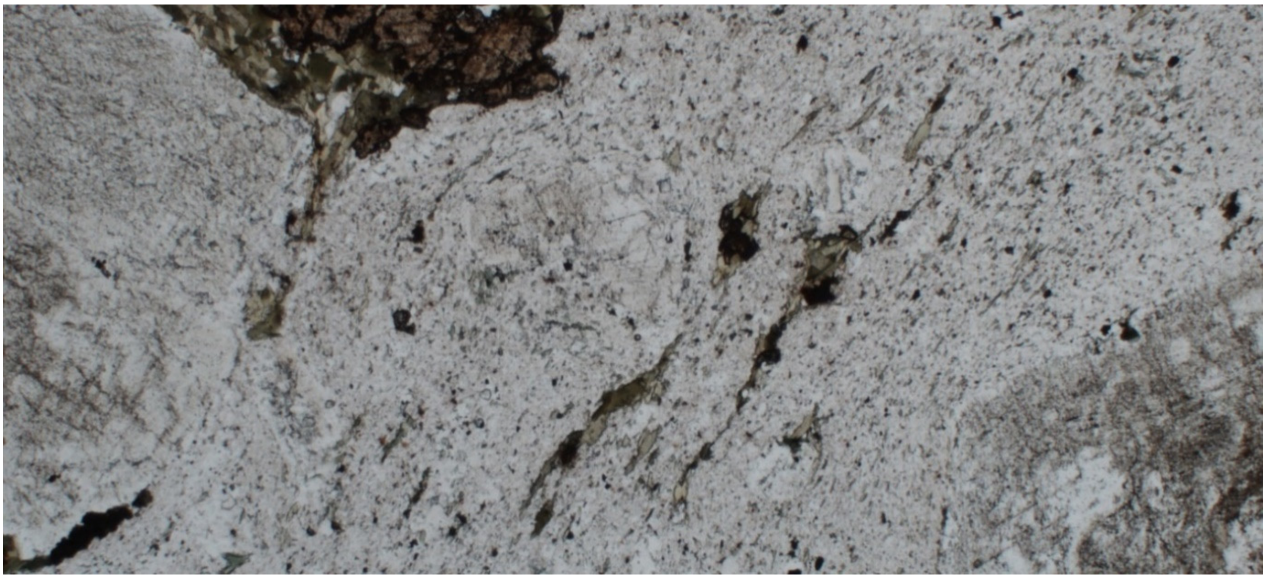
Titanite: Present as one large subhedral megacryst, 6 mm long. It has multiple fractures and two large (1 mm) magnetite grains in the center.

Magnetite:	Anhedral grains up to 1 mm in diameter. Often positioned in conjunction with chlorite. Possible that biotite is altering to magnetite.
Hematite:	Along outer borders of the magnetite grains and as inclusions. Product of martitization.
Ilmenite:	Anhedral grains positioned in the center of two large titanite megacrysts.
Chalcopyrite:	Yellow anhedral grains, some along outer rims of magnetite/hematite grains.

Sample number: 48







Rock type: Qp2
Glomerophyric texture with very fine-grained groundmass and large feldspar phenocrysts. The feldspar phenocrysts are joined together, creating glomerocrysts. These glomerocrysts may also contain of green biotite, titanite and carbonate. Very thin veins, <0.1 mm, filled with carbonate and minor amounts of biotite. The groundmass, consisting of feldspar, quartz and biotite, display magmatic flow structures. Feldspar and biotite grains display parallel alignment along flow direction. Determined as Qp2 based on the amount of quartz.

Minerals:		
	Feldspar	65-75%
	Quartz	10-15%
	Biotite	5-15%
	Carbonate	3-7%
	Titanite	1-5%
	Chlorite	1-3%
	Allanite	1%
	Magnetite	1%
	Pyrite	1%

Feldspar: Phenocrysts with euhedral to subhedral tabular habit. Carlsbad twinning as well as some albite twinning present in the phenocrysts. Epidote alteration occurs in some phenocrysts. The groundmass contains very fine-grained feldspars aligned in direction of foliation, displaying flow structures.

Quartz: Occurs in the groundmass as well as small aggregates of anhedral grains, 0.1 mm.

Biotite: Small subhedral bladed grains in groundmass aligned in the direction of the flow structure. Larger subhedral grains, 0.1-0.2 mm make up aggregates of biotite. These aggregates often contain rounded grains of titanite. The biotite contains inclusions of a fine-grained brown radioactive mineral. Possibly monazite.

Carbonate: Anhedral grains in carbonate-aggregates and some smaller irregular grains in groundmass. Some of the aggregates are part of larger glomerocrysts along with feldspar, biotite and titanite.

Titanite: Mostly rounded grains, 0.1-0.3 mm, in aggregates of biotite, and as inclusions in feldspar phenocrysts.

Chlorite: Subhedral, tabular pale-green grains. Positioned in glomerocrysts of feldspar, biotite and muscovite, possibly replacing all of them.

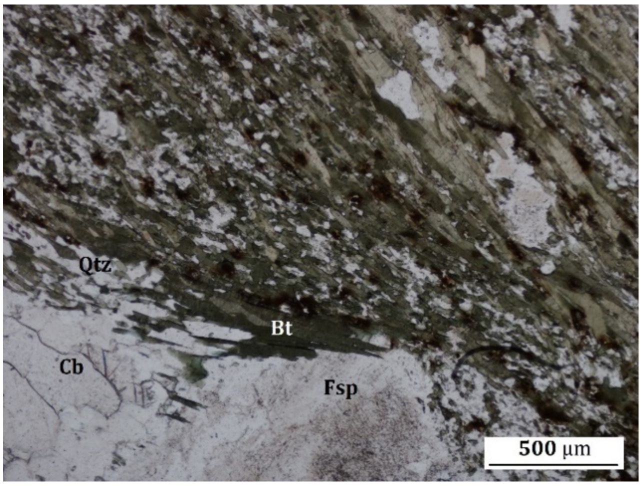
Allanite: Anhedral rounded grains with red-brown colour in groundmass. <0.1 mm.

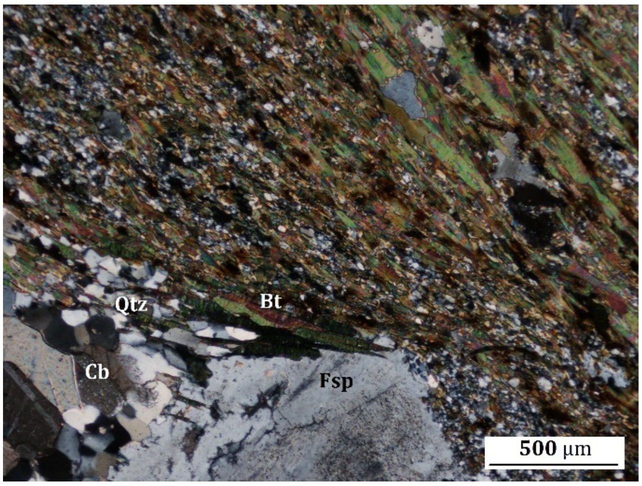
Magnetite: Rounded grains, <0.1 mm, in groundmass and as inclusions in feldspar.

Pyrite: Isotropic opaque grains with white colour and high reflectance. Fine subhedral cubes.

Ilmenite: Subhedral grains. Anisotropic in shades of grey.

Sample number: 49





Rock type: Qp
Porphyritic texture with feldspar phenocrysts. Aggregates of bladed biotite, as well as carbonate and quartz. Some of the feldspar phenocrysts are intergrown with each other and lined with quartz. Groundmass of feldspar, biotite and lesser amounts of quartz. Signs indicating solid-state deformation occurs in the thin section, the major one being the pressure shadows containing aggregates of quartz, carbonate and biotite. Determined as Qp based on the amount of quartz, and lack clinopyroxene and nodules.

Minerals:		
	Feldspar	15-25%
	Quartz	20-30%
	Biotite	25-35%
	Carbonate	5-15%
	Anhydrite	1-3%
	Monazite	1-3%
	Zircon	1%

Feldspar: Phenocrysts exposed to substantial alteration by sericite and albite. Some inclusions of biotite. Up to 10 mm in diameter. Subhedral blocky shapes with phenocrysts often intergrown. Some polysynthetic twinning. A few phenocrysts appear to have been rotated. The groundmass contains fine-grained rounded and elongated feldspar grains.

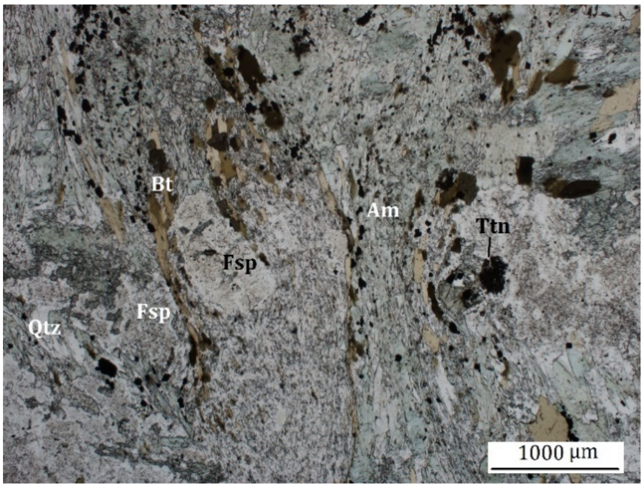
Quartz: Anhedral, rounded grains in aggregates along with biotite and along borders of carbonate aggregates. 0.05-0.2 mm. Quartz grains are present in the groundmass, generally larger than the feldspar grains. Pressure shadows around feldspar phenocrysts contain aggregates of quartz.

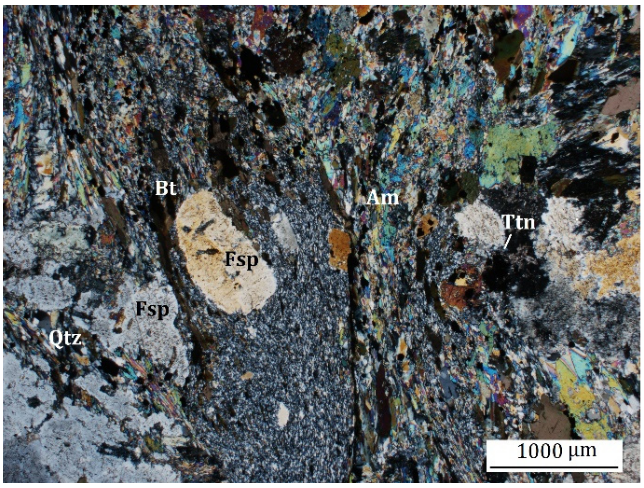
Biotite: Green bladed grains in aggregates aligned in direction of foliation. Length up to 0.25 mm. Smaller and more irregular grains in groundmass. Inclusions of zircon causing brown halos.

Carbonate: Aggregates of anhedral grains. Often elongated in a uniform direction of foliation. The carbonate, being non-deformed, are most probably the youngest mineral in the sample, postdating the solid-state deformation. Surrounded primarily by quartz.

Anhydrite:	Fine anhedral grains positioned in carbonate aggregates and in the groundmass.
Monazite:	Fine-grained inclusions in biotite, radiating pleochroic brown radioactive halos.
Zircon:	Fine-grained inclusions in biotite. Brown pleochroic radioactive halos. Occurs as euhedral to subhedral crystals with pyramidal terminations.

Sample number: 50





Rock type: Qp

Glomerophyric texture with feldspar phenocrysts and glomerocrysts in a very fine-grained groundmass of feldspar, amphibole needles, rounded quartz and bladed biotite. Glomerocrysts consist of feldspar, amphibole and biotite. Aggregates of amphibole, biotite, chlorite and magnetite, partly aligned in direction of foliation. Pressure shadows around feldspar phenocrysts filled with quartz and biotite aggregates occur, implying solid-state deformation. Possible signs of minor magmatic flow structures, as parallel alignment of feldspar and amphibole grains. Classified as Qp due to the high amount of quartz and lack of clinopyroxene.

Minerals:	Feldspar	60-65%
	Quartz	10-15%
	Biotite	10-15%
	Amphibole	15-20%
	Chlorite	1-5%
	Carbonate	1-5%
	Anhydrite	1-3%
	Titanite	1-5%
	Magnetite	3-7%
	Ilmenite	1%

Feldspar: Large subhedral phenocrysts, altered mostly to sericite and to lesser extent albite. Glomerocrysts often occur. Titanite, biotite and amphibole are present as inclusions. Fractures are in some cases filled with carbonate. The groundmass contains very fine-grained feldspar, aligned parallel to the direction of the foliation.

Quartz: Rounded anhedral grains in aggregates of amphibole and biotite and in between feldspar phenocrysts. Minor amount of quartz in groundmass. Quartz aggregates occur in pressure shadows in proximity of feldspar phenocrysts.

Biotite: Present as bladed and subhedral grains, 0.1-0.3 mm, in thin aggregates positioned in the flow direction. More subhedral and blocky grains located in amphibole aggregates and as inclusions in feldspar phenocrysts. Smaller anhedral grains in groundmass.

Amphibole: Columnar crystals with pale green colour, some making up aggregates of bladed grains. Present in aggregates alongside biotite, chlorite and magnetite. The amphibole possibly alters into chlorite. Smaller grains are present in groundmass as bladed grains aligned in the direction of foliation.

Chlorite: Pale green bladed grains in amphibole aggregates. Shares texture and shape with neighboring amphibole.

Carbonate: Anhedral grains along with quartz in between feldspar phenocrysts. Displays higher birefringence than the carbonate.

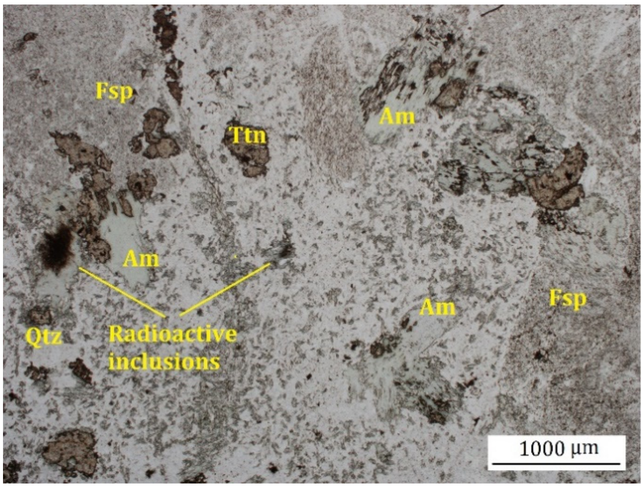
Anhydrite: Colourless anhedral grains positioned in carbonate aggregates and in the groundmass.

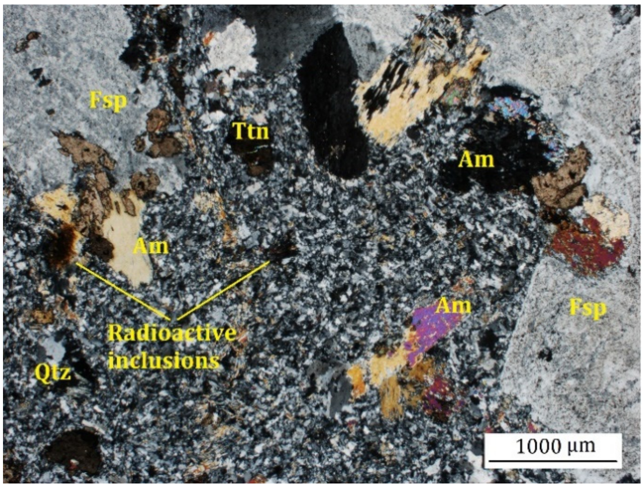
Titanite: Irregular grains, 0.1-0.5 mm, as inclusions in feldspar phenocrysts and amphibole masses.

Magnetite: Anhedral rounded grains, up to 0.2 mm. Present in both groundmass as well as inclusions in biotite, feldspar and amphibole. Grains are concentrated along biotite and amphibole aggregates following flow direction.

Ilmenite: Anisotropic grey grains as rounded inclusions inside magnetite.

Sample number: 51





Rock type: Gp
Glomerophyric texture with glomerocrysts and phenocrysts of feldspar. Glomerocrysts consisting of feldspar, titanite and amphibole occurs. Groundmass of feldspar, bladed amphibole and quartz. A vein of acicular amphibole and titanite run diagonally through the thin section. Another thin vein is filled with quartz and carbonate. Classified as Gp due to the large amount of amphibole, and low amount quartz.

Minerals:	Feldspar	50-60%
	Quartz	3-7%
	Amphibole	25-35%
	Apatite	1-5%
	Carbonate	1-3%
	Anhydrite	1-3%
	Titanite	3-7%

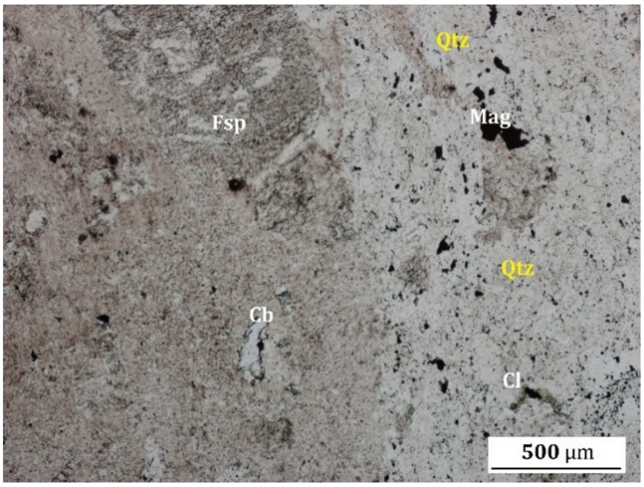
Feldspar: Present in groundmass as fine grains with irregular shape. Phenocrysts are up 12 mm in diameter and display epidote-alteration and some perthitic texture. Some phenocrysts are in fact glomerocrysts, consisting of multiple large feldspar crystals as well as crystals of amphibole and titanite. A few feldspar phenocrysts contain minor inclusions of an unknown radioactive mineral. Groundmass contain subhedral tabular feldspar grains.

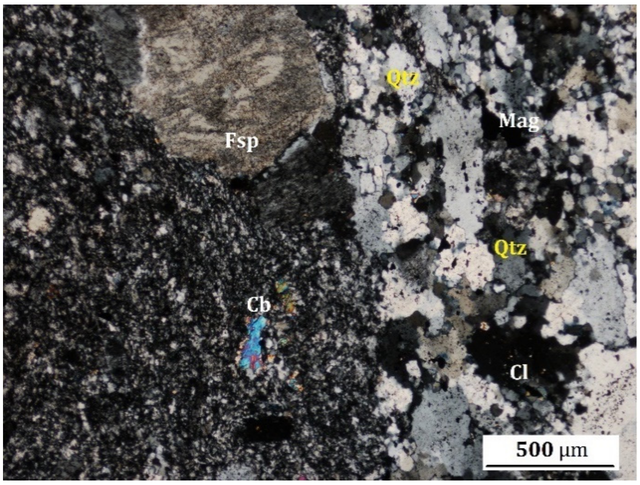
Quartz: Grains make up a minor part of the groundmass. These grains are more rounded than the neighboring feldspars. Vein fill in minor vein.

Amphibole: Pale green megacrysts, some part of feldspar phenocrysts and megacrysts of titanite. Some of the amphibole megacrysts display low interference colours. This most probably a result of the crystal being cut along a specific axis. Some megacrysts contain radioactive inclusions of an unknown colourless mineral. Amphibole is also present in the groundmass as fine bladed grains. Acicular amphibole acts as filling in a vein.

Apatite:	Appears as colourless grains in the groundmass, larger than the surrounding feldspar grains. Low interference colours. Moderate relief, noticeably higher than the feldspar and the quartz.
Carbonate:	Anhedral grains, <0.1 mm, most often located in small aggregates of carbonate. Filling in veins.
Anhydrite:	Colourless anhedral grains positioned in the groundmass.
Titanite:	Rounded and anhedral megacrysts, and as inclusions in feldspar phenocrysts and in nodules alongside amphibole. Small grains as filling in a vein dominated by amphibole. Some titanite grains seem to contain fine inclusions of possible rutile.

Sample number: 52





Rock type: Hanging wall
Porphyritic and glomerophyric texture with feldspar phenocrysts, some of them joined to create glomerocrysts. Light streaks of aggregates containing quartz, carbonate and anhydrite is often positioned in proximity to the magnetite megacrysts. Aggregates of quartz of varying size occur in connection to feldspar phenocrysts. The groundmass has a red colour that is more apparent in hand sample, as a result of very fine-grained ore minerals. The groundmass, consisting of feldspar, quartz and magnetite, displays minor magmatic flow structures, with faint alignment of feldspar grains. Fine-grained radioactive minerals are present in the groundmass.

Minerals:	Feldspar	75-85%
	Quartz	5-15%
	Anhydrite	1-5%
	Apatite	1-3%
	Carbonate	1-5%
	Chlorite	1-5%
	Magnetite	5-15%
	Chalcopyrite	<1%

Feldspar: Subhedral phenocrysts with tabular and blocky shape. Albite alteration, Carlsbad twinning and cross-hatched twinning is present. The red groundmass contains irregular feldspar grains of largely varying size, from very fine-grained to coarser grains. Part of it is probably plagioclase.

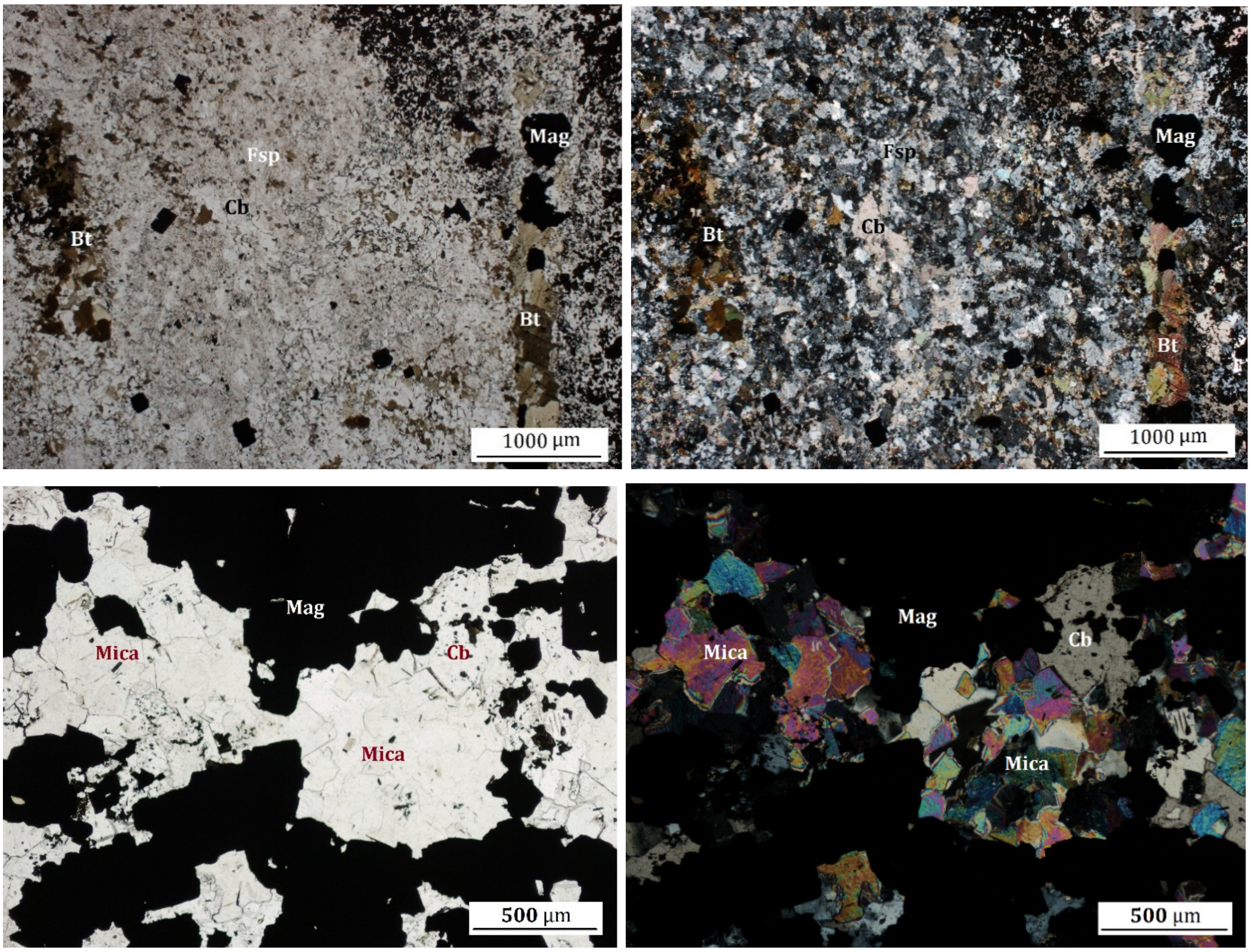
Quartz: Aggregate of anhedral grains with irregular, wavy boundaries, 0.1-0.4 mm. These aggregates are either scattered through the groundmass or part of nodules of quartz, magnetite and carbonate.

Anhydrite: Colourless anhedral grains with high interference colours. Extinction angle is parallel to cleavage.

Apatite: Colourless grains with low birefringence and moderate to high relief. Often surrounded by anhydrite.

Carbonate:	Anhedral grains with high interference colours and varying relief. Mostly positioned along rims of feldspar phenocrysts.
Chlorite:	Pale green anhedral grains inside aggregates of feldspar and quartz.
Magnetite:	Small rounded grains and anhedral masses, up to 3 mm in diameter. The red colour of the groundmass is a result of very fine-grained ore minerals.
Pyrite:	Very fine rounded grains on rim of magnetite grain. Yellow colour, high reflectance and isotropic.

Sample number: 53



Rock type: Hanging wall
Megacrysts of magnetite and phenocrysts of feldspar. Groundmass of feldspar, quartz, carbonate as well as minor amounts of biotite, epidote, magnetite and possibly rutile. Aggregates of titanite and carbonate, separately. Minor amounts of anhydrite, gypsum and tourmaline occur in the thin section, as well as aggregates of an unknown mica.

Minerals:	Feldspar	15-25%
	Quartz	20-30%
	Biotite	5-15%
	Epidote	1-5%
	Carbonate	25-35%
	Anhydrite	1-3%
	Gypsum	1-3%
	Tourmaline	1%
	Unknown Mica	1-3%
	Rutile	1%
	Titanite	5-15%
	Magnetite	10-15%

Feldspar: Minor amount of feldspar phenocrysts. These have perthitic texture and are extensively altered by quartz and carbonate. Some of the phenocrysts are secondary K-feldspar with cross-hatched twinning. Feldspars in the groundmass display polysynthetic twinning and perthitic texture.

Quartz: Present as round, anhedral grains in groundmass and as small aggregates of similar grains.

Biotite: Brown-green anhedral and subhedral bladed grains with primarily irregular shape. 0.1-0.5 mm. Often positioned in spotty aggregates. Fine subhedral grains are present as a minor element in the groundmass.

Epidote: Pale green anhedral, often elongated or tabular, grains in groundmass. <0.1 mm. Parallel extinction and high birefringence.

Carbonate: Anhedral grains in aggregates of carbonate and in separate grains in groundmass.

Anhydrite: Colourless anhedral grains with distinctive high birefringence.

Gypsum: Anhedral colourless grains positioned close to the tourmaline. Similar to the anhydrite, but with 1st order interference colours and softer texture.

Tourmaline: Subhedral columnar prism with blue-green colour. Only one grain observed in the thin section.

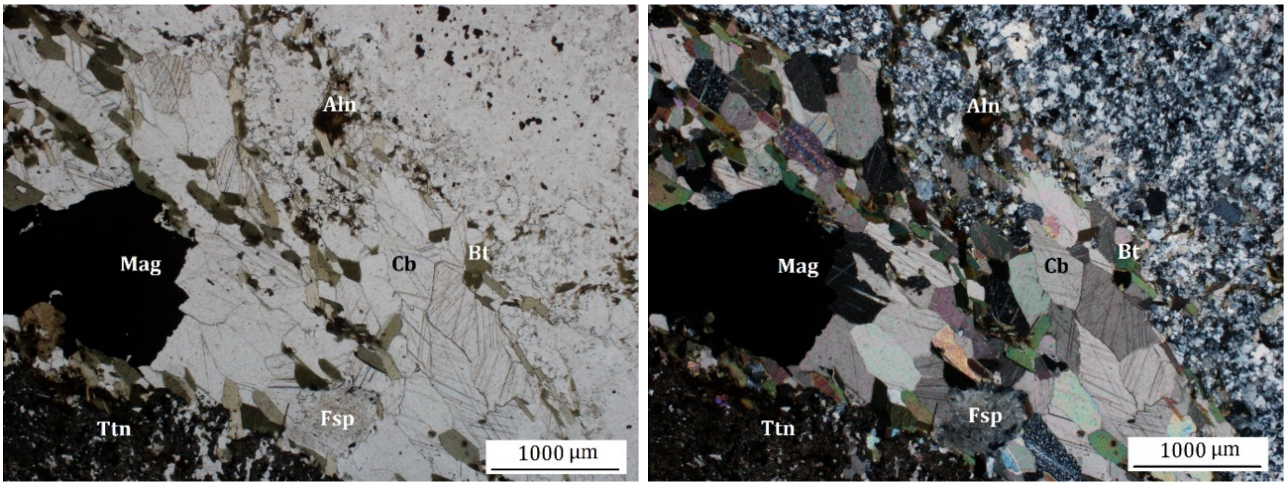
Unknown Mica: Anhedral and subhedral flakes, 0.1-0.3 mm. Colourless with high birefringence. Parallel extinction. Positioned between magnetite megacrysts. Most probably an unknown mica.

Rutile: Small anhedral grains with brown-golden colour and no radioactive halos, <0.1 mm.

Titanite: Anhedral grains positioned in aggregates in contact with large magnetite grains. The outline of the aggregates is similar to the neighboring magnetite, probably indicating an equilibrium during their formation.

Magnetite: Large anhedral grains, often in conjunction with titanite.

Sample number: 54



Rock type: Hanging wall
Porphyritic texture with feldspar phenocrysts. Cut through the middle by a thick vein of titanite, magnetite and carbonate. The groundmass consists of feldspar, quartz, magnetite, biotite and carbonate. Biotite occur as bladed aggregates containing fine-grained radioactive inclusions.

Minerals:

Feldspar	15-25%
Quartz	5-10%
Biotite	10-15%
Carbonate	10-20%
Apatite	1-5%
Titanite	35-45%
Allanite	1%
Magnetite	5-10%
Ilmenite	10-15%
Chalcopyrite	1-3%
Pyrite	<1%

Feldspar: Tabular phenocrysts with irregular borders, 0.5-0.9 mm. Fractures and rims are lined with fine grained carbonate. Phenocrysts display polysynthetic twinning. Smaller grains make up majority of the groundmass. These grains are irregular and display some polysynthetic twinning. Eds analysis indicate that feldspar phenocrysts and groundmass consist of alkali feldspar and albite (table 7).

Quartz: Rounded anhedral grains with undulatory extinction. Positioned in groundmass along with feldspar.

Biotite: Subhedral tabular and bladed grains with green colour. Grains are 0.3-0.5 mm in diameter. Forms aggregates along with carbonate. Titanite aggregates encroach upon the biotite in most cases. Brown, radioactive inclusions occur in more than half of the biotite grains. Biotite grains positioned under titanite can generate a darker brown colour in the titanite.

Carbonate: Aggregates of anhedral grains, 0.2-0.8 mm.

Apatite: Anhedral colourless grains positioned as inclusions inside titanite aggregates.

Titanite: Brown titanite covering the middle part of the thin section. Aggregates of grains with varying shape and size. The aggregates contain cavities partly filled by carbonate and biotite. Areas where biotite grains are positioned underneath titanite can give rise to a darker brown colour in the titanite.

Allanite: Fine-grained allanite with brown colour, with possibly masked high interference colours. Creates brown halos in biotite. Eds analysis indicate that allanite is present (table 7). It is likely that there are more minerals in proximity to the allanite. Epidote is one of the possible minerals.

Magnetite: Rounded anhedral grains in groundmass, approximately 0.1 mm in diameter, as well as a few larger megacrysts.

Ilmenite: Anhedral grains positioned in the center parts of titanite megacrysts. These ilmenite grains are more elongated, similar in shape to the surrounding titanite.

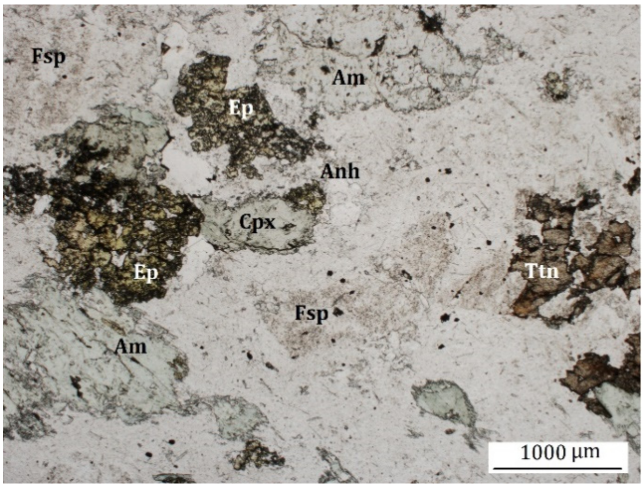
Chalcopyrite: Sulfide with yellow-orange colour, high reflectance and isotropy. An anhedral shape with a length of 8 mm and a few smaller grains, <0.05 mm.

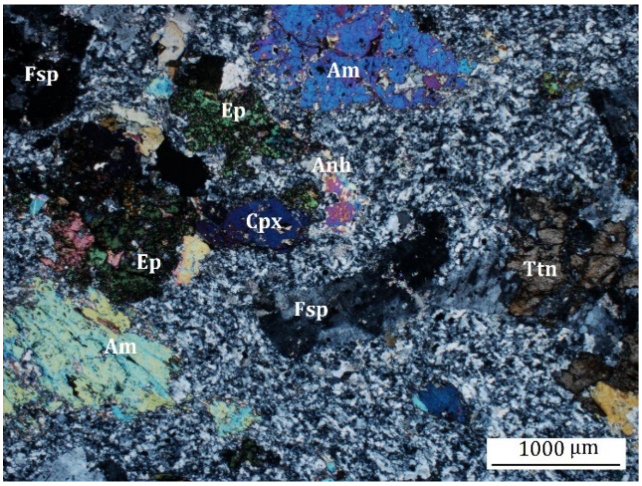
Pyrite: Very fine rounded grains, <0.05 mm, in groundmass. Isotropic pale-yellow colour with high reflectance.

Table 7. EDS-data. Mass percentages and atom percentages of chemical elements.

	Albite		*Unknown Y-silicate*		*K-fsp*		*Ttn*	
Chemical formula	mass%	Atom%	mass%	Atom%	mass%	Atom%	mass%	Atom%
O	43.09	56	43.24	69.32	40.44	56.15	36.24	57.75
Al	11.5	8.86			10.36	8.53	0.72	0.68
Si	36.09	26.72	17.27	15.77	33.09	26.17	15.14	13.74
K					16.1	9.14		
Na	9.32	8.43						
Mg								
Ca			7.35	4.7			22.42	14.26
Fe			5.45	2.5				
Ti							25.48	13.56
Y			26.68	7.7				

Sample number: 55





Rock type: Sp

Porphyritic texture. Feldspar is present as phenocrysts. Amphibole and epidote are present as megacrysts. These minerals also make up green coloured nodules in different combinations. A large vein filled primarily with titanite and by magnetite run diagonally across the thin section. Groundmass with feldspar, needles of amphibole as well as grains of magnetite and epidote.

Minerals:		
	Feldspar	45-55%
	Amphibole	10-20%
	Chlorite	3-7%
	Epidote	10-15%
	Anhydrite	3-7%
	Titanite	10-20%
	Magnetite	3-7%
	Ilmenite	3-7%
	Hematite	3-7%

Feldspar: Subhedral rectangular and prismatic phenocrysts displaying cross-hatched twinning, albite and sericite alteration and perthitic texture. Some Carlsbad twinning is also observed. 0.3-1.5 mm.

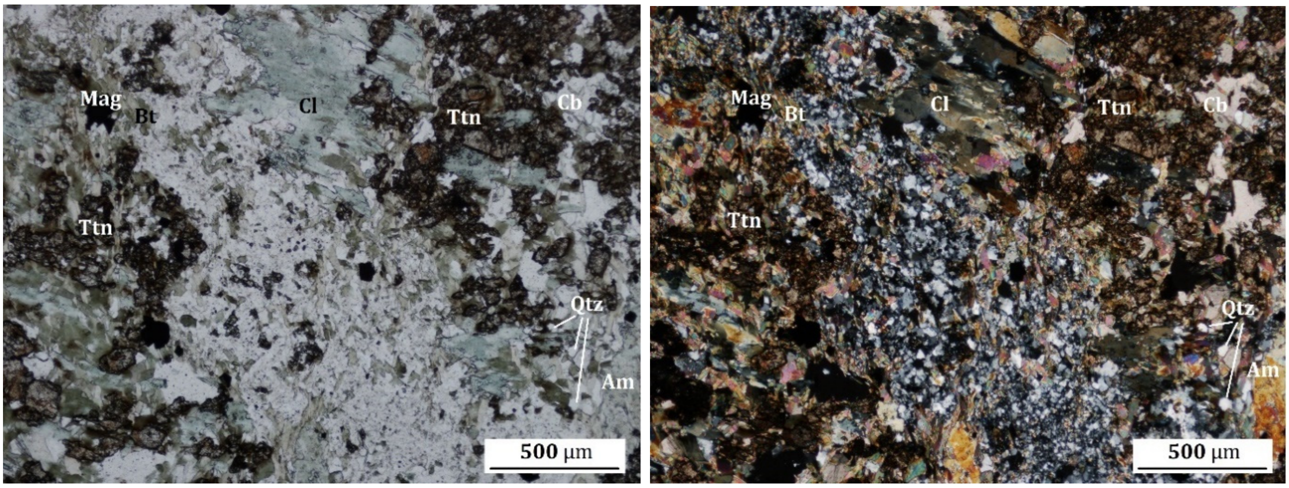
Amphibole: Present in groundmass and as megacrysts. Pale green bladed and acicular grains in groundmass. The megacrysts have the same colour, with rounded shape and acicular boundaries. Some of these are part of nodules. Possibly replaced by chlorite.

Clinopyroxene: Pale green rounded crystalline phenocrysts without the bladed habit of the amphibole and chlorite. Present in nodules and as inclusions in titanite. Possibly alters to amphibole.

Chlorite: Megacrysts and grains with pale green colour and similar, bladed habit as the amphibole. Low 1st order interference colours. May have inclusions of higher birefringence, most probably amphibole. Replaces amphibole.

Epidote:	Yellow-green mineral as rounded, anhedral granular megacrysts. These granular masses are part of nodules
Anhydrite:	Colourless grains with interference colour up to 2nd order yellow. Irregular grains positioned in contact with epidote and feldspar. <0.1 mm.
Titanite:	Anhedral grains, often as small inclusions in feldspar phenocrysts. A thick mass of titanite runs through the sample with an average width of 6-10 mm. These megacrysts seem to consist of other Ti-bearing minerals in addition to the titanite. This is apparent in the different texture and colour in some areas of the titanite. The large titanite megacrysts contains inclusions of magnetite and ilmenite.
Magnetite:	Occurring as small anhedral grains, <0.05 mm, in groundmass. Grains are grow larger in proximity of the large titanite vein. Appears as well as inclusions in the titanite.
Ilmenite:	Anhedral grains occurring as inclusions in the thick titanite mass.
Hematite:	Grayish white grains lining most magnetite grains. Possible product of martitization.

Sample number: 56



Rock type: Foot wall
Titanite megacrysts exposed to extensive fracturing, with inclusions of ilmenite, Magnetite and hematite. Aggregates of biotite and chlorite in groundmass and lining the titanite megacrysts. Carbonate and amphibole aggregates as fracture fill. Groundmass of feldspar, biotite, magnetite and minor amounts of carbonate.

Minerals:	Feldspar	25-35%
	Quartz	1-5%
	Biotite	20-30%
	Amphibole	1-5%
	Chlorite	1-5%
	Carbonate	1-5%
	Titanite	15-25%
	Magnetite	3-7%
	Ilmenite	3-7%
	Hematite	1-3%
	Pyrite	<1%

Feldspar: Fine feldspar grains in groundmass.

Quartz: Anhedral grains, <0.2 mm, in fractures of titanite.

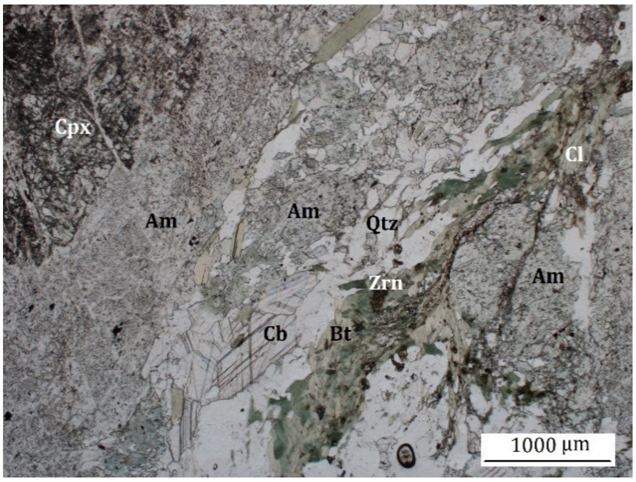
Biotite: Subhedral bladed grains in aggregates. Surrounds titanite grains and positioned along with chlorite. Acts as filling in a few thin veins. Possibly alters to chlorite. Smaller anhedral grains in groundmass. Small amounts of fine-grained radioactive inclusions appear in the biotite.

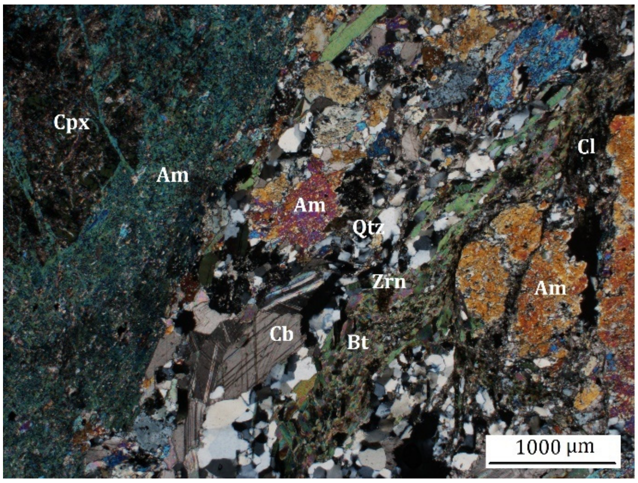
Amphibole: Pale green bladed grains with moderate to high interference colours. Surrounded by biotite. Possible alteration process into biotite.

Chlorite: Pale green bladed and tabular crystals with moderate pleochroism. 1st order interference colours. Positioned together with biotite and carbonate. Possible alteration product of biotite.

Carbonate:	Grey-beige grains with negative relief changing during rotation. Mostly present as fracture-filling along with biotite and in small aggregates.
Titanite:	Large fractured megacrysts with carbonate and groundmass material as fracture fill. Lined with biotite. Smaller rounded granular masses present as inclusions in biotite and chlorite aggregates. Up to 15 mm in diameter. The center parts of some titanite grains consists of anhedral ilmenite.
Magnetite:	Subhedral square-shaped grains in groundmass. Anhedral magnetite grains are found in center of titanite grains along with ilmenite.
Ilmenite:	Anhedral grains located in center parts of large titanite grains.
Hematite:	Anhedral grains occurring in conjunction with ilmenite as inclusions in the centre of titanite grains.
Pyrite:	White-yellow anhedral isotropic grains with high reflectance. 0.05 mm.

Sample number: 57





Rock type: Foot wall
Porphyritic texture with phenocrysts of clinopyroxene surrounded by megacrysts of uralitic amphiboles. The groundmass consists of feldspar, biotite and minor amounts of magnetite. Aggregates of quartz replaces the groundmass in part of the sample, and acts as lining for biotite and carbonate aggregates. Evidence of solid-state deformation is present in deformation of aligned feldspar grains and elongation of recrystallized quartz aggregates. All minerals in this thin section are secondary, most probably products of hydrothermal fluids, except the feldspars.

Minerals:

Feldspar	10-15%
Quartz	10-15%
Biotite	20-30%
Clinopyroxene	3-7%
Amphibole/Uralite	20-30%
Carbonate	5-15%
Chlorite	1-5%
Zircon	1-3%
Allanite	<1%

Feldspar: Fine grained groundmass. Some of the grains display deformation and are aligned in uniform direction, most probably indicating solid-state deformation. No phenocrysts are present.

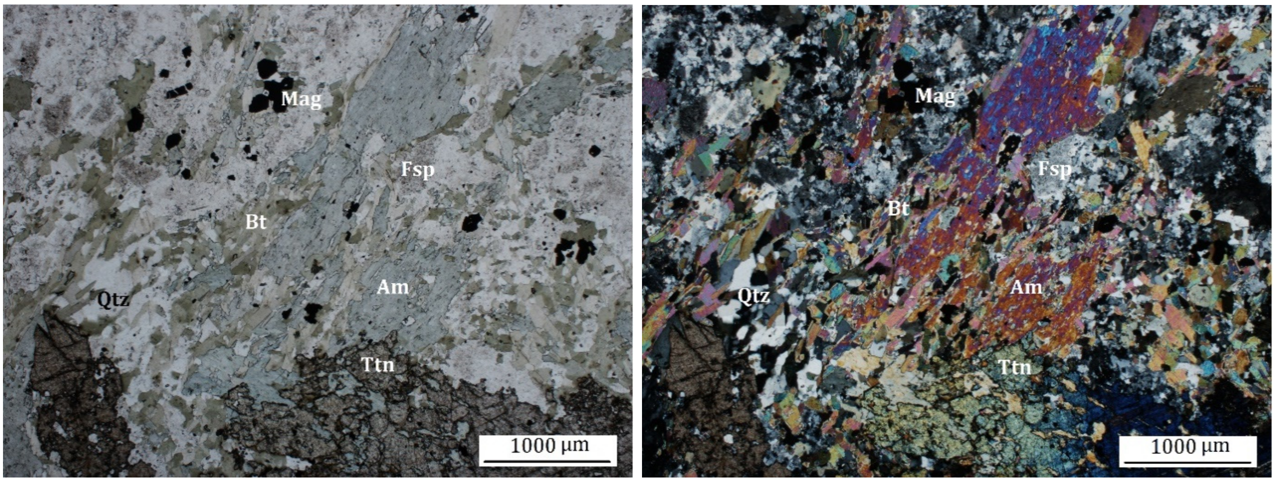
Quartz: Anhedral grains, 0.1-0.4 mm, in aggregates lining biotite and carbonate grains. Replaces the feldspar groundmass in a portion of the thin section. The high amount of quartz may be a product of alteration.

Biotite: Aggregates of bladed biotite with a green-blue colour, indicating high Mg-content. Contains inclusions of zircon. Smaller anhedral grains in groundmass, some are aligned in the direction of the flow structure.

Clinopyroxene: Pale green, rounded and partly replaced grains and phenocrysts. Displays 2nd order interference colours. Positioned in the center of amphibole megacrysts.

Amphibole:	Pale green, alteration product of clinopyroxene. 1st-2nd order interference colours. Anhedral shaped megacrysts with irregular borders and inclined extinction. Some megacrysts display simple twinning. The largest amphibole megacrysts are probably uralite, as grains of clinopyroxene occur in the center of some amphibole megacrysts. These uralite grains have a very pale green colour, compared to the more green, neighboring smaller amphibole megacrysts. This is most probably due to lower Fe-content in the uralite.
Carbonate:	Aggregates of anhedral grains. Present in between megacrysts of amphibole.
Chlorite:	Pale green fibrous grains. Chlorite veins is running through some of the biotite aggregates. Possible alteration product of biotite.
Zircon:	Inclusions in biotite creating brown halos. The grains are colourless subhedral crystals with pyramidal terminations.
Allanite:	Very fine orange-red grains in groundmass. Possible rutile.

Sample number: 58



Rock type: Foot wall
Megacrysts of biotite and amphibole, where the amphibole is often lined with aggregates of bladed biotite. Titanite and feldspar is present as irregular megacrysts and phenocrysts. Aggregates of carbonate and quartz. Groundmass of feldspar, magnetite and biotite. Minor amounts of anhydrite and gypsum.

Minerals:		
	Feldspar	25-35%
	Quartz	1-5%
	Biotite	10-20%
	Amphibole	15-25%
	Titanite	15-25%
	Carbonate	1-5%
	Anhydrite	1-5%
	Gypsum	1%
	Magnetite	5-10%
	Ilmenite	1-5%

Feldspar: A few phenocrysts with polysynthetic twinning and inclusions of titanite and magnetite. Tabular shape. Groundmass contain irregular grains in varying sizes with some epidote alteration causing yellow-grey colour. Both phenocrysts and groundmass appear to be exposed of considerable alteration. Eds analysis indicate alkali feldspar in groundmass (table 8).

Quartz: Anhedral grains in aggregates surrounded by biotite and titanite.

Biotite: Moss-green subhedral and anhedral biotite as megacrysts and aggregates. Habit varies from bladed to tabular. Possible product of amphibole alteration, as it lines many amphibole megacrysts.

Amphibole: Prismatic grains with distinct 124/56-cleavage in aggregates. High first order interference colours. Also present as pale green megacrysts with higher birefringence, up to 5 mm in diameter. Most probably product of clinopyroxene. Minor clinopyroxene may remain in the sample. The amphibole seems to alter to biotite.

Titanite: Anhedral megacrysts and grains, 0.2-10 mm. Fine grained inclusions in bladed biotite grains causing brown halos. Large irregular megacrysts with extensive fracturing.

Carbonate: Colourless anhedral grains, megacrysts and aggregates, 0.05-0.2 mm, exposed to extensive fracturing. Inclusions of ilmenite.

Anhydrite: Anhedral grains, 0.1 mm, often in contact with biotite and amphibole.

Gypsum: Small amounts of colourless, anhedral grains with distinct soft structure.

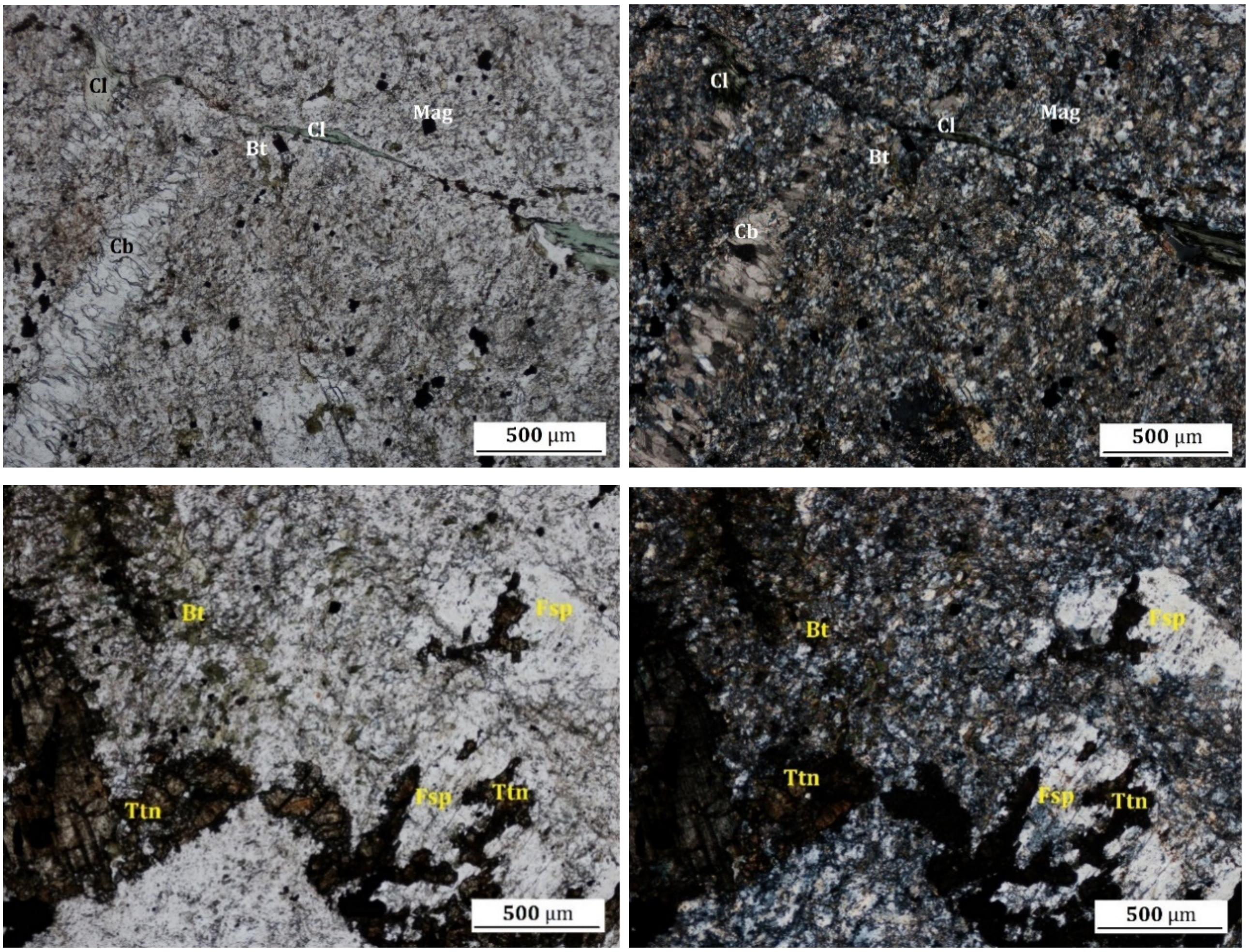
Magnetite: Subhedral and anhedral square-shaped grains in groundmass and as inclusions in biotite and amphibole.

Ilmenite: Anhedral grains inside center of large titanite grain. Alters to titanite.

Table 8. EDS-data. Mass percentages and atom percentages of chemical elements.

	Anh		*Act*		*K-fsp*	
Chemical formula	Mass%	Atom%	Mass%	Atom%	Mass%	Atom%
O	40.24	60.32	41.14	57.06	40.5	56.2
Al					10.36	8.52
Si			29.32	23.16	33.1	26.17
K					16.04	9.11
Na						
Mg			13	11.87		
Ca	33.63	20.13	8.59	4.76		
Fe			7.94	3.16		
S	26.14	19.55				

Sample number: 59



Rock type: Foot wall

Porphyritic texture with feldspar phenocrysts and titanite megacrysts in a very fine groundmass of feldspar, biotite, magnetite, carbonate and quartz. Thin veins, 0.05-0.2 mm thick, are filled with biotite, carbonate, chlorite and quartz.

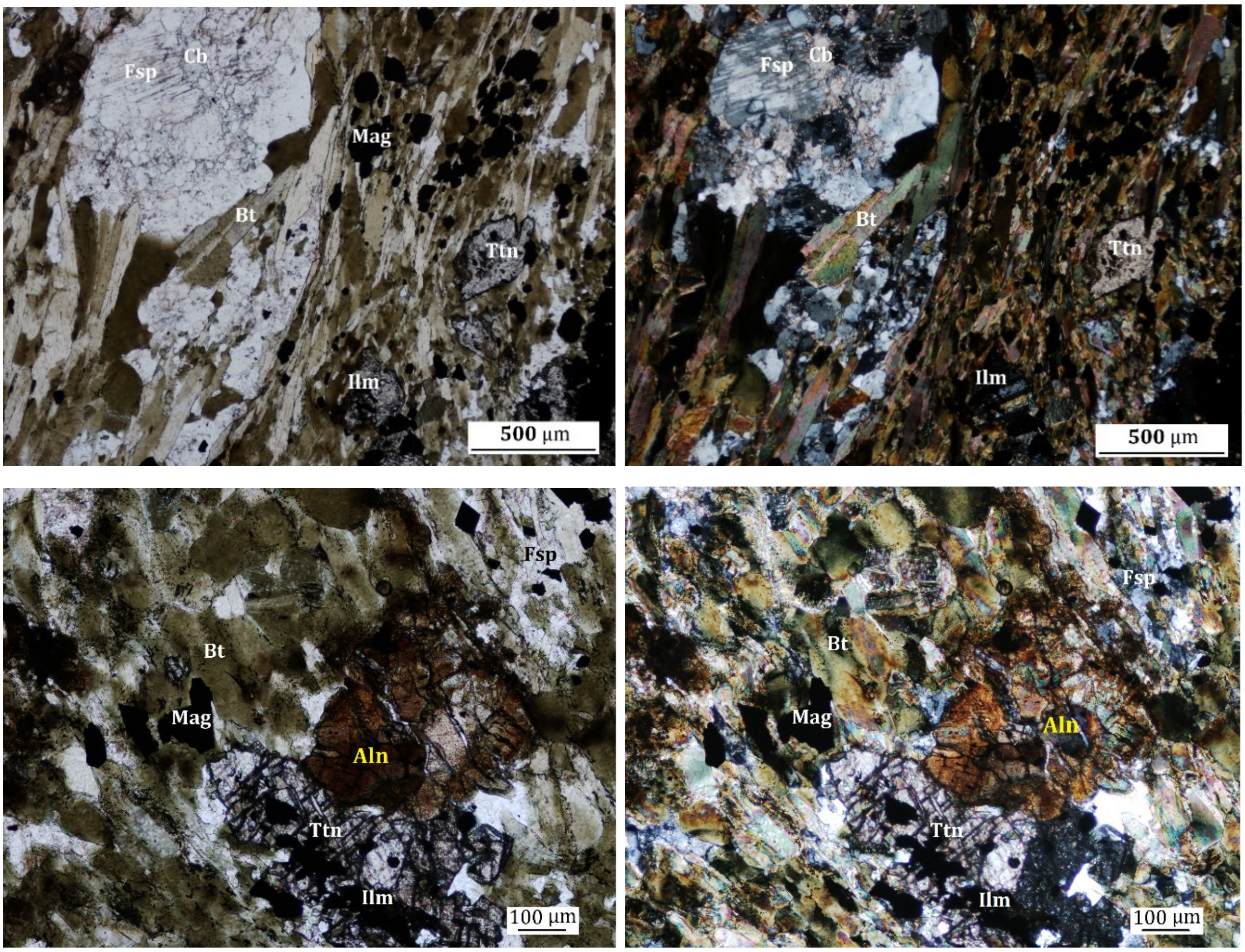
Minerals:		
	Feldspar	40-50%
	Quartz	3-7%
	Biotite	5-15%
	Chlorite	1-5%
	Carbonate	15-25%
	Titanite	5-10%
	Zircon	1-5%
	Magnetite	3-7%
	Ilmenite	1-3%

Feldspar: Subhedral phenocrysts exposed to extensive sericite alteration. Tabular shape with some polysynthetic and Carlsbad twinning present. Epidote alteration occurs in some phenocrysts.

Quartz: Small anhedral grains with undulatory extinction in veins. It is possible that the groundmass contains minor parts of quartz.

Biotite:	Filling in veins and subhedral bladed grains in aggregates and groundmass. Aggregates are <0.3 mm in diameter. Alters to chlorite.
Chlorite:	Green chlorite as filling in thin veins, were it seems to replace biotite.
Carbonate:	Present in groundmass as very fine grains, as filling in veins and in large aggregates of anhedral grains, 0.1-0.2 mm.
Titanite:	Brown anhedral grain as inclusions in biotite and carbonate as well as larger irregular titanite megacrysts, up to 10 mm in diameter.
Zircon:	Pale brown subhedral tetragonal crystals as inclusions in biotite, giving rise to brown halos.
Magnetite:	Anhedral and subhedral cubical grains in groundmass, 0.1-0.2 mm.
Ilmenite:	Anhedral, some grains lath-like, inside larger titanite grains.

Sample number: 60



Rock type: Foot wall

Extensive aggregates of biotite aligned in foliation direction, partly as vein fill, in a groundmass of feldspar, magnetite and quartz. Megacrysts and large granular masses of titanite with inclusions of magnetite and ilmenite.

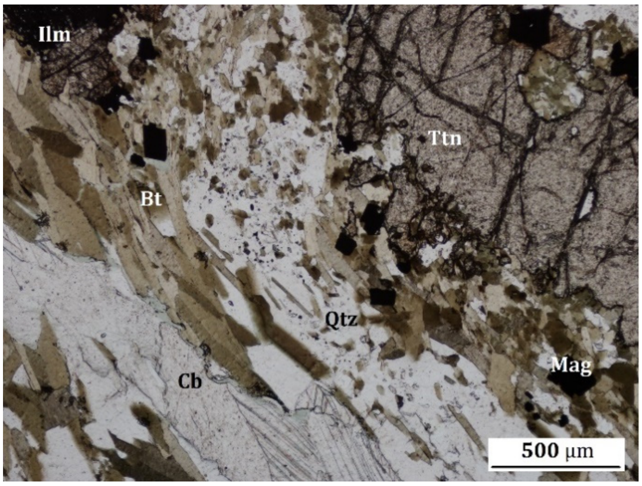
Minerals:		
	Feldspar	20-30%
	Quartz	5-10%
	Biotite	30-35%
	Titanite	5-15%
	Allanite	1-3%
	Magnetite	15-20%
	Ilmenite	1-5%

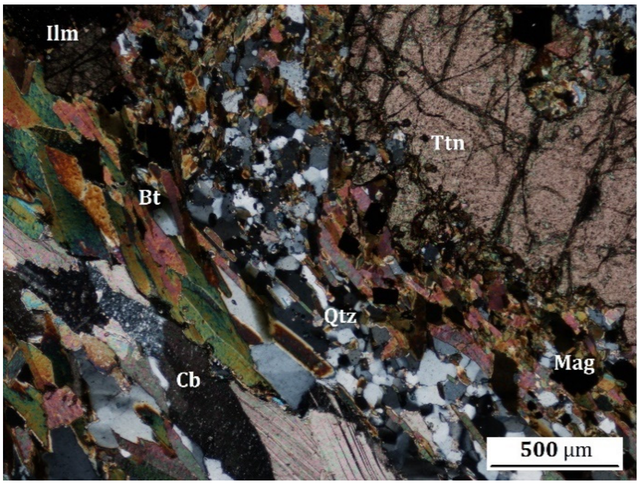
Feldspar: Groundmass contain fine, irregular grains of varying size. Phenocrysts with irregular boundaries, polysynthetic twinning and sericite alteration, 0.3-0.5 mm. Grains with distinct polysynthetic twinning is most likely plagioclase.

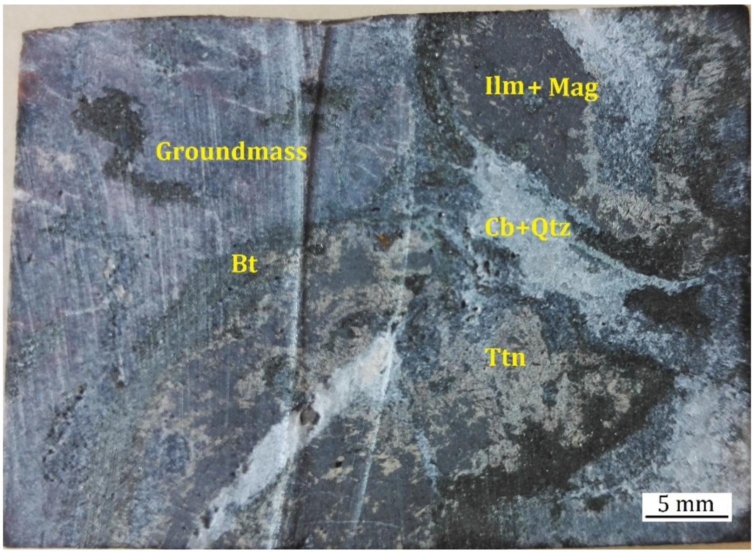
Quartz: Rounded anhedral grains in veins and aggregates of biotite and chlorite. 0.1 mm.

Biotite:	Aggregates of bladed and stubby grains. Aligned in certain direction, indicating flow structure. Also present in a couple of thin veins. Inclusions of magnetite, titanite and allanite
Titanite:	Pale brown titanite as granular aggregates, present as inclusions in biotite-chlorite aggregates. The titanite has inclusions of the allanite.
Allanite:	Red-brown anhedral grains as inclusions in biotite, along with titanite. Strong pleochroism and moderate to high interference colours. Generates radioactive brown halos in surrounding biotite.
Magnetite:	Rounded and square-shaped grains distributed evenly across the groundmass and feldspar megacrysts. 0.2-0.3 m. A minor amount of the grains acts as inclusions in the biotite aggregates.
Ilmenite:	Fine-grained ilmenite inclusions as anhedral grains in larger aggregate of granular titanite. Grey to grey-brown polarization colours.

Sample number: 61







Rock type: Foot wall

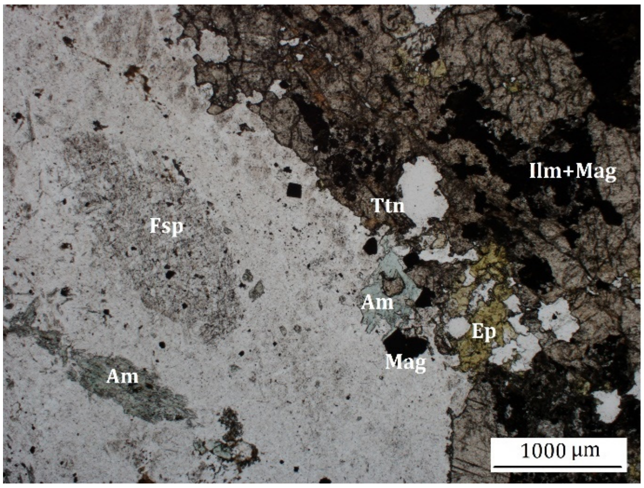
Groundmass consists of feldspar, quartz, biotite, carbonate and sericite. A very large vein running through the thin section is filled with biotite, titanite, magnetite, ilmenite, carbonate and quartz, positioned in order towards the center of the vein. Large megacrysts of titanite, magnetite and ilmenite. Aggregates of biotite with some chlorite present and more coarse-grained carbonate and quartz aggregates.

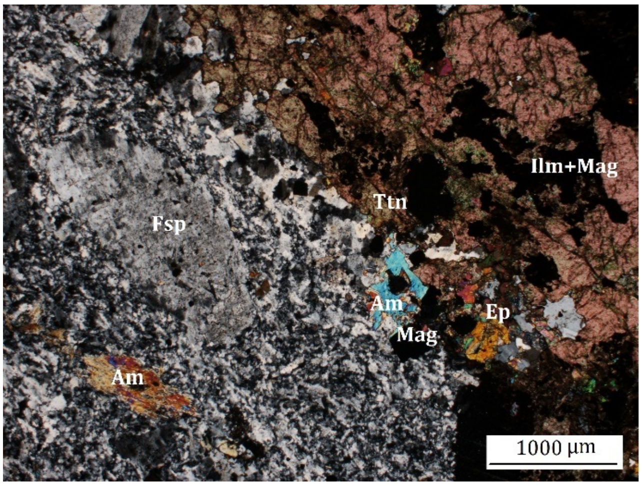
Minerals:		
	Feldspar	5-15%
	Quartz	10-20%
	Biotite	15-25%
	Chlorite	1-5%
	Carbonate	10-20%
	Titanite	10-20%
	Zircon	1%
	Magnetite	10-15%
	Ilmenite	3-7%
	Pyrite	<1%

Feldspar: Very fine, irregular grains in groundmass. Phenocrysts with irregular boundaries, polysynthetic twinning, biotite inclusions and sericite alteration.

Quartz:	Rounded grains in groundmass and rimming biotite and carbonate.
Biotite:	Large aggregates of biotite lining the vein and distributed in the groundmass. The aggregates in the large vein are aligned in the direction of the vein and have a brown-green colour.
Chlorite:	Anhedral and tabular rectangular green and turquoise grains in biotite aggregates and veins. Veins running through the biotite aggregates filled with colourless or pale green chlorite. Probable product of biotite.
Carbonate:	Aggregates of anhedral grains, 0.5-1 mm. Some inclusions of quartz and biotite. Aggregates are positioned in fractures in the large biotite/titanite vein running through the sample.
Titanite:	Large anhedral grains in the large vein, surrounded mostly by biotite. Inclusions of ilmenite and magnetite towards the center of the titanite.
Zircon:	Colourless equant grains as inclusions in biotite. Faint radioactive halos with brown colour occur.
Magnetite:	Anhedral and subhedral square grains in groundmass, 0.1-0.2 mm.
Ilmenite:	Appear as large anhedral crystals positioned in the center of titanite megacrysts, up to 10 mm in diameter. Brown-grey anisotropy. Contains inclusions of unknown Mn-rich mineral.
Pyrite:	Very fine grains of anhedral pyrite. Pale yellow colour with high reflectance.

Sample number: 62





Rock type: Foot wall
Two large titanite veins with inclusions of amphibole and epidote run through the thin section. The titanite have inclusions of magnetite and ilmenite. Groundmass of alkali feldspar and albite, amphibole and magnetite.

Minerals:		
	Feldspar	25-35%
	Amphibole	10-20%
	Epidote	1-5%
	Titanite	15-25%
	Magnetite	10-20%
	Ilmenite	5-10%

Feldspar: Feldspar grains in groundmass with varying size and irregular shape. Lath-like shape is common. Some polysynthetic twinning. Seems to be exposed to alteration. Eds analysis indicate an even mixture of albite and alkali feldspar. Subhedral phenocrysts with cross-hatched twinning and polysynthetic twinning.

Amphibole: Pale green bladed and fibrous grains in groundmass and larger megacrysts, up to 1.1 mm in diameter.

Epidote: Yellow epidote as granular aggregates and subhedral octahedral grains. Present as inclusions in titanite and amphibole. Often positioned along rims of titanite.

Titanite: Subhedral elongated rhomb-shaped grains that are broken up and fractured. Other grains are anhedral. Two large veins of anhedral titanite, up to 30 mm in width, run through the thin section.

Magnetite: Subhedral cubical grains in groundmass

Ilmenite: Inclusions in magnetite, displaying grey to grey-blue polarization colours.

WDS-data

Table 9. Allanite group minerals – Weight percentages of chemical elements.
* Ferri-allanite.
** Possible REE-bearing epidote.

Chemical element/ Sample no.	*37.02**	*37.03*	*37.07**	*39.01**	*39.02*
F	0	0.0526	0.1028	0	0
Na_2O	0	0	0	0	0
SiO_2	28.15	29.47	28.44	28.53	31.1
Al_2O_3	6.08	11.19	6.07	6.3	13.87
MgO	0.9602	0.2955	1.0025	1.0843	0.4658
K2O	0.0261	0.0195	0	0	0.0068
Cl	0	0.0001	0.005	0.0063	0
CaO	9.75	11.2	9.62	9.97	13.14
BaO	1.73	0.2809	1.79	0.0201	0
TiO_2	0	0.0427	0	2.17	0.1705
NiO	0.0303	0	0	0	0
FeO	22.95	18.19	22.04	22.04	15.37
MnO	0.2057	0.4868	0.1779	0.1031	0.2782
Cr_2O_3	0.0355	0.0023	0.0179	0	0
V_2O_3	0	0	0	0	0
Total	69.9179	71.2305	69.2661	70.224	74.4013

Chemical element/ Sample no.	*54.04***	*54.05***	*54.06***	*54.07***
F	0	0	0.0544	0
Na_2O	0	0.022	0	0.0118
SiO_2	35.43	36.27	28.54	28.51
Al_2O_3	20.17	20.78	0	0
MgO	0.0709	0.0874	0.3006	0.3312
K2O	0.1011	0.1075	0.0242	0.0125
Cl	0.0233	0.0018	0.0047	0.0166
CaO	20.81	20.91	8.17	8.36
BaO	0.0604	0.0353	0	0.0407
TiO_2	0.0136	0.0239	0.0087	0
NiO	0	0	0	0
FeO	12.89	12.93	6.76	6.79
MnO	0.4293	0.3468	0.1594	0.1863
Cr_2O_3	0	0	0.0189	0.0047
V_2O_3	0.0437	0.0026	0	0
Total	90.0423	91.5174	44.041	44.2639

Table 10. Amphibole/Actinolite – Weight percentages of chemical elements.
* Low total due to unknown error, possibly irregular mineral surface.

Chemical element/ Sample no.	*35.02**	*35.05*	*35.06*	*37.04*	*37.051*	*37.052*
F	0.2398	na	na	0.843	0.8211	0.9542
Na_2O	0.4128	1.141	0.376	0.4887	0.5262	1.316
SiO_2	50.49	50.790	53.270	56.34	56.38	53.98
Al_2O_3	0.6182	0.454	0.844	0.1911	0.2036	1.1551
MgO	16.83	12.690	17.290	19.74	20.41	17.31
K_2O	0.0586	0.027	0.092	0.2131	0.2001	0.6124
Cl	0.0166	na	na	0	0.0017	0.0167
CaO	10.69	22.230	12.840	12.29	12.27	10.98
TiO_2	0	0.091	0.012	0	0.0155	0.1037
SO_3	0.021	na	na	0.0614	0.0509	0.0629
NiO	0	0.000	0.000	0.0083	0.0166	0.0062
FeO	7.59	9.390	9.830	6.22	6.29	10.46
MnO	0.2877	0.410	0.268	0.2322	0.2531	0.2121
Cr_2O_3	0.0193	0.000	0.010	0	0.0024	0.031
V_2O_3	0.0156	0.049	0.016	0.0314	0.055	0.0155
Total	87.2897	97.271	94.849	96.6593	97.4963	97.216

Chemical element/ Sample no.	*39.03*	*39.04*	*58.01*
F	0.1346	0.44	0.473
Na_2O	0.3801	1.1108	1.5
SiO_2	55.19	54.03	53.92
Al_2O_3	0.9859	1.0978	2.04
MgO	18.06	17.3	17.79
K_2O	0.0711	0.502	0.5438
Cl	0	0.0098	0.0207
CaO	12.16	10.48	10.75
TiO_2	0	0.0681	0.1319
SO_3	0.0087	0.0279	0.014
NiO	0.0434	0	0
FeO	9.4	10.37	9.94
MnO	0.1682	0.1743	0.2296
Cr_2O_3	0	0.0047	0.036
V_2O_3	0.0336	0	0.0182
Total	96.6356	95.6154	97.4072

Table 11. Biotite – Weight percentages of chemical elements.

Chemical element/ Sample no.	*40.01*	*40.02*	*54.01*	*54.02*
F	2.98	1.6	0	0
Na_2O	0.0432	0.0571	0.0519	0.0659
SiO_2	41.45	41.28	38.33	38.37
Al_2O_3	11.06	10.87	13.88	13.51
MgO	23.78	22.82	13.91	13.94
K_2O	9.74	9.18	9.91	9.92
Cl	0.0403	0.0577	0.1756	0.1756
CaO	0.0108	0.0266	0.0535	0.0325
BaO	0.0741	0.0926	0.0363	0.1634
TiO2	0.7155	0.7348	1.3417	1.3674
NiO	0.0144	0.0577	0	0
FeO	5.58	6.79	16.76	16.74
MnO	0.0248	0.1244	0.2424	0.2544
Cr_2O_3	0.0144	0.0384	0.0441	0.0163
V_2O_3	0	0	0.0682	0.0076
Total	95.5276	93.7294	94.8038	94.563

Table 12. Carbonate – Weight percentages of chemical elements.

Chemical element/ Sample no.	*40.031*	*40.032*	*40.08*
MgO	0.039	0.231	16.419
CaO	52.794	52.049	28.994
BaO	0	0.013	0
FeO	0.207	0.084	1.471
MnO	1.128	1.301	2.122
CO_2	42.3	41.961	42.897
Total	96.468	95.639	91.903

Table 13. Chlorite – Weight percentages of chemical elements.
* Possible chlorite-calcite mix.

Chemical element/ Sample no.	*40.021*	*40.022*	*40.023**	*40.07*
F	0.3711	0.0637	0.1585	0.2463
Na_2O	0	0.0166	0	0.0161
SiO_2	34.13	32.71	25.51	31.53
Al_2O_3	12.25	13.69	8.59	11.42
MgO	32.26	32.02	22.31	28.86
K_2O	0.3655	0.0492	0.0657	0.073
Cl	0	0.0114	0.0049	0.0141
CaO	0.0268	0.004	14.08	5
BaO	0	0.0345	0	0
TiO_2	0	0.025	0	0.0123
NiO	0.1059	0.0332	0.0166	0.077
FeO	3.98	4.48	3.25	5.22
MnO	0.0479	0.0812	0.3735	0.1942
Cr_2O_3	0.0024	0.0216	0.0073	0
V_2O_3	0.039	0.0596	0.0236	0.0234
Total	83.5786	83.3	74.3901	82.687

Table 14. Clinopyroxene – Weight percentages of chemical elements.
* Low total due to unknown errors.

Chemical element/ Sample no.	*35.01**	*35.05*	*35.06*	*35.11*	*35.12*
Na_2O	0.3566	1.1406	0.3756	0.4088	1.44
SiO_2	48.49	50.79	53.27	53.7	50.06
Al_2O_3	1.0311	0.454	0.8442	0.894	0.4272
MgO	16.49	12.69	17.29	17.59	11.3
K_2O	0.063	0.0269	0.0921	0.0899	0.002
CaO	10.84	22.23	12.84	12.87	21.39
TiO_2	0.023	0.091	0.0124	0.0119	0.159
NiO	0.0106	0	0	0	0.089
FeO	7.71	9.39	9.83	9.98	12.31
MnO	0.1959	0.4097	0.2681	0.2608	0.4158
Cr_2O_3	0.0049	0	0.0098	0	0
V_2O_3	0.0027	0.0489	0.0162	0.0135	0.0378
Total	85.2179	97.2712	94.8485	95.819	97.6308

Table 15. Feldspar – Weight percentages of chemical elements.
* Low total due to unknown errors.

Chemical element/ Sample no.	*35.04**	*35.07*	*35.08*	*35.09*	*35.1*	*43.01*	*43.02*
Na_2O	10.9	10.98	11.22	0.2439	0.2462	0.2564	11.16
SiO_2	63.78	69.11	68.81	64.42	63.73	65.06	68.38
Al_2O_3	17.78	18.87	19.11	17.78	17.68	18.04	18.85
MgO	0.0026	0	0	0.0125	0.008	0	0
K_2O	0.0736	0.0494	0.0925	16.3	15.89	16.76	0.0506
CaO	0.1316	0.2726	0.0823	0	0.03	0	0.1772
BaO	0	0.0362	0	0.1459	0.7617	0.2213	0.0582
TiO_2	0.0027	0	0	0	0.0202	0	0
FeO	0.0078	0.1067	0.0218	0	0.376	0.0491	0.0934
MnO	0	0.0043	0.0171	0.0298	0.017	0.0426	0.0599
Total	92.6783	99.4292	99.3537	98.932	98.7592	100.429	98.8293

Chemical element/ Sample no.	*45.01*	*45.02*	*62.01*	*62.02*
Na_2O	11.12	11.08	11.17	0.1682
SiO_2	68.41	68.67	68.83	65.15
Al_2O_3	18.85	18.98	19.13	17.87
MgO	0	0.0099	0.0174	0
K_2O	0.0495	0.0448	0.1656	16.65
CaO	0.1233	0.3528	0.2213	0
BaO	0.0181	0.0595	0	0.1575
TiO_2	0.0053	0	0	0
FeO	0.0513	0.0177	0.2412	0
MnO	0	0.0277	0	0
Total	98.6276	99.2425	99.7755	99.9958

Table 16. Iron-titanium oxide – Weight percentages of chemical elements.
* Low totals due to unknown errors.

Chemical element/ Sample no.	*40.041**	*40.042**	*40.05**	*40.06**	*54.1*
Na_2O	0	0	0	0.045	0.013
SiO_2	0.022	0.029	0.023	0.032	0.079
Al_2O_3	0.028	0.013	0.01	0.02	0.036
MgO	0	0.028	0.057	0.08	0.075
K_2O	0.019	0.008	0.02	0.005	0.007
P_2O_5	0	0.007	0.014	0.04	0
CaO	0.047	0.015	0.008	0.214	0.362
TiO_2	1.382	3.919	6.844	1.68	51.401
NiO	0.031	0	0	0.027	0.033
FeO	86.683	82.343	79.529	87.04	40.643
MnO	0.037	0	0.152	0.104	6.977
Cr_2O_3	0.014	0	0.009	0	0.013
V_2O_3	0.072	0.215	0.076	0.087	0.368
Total	88.335	86.577	86.742	89.374	100.007

Table 17. Quartz – Weight percentages of chemical elements.

Chemical element/ Sample no.	*38.01*
Na_2O	0.0291
SiO_2	100.75
Al_2O_3	0
MgO	0.0049
K_2O	0.014
CaO	0.0033
BaO	0
TiO_2	0
FeO	0.0174
MnO	0
Total	100.819

Table 18. Titanite – Weight percentages of chemical elements.
* Probably REE-bearing to some degree.
** Inferior analysis due to unknown error.

Chemical element/ Sample no.	*35.03***	*35.13**	*37.01**	*37.06**	*45.03**	*54.03*	*54.08*	*54.09*
Na_2O	0.0934	0.049	0.0785	0.061	0.031	0.010	0.023	0.048
SiO_2	25.92	28.7	28.32	28.68	28.83	29.85	29	29.24
Al_2O_3	0.4714	0.433	0.974	0.923	0.599	1.308	1.473	1.698
MgO	0.073	0.071	0.073	0.090	0.0194	0.0276	0.0222	0.0234
K_2O	0.0174	0.008	0.004	0.033	0.0038	0.0062	0.0247	0.0121
CaO	22.95	27.61	26.93	27.22	28.53	29.15	29.6	29.09
TiO_2	30.15	37.02	34.67	35.55	37.72	38.74	38.77	38.32
NiO	0.004	0	0	0	0	0	0.0082	0
FeO	1.93	2.32	3.36	2.98	1.97	0.8828	0.9702	0.8183
MnO	0.0334	0.074	0.0167	0.054	0.0125	0.1256	0.0335	0.0816
Cr_2O_3	0.0049	0	0	0.055	0	0.0548	0	0
V_2O_3	0.2333	0.203	0.2301	0.344	0.3396	0.4064	0.3609	0.3849
Total	81.881	96.487	94.655	95.99	98.056	100.561	100.286	99.7155

Table 19. Amphibole recalculation and classification spreadsheet.
http://www.open.ac.uk/earth-research/tindle/AGT/AGT_Home_2010/Microprobe-2.html

Sample number	*35.02*	*35.05*	*35.06*	*37.04*	*37.051*	*37.052*	*39.03*
SiO_2	50.49	50.79	53.27	56.34	56.38	53.98	55.19
TiO_2	0	0.091	0.0124	0	0.0155	0.1037	0
Al_2O_3	0.6182	0.454	0.8442	0.1911	0.2036	1.1551	0.9859
FeO	7.59	9.39	9.83	6.22	6.29	10.46	9.4
MnO	0.2877	0.4097	0.2681	0.2322	0.2531	0.2121	0.1682
MgO	16.83	12.69	17.29	19.74	20.41	17.31	18.06
CaO	10.69	22.23	12.84	12.29	12.27	10.98	12.16
Na_2O	0.4128	1.1406	0.3756	0.4887	0.5262	1.316	0.3801
K_2O	0.0586	0.0269	0.0921	0.2131	0.2001	0.6124	0.0711
BaO							
SrO							
PbO							
ZnO							
F	0.2398			0.843	0.8211	0.9542	0.1346
Cl	0.0166			0	0.0017	0.0167	0
Cr_2O_3	0.0193	0	0.0098	0	0.0024	0.031	0
NiO	0	0	0	0.0083	0.0166	0.0062	0.0434
Reformatted oxide %			0.00	0.00	0.00	0.00	0.00
	35.02	35.05	35.06	37.04	37.051	37.052	39.03
SiO_2	50.49	50.79	53.27	56.34	56.38	53.98	55.19
TiO_2	0.00	0.09	0.01	0.00	0.02	0.10	0.00
$Al2O_3$	0.62	0.45	0.84	0.19	0.20	1.16	0.99
Cr_2O_3	0.02	0.00	0.01	0.00	0.00	0.03	0.00
Fe_2O_3	2.73	0.00	0.32	0.20	2.38	3.16	2.73
FeO	5.13	9.39	9.54	6.04	4.15	7.62	6.94

MnO	0.29	0.41	0.27	0.23	0.25	0.21	0.17
MgO	16.83	12.69	17.29	19.74	20.41	17.31	18.06
NiO	0.00	0.00	0.00	0.01	0.02	0.01	0.04
ZnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	10.69	22.23	12.84	12.29	12.27	10.98	12.16
Na_2O	0.41	1.14	0.38	0.49	0.53	1.32	0.38
K_2O	0.06	0.03	0.09	0.21	0.20	0.61	0.07
BaO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
SrO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PbO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
F	0.24	0.00	0.00	0.84	0.82	0.95	0.13
Cl	0.02	0.00	0.00	0.00	0.00	0.02	0.00
*H_2O**	1.79	2.02	2.04	1.71	1.74	1.62	2.04
	89.32	99.24	96.91	98.30	99.37	99.08	98.91
O=F,Cl	0.10	0.00	0.00	0.35	0.35	0.41	0.06
Total	89.22	99.24	96.91	97.94	99.03	98.67	98.85
No. of oxygens	23	23	23	23	23	23	23
Structural formulae							
Si	7.916	7.557	7.825	8.014	7.920	7.781	7.857
Al iv	0.084	0.080	0.146	0.000	0.034	0.196	0.143
Al vi	0.030	0.000	0.000	0.032	0.000	0.000	0.023
Ti	0.000	0.010	0.001	0.000	0.002	0.011	0.000
Cr	0.002	0.000	0.001	0.000	0.000	0.004	0.000
Fe^{3+}	0.322	0.000	0.035	0.022	0.251	0.343	0.293
Fe^{2+}	0.673	1.168	1.172	0.718	0.488	0.918	0.826
Mn	0.038	0.052	0.033	0.028	0.030	0.026	0.020
Mg	3.934	2.815	3.786	4.186	4.274	3.720	3.833
Ni	0.000	0.000	0.000	0.001	0.002	0.001	0.005
Zn	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Li (not implemented)*	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	1.796	3.544	2.021	1.873	1.847	1.696	1.855
Na	0.125	0.329	0.107	0.135	0.143	0.368	0.105
K	0.012	0.005	0.017	0.039	0.036	0.113	0.013
Ba	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Sr	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pb	0.000	0.000	0.000	0.000	0.000	0.000	0.000
F	0.119	0.000	0.000	0.379	0.365	0.435	0.061
Cl	0.004	0.000	0.000	0.000	0.000	0.004	0.000
*OH**	1.877	2.000	2.000	1.621	1.635	1.561	1.939
Total	16.933	17.560	17.145	17.046	17.026	17.176	16.973
Calculation scheme	∑13	∑13	∑13	∑13	∑13	∑13	∑13
Amphibole group	Ca	Ca	Ca	Ca	Ca	Ca	Ca
(Ca+Na) (B)	1.921	3.544	2.021	2.000	1.990	2.000	1.960
Na (B)	0.125	0.000	0.000	0.127	0.143	0.304	0.105
(Na+K) (A)	0.012	0.334	0.124	0.046	0.036	0.176	0.013
Mg/(Mg+Fe2)	0.854	0.707	0.764	0.854	0.898	0.802	0.823
$Fe^3/(Fe^3+Alvi)$	0.914	0.000	1.000	0.403	1.000	1.000	0.928

Sum of S2	13.000	11.682	13.000	13.000	13.000	13.000	13.000
Amphibole names	actinolite	actinolite	actinolite	actinolite	actinolite	actinolite	actinolite

S. ACADEM

ATIAE

RITAS