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Protolith of a kyanite-bearing, quartz-rich rock in Hålsjöberg, western Sweden

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Abstract

Hålsjöberg, situated 20 km northeast of Torsby in eastern Sweden, hosts several bodies of a rare kyanite-bearing quartz-rich rock with Al-phosphates and what appears to be sedimentary structures. Several interpretations of the Hålsjöberg kyanite-rich rocks have been made, each one slightly different from the other. Despite the many attempts to discern the origins of the kyanite-bearing rocks at Hålsjöberg, its mode of formation remains unclear. Currently, the most commonly presented hypothesis is a two-stage evolution of acid leaching or hydrothermal alteration, possibly in a hot spring or epithermal volcanic environment, followed by amphibolite facies metamorphism. While this hypothesis holds fast to close scrutiny in some aspects, it fails to explain the structures of apparent sedimentary origin found in the kyanite-bearing rocks

Some authors suggest that the protolith must have been a granitoid, based on chemistry and field observations, while other authors advocate a sedimentary origin, mainly based on field observations. In an attempt to choose between these hypotheses, fieldwork was conducted during the summer and autumn of 2016. Samples were collected for chemical and petrographic analysis, and structures of possible sedimentary origin in the outcrops were documented with photographs and field sketches. A comparison of major and minor element concentrations of the kyanite rock with representative examples of various possible protoliths suggests that the protolith probably had a pelitic composition. Some authors also suggest that there was only a single protolith of granitoid composition for all rock units close to and including the kyanite rock. This is not supported by the data acquired during this master's thesis; multiple protoliths of varied chemistry is a more plausible explanation. The mineralogy and major and minor element chemistry suggest that the gneissose granite falls under the S-category, i.e. is derived either from a subduction environment or a supracrustal sedimentary environment. The possible sedimentary structures found include graded bedding, cross-bedding, scour-and-fill structures, and flaser bedding, of which the most compelling structures for a sedimentary origin are the latter three. There are other structures as well that are most likely sedimentary but that can form in igneous or metamorphic environments as well, and while they are not conclusive on their own, in combination with the more compelling structures they present a strong case for a sedimentary origin.

Sammanfattning

Hålsjöberg, beläget 20 km nordöst om Torsby i östra Sverige, uppvisar ett flertal hållar av en ovanlig kyanitförande och kvartsrik bergart med aluminiumfosfater och vad som tycks vara sedimentära strukturer. Ett flertal tolkningar kring den kyanitförande bergarten i Hålsjöberg har gjorts, och var och en skiljer sig något från varandra. Trots många försök att utreda ursprunget till den kyanitförande bergarten i Hålsjöberg är det fortfarande oklart. Den i dagsläget mest godtagna hypotesen är en tvåstegsmodell där hydrotermal alteration eller urlakning i ett epitermalt vulkaniskt område eller kring en varmvattenkälla har följts av metamorfos vid amfibolitfacies. Denna hypotes har än så länge inte motbevisats, men den förklarar inte de strukturer som återfinns i den kyanitförande bergarten.

Ett antal forskare anser att den kyanitförande bergarten har sitt ursprung i en granit med argument baserade på kemiska analys och fältobservationer. Andra forskare föreslår ett sedimentärt ursprung, huvudsakligen baserat på fältobservationer. I ett försök att välja mellan dessa två hypoteser utfördes fältarbete i Hålsjöberg sommaren och hösten 2016. Prover togs för kemisk och petrografisk analys och strukturer av möjligt sedimentärt ursprung dokumenterades med fotografier och fältskisser. En jämförelse mellan den kyanitförande bergartens kemi med representativa exempel på olika protoliter antyder att en lersten är den mest troliga protoliten. Vissa forskare anser också att den kyanitförande bergarten och närbelägna bergarter har en och samma protolit, en granit. Kemisk data insamlad under detta arbete talar emot detta, och föreslår istället att de olika bergarterna har olika protoliter. Mineralogin och kemin för graniter som påträffas i området indikerar att de är av S-typen enligt SIAM-klassificeringen, vilket innebär att de bildats i subduktionsområden eller sedimentära områden. De sedimentära strukturerna som hittades inkluderar sorterade bäddar, korslagradebäddar, erosionsstrukturer och flaserbäddar. De mest övertygande strukturerna är de tre sistnämnda. Andra strukturer med ett troligt sedimentärt ursprung men som även kan bildas i magmatiska miljöer återfinns också i området. Trots att de på egen hand inte kan avgöra om den kyanitförande bergarten är sedimentär så kan de i samband med de mer tydliga sedimentära strukturerna bidra till en starkare uppfattning om den kyanitförande bergartens ursprung.

Introduction

Hålsjöberg, situated 20 km NE of Torsby in eastern Sweden, hosts several bodies of a rare kyanite-bearing quartz-rich rock with Al-phosphates, distinct banding and what appears to be sedimentary structures. It has been the topic of several papers during the last 160 years, including Igelström (1854), Geijer (1963), Andréasson and Stanfors (1988), Ek and Nysten (1990), Rodhe and Andréasson (1992), Lundegårdh (1995), Andréasson and Dallmeyer (1995), and Larsson (2001). The reason for this long-lived interest in these kyanite-rich rocks found at Hålsjöberg, as well as in three other localities in Sweden; Diksberg, Hökensås and Västana, is their ambiguous origin. Several interpretations of the Hålsjöberg kyanite-rich rocks have been made, each one slightly different from the other. Geijer (1963) suggested that the kyanite-bearing rock was linked to the tectonic evolution of the Protogine Zone; a tectonic zone that follows the boundary between the Sveconorwegian province in the west, and the Svecofennian province and the Transscandinavian Igneous Belt in the east (Andréasson and Dallmeyer, 1995). The Protogine Zone (PZ) has been intruded by magmas of mafic, granitic and syenitic composition (Andréasson and Dallmeyer, 1995). According to Geijer (1963), phosphoric acid derived from magmatic fluids related to the PZ could have interacted with the protolith rock, likely a sedimentary quartzite of some sorts, and formed the Al-phosphates observed in the Hålsjöberg rocks. Geijer (1963) thus attempted to explain the paragenesis with phosphorous and also titanium being added from magmatic fluids. Andréasson and Stanfors (1988) suggested that kyanite formed as a result of hydrolysis, with fluids that originated along fractures during the opening of Lake Vättern to the southeast. Later, Rodhe and Andréasson (1992) observed a gradual transition between the kyanite-bearing rock and a nearby granite at Hålsjöberg, and at Hökensås a transition between granite and a quartzite that had initially been assumed by the authors to be of sedimentary origin, with many similarities to the kyanite-bearing rock at Hålsjöberg. They thus concluded that the kyanite-bearing quartz-rich rock at Hålsjöberg might be granitoid in origin. Lundegårdh (1995) interpreted the structures in the kyanite-bearing rock as primary sedimentary structures. Larsson (2001) further suggested that these structures might be stratified turbidite deposits or stratified ash flows. Ek and Nysten (1990) also interpreted the kyanite-bearing rocks to be sedimentary in origin, but suggested that hydrothermal alteration first affected the rock without destroying the sedimentary structures, followed by metamorphism that formed the kyanite. Larsson (2001) explained the kyanite-bearing rocks as being the result of an initial stage of acid leaching, facilitated by magmatic fluids, which resulted in chemical zonation of a granitoid protolith. This chemical zonation altered a section of the protolith into high-alumina rocks, which were later metamorphosed to form kyanite.

Though the kyanite rock at Hålsjöberg and the three other localities in Sweden cannot be found anywhere else there are a few analogues in other parts of the world, for instance Haile Mine, South Carolina, and Champion Mine, California. For the Haile Mine locality, Spence et al. (1980) suggested a similar chain of events to Larsson (2001) with a hot spring environment where the protolith was altered into a silica- and clay-rich residual rock due to reaction with acidic water, followed by metamorphism. Wise and Loh (1976) interpreted the Champion Mine locality in a similar fashion, with hydrothermal alteration of a muscovite-albite-quartz-schist due to interaction with acidic fluids from a nearby granitoid intrusion. Ek and Nysten (1990) suggested that the

Småland-Värmland granite intrusion might have had a similar effect on the Hålsjöberg kyanite-bearing rocks.

Despite the many attempts to discern the origins of the kyanite-bearing rocks at Hålsjöberg, its mode of formation remains unclear. Currently, the most commonly presented hypothesis is a two-stage evolution of leaching or alteration followed by metamorphism. While this hypothesis holds fast to close scrutiny in some aspects, it does not attempt to determine the protolith nor explain the structures of apparent sedimentary origin found in the kyanite-bearing rocks thoroughly enough, and it does not explain the effects that other local rock units found at Hålsjöberg might have had on the formation of the kyanite-bearing rock. This master's thesis will attempt to explain this, with the primary goal being to answer whether or not the protolith of the kyanite-bearing rocks at Hålsjöberg was sedimentary or igneous.

Previous research and findings

In order to not impose a sedimentary origin on the kyanite-bearing rock, the genetic term "quartzite" will not be used. Instead, the kyanite-bearing rock will be referred to as simply the "kyanite rock" or the "kyanite-bearing rock".

The Swedish government-owned company LKAB Prospektering AB, a phalanx of the LKAB concern mined the Hålsjöberg area during the 1980's. The element of interest was aluminium from the kyanite rock. Several reports from this period are publicly available and shed some light on the area. According to surveys done by LKAB, and published in the reports, the main body of kyanite rock is located in Hålsjöberg (Bida, 1983). Two smaller bodies were found roughly 1-2 km to the east and to the west of Hålsjöberg, in Kårebol and Nordtorpsättern (Bida, 1983). The kyanite rock was described as "a metamorphic, kyanite-bearing quartzite belonging to the supracrustal bedrock series within the Värmland gneissose granite area" (Bida, 1983). "The kyanite quartzite can be described as layered, homogenous and with small variations in chemical and mineralogical composition, with the presence of layers of mica" (Bida, 1983).

Surveys of the neighbouring rock units led to the hypothesis that they were of metasedimentary and metavolcanic origin, mainly dacites and mica schists, and that they were likely part of the same bedrock formation as the kyanite rock (Bida, 1983). Lundegårdh (1995) confirmed this mineralogy but expanded on the dacites as being feldspar-porphyrysts of dacitic composition. In general, gneissose granites are prevalent in the area, though in Hålsjöberg they are not dominant (Larsson, 2001). A common rock type in the area is a local species of mafic rock that can be described as fine- to medium grained gabbro, called hyperite, or hyperite diabase. The hyperite is the youngest in the area, and appears as dikes and irregular discordant bodies (Bida, 1983).

Lundegårdh (1980) observed that metagreywacke with graded bedding borders conformably with the kyanite rock northeast of Torsby, and that based on the grading of the metagreywacke the kyanite rock was deposited on top of the metagreywacke. Lundegårdh (1980) also proposed that aluminium from the greywacke might be the source of the Al needed for the formation of the kyanite in the kyanite rock, and that rutile (containing Ti) and the Al-phosphates found in the kyanite rock are likely metasomatic from the metagreywacke as well. The fluids that facilitated the transfer of

elements might have been derived from the magmatic intrusions that formed the local hyperite.

The area has been metamorphosed to amphibolite facies, as first observed by Sjögren (1877) by the alteration of hyperite to amphibolite, and based on the presence of hornblende, feldspar, garnet, mica and quartz. This was later reinforced by Ek and Nysten (1990) by the occurrence of kyanite, staurolite, garnet, chlorite and muscovite. Peak metamorphism was estimated to pressures of more than 2 kbar and temperatures of between 520°C and 575°C, according to Ek and Nysten (1990). The upper limit was determined by the lack of biotite-kyanite intergrowths, and no staurolite breakdown, which occurs at 575°C. Amphibolite facies metamorphism can be inferred and supported through other observations as well. The Al-phosphate scorzalite has been observed in Hålsjöberg, which has a stability field that correlates with the estimated temperatures of metamorphism (Ek and Nysten, 1990).

Larsson (2001) used the alumina-to-alkali ratio to determine if the kyanite rock was the product of hydrothermal alteration that affected a granitoid protolith, or if some other origin of the protolith could be inferred. As Al is less mobile than alkalis, a high-alumina rock such as the kyanite rock should thus have a ratio that reflects this. According to Larsson (2001), Al has been depleted in the rocks surrounding the kyanite rock, and the ratio increases towards and into the kyanite rock itself, indicating higher concentrations of alumina. To determine if mass loss during alteration might have contributed to this, Larsson (2001) measured the concentrations of immobile elements and found that the kyanite rock samples had experienced a 30-40% mass loss, although most of it appeared to be silica and only minor amounts of alumina. Larsson (2001) also states that there is very little evidence for silica being added from external sources, which would be needed to explain the quartzitic nature of the kyanite rocks, as quartz veins are rare. The quartzitic nature is, according to Larsson (2001), the result of extensive acid leaching, which left only silica, aluminium and immobile elements.

The two-stage model is supported by the presence of sulphides in the kyanite rock, which suggests that the hydrothermal fluids contained sulphur. However, sulphuric acid only forms at temperatures below 400°C, which is too low for amphibolite facies metamorphism. Also, the area lacks pegmatities, which form at pressures exceeding 2 kbar, while pressures below 2 kbar promotes fracturing that in turn cause separation of magmatic fluids from crystallized magma; which goes well in hand with the hydrothermal alteration hypothesis. Larsson (2001) suggested a shallow, epithermal and/or volcanic environment as the cause of the hydrothermal alteration and acid leaching of the granitoid protolith, followed by a regional metamorphic event at amphibolite facies.

While Larsson (2001) presented strong case for the granitoid origin of the kyanite rock, the banding and alternating kyanite and Al-phosphate layers in the kyanite rock does present some difficulties. The close relationship between the kyanite and the Al-phosphates indicate that both formed at the same time and by the same mechanism (Ek and Nysten, 1990). The Al-phosphates found at Hålsjöberg include scorzalite (Ek and Nysten, 1990), svanbergite and woodhouseite (Larsson, 2001). The two latter ones are isostructural with alunite (Wise, 1975), which in turn is a good indicator for advanced

argillic alteration, and is usually present in epithermal hydrothermal deposits (Larsson, 2001). Larsson (2001) does not explain how the banding was formed.

This is the fundamental and yet unanswered question at Hålsjöberg, which this master's thesis aims to answer: if the protolith of the kyanite rock was sedimentary or igneous. Some authors, including Larsson (2001) and Rodhe and Andréasson (1992) suggested that the protolith must have been a granitoid, based on chemistry and field observations, while other authors, such as Geijer (1967), Lundegårdh (1980) and Ek and Nysten (1990) advocated a sedimentary origin, mainly based on field observations. While Larsson (2001) presented a strong empirical case in favour of an igneous protolith, the structures observed in the kyanite rock does have a distinctly sedimentary appearance that make geologists revisit this peculiar place time and time again.

Methods

Fieldwork

Fieldwork was conducted during the summer and autumn of 2016. It involved a total of three weeks of fieldwork. A preliminary reconnaissance of the area was conducted during June 2016 with supervision by professor Alasdair Skelton and Dan Zetterberg as well as a student with previous experience from the area, Carola Lindström. During this preliminary reconnaissance a number of areas of interest were identified, including the quarry, and the preliminary outlines of the fieldwork were set.

Initially, the area was thoroughly surveyed and as much data as possible was gathered since the area was unfamiliar and in order to confirm observations from the previous research done on the area. Firstly, the areas of interest found during the preliminary reconnaissance of the area in June 2016 were investigated and structural measurements were collected from these areas. Signs of sedimentary structures were documented, as were the different geological units, their spatial coordinates and their relationship and contacts to each other. A large portion of the time in the field was spent in a quarry (fig. 1), from which a lot of information could be gathered. Special focus was also given to freshly cut surfaces or surfaces that had been polished by LKAB allowing for good observations to be made.

Secondly, attempts were made to map the geology of the entire study area and to find contacts or transitions between different geological units. First, Google Earth and topographical maps were used to find clearings, hilltops and other features in the terrain that could be the site of an outcrop. These were marked on a map and investigated. Following this the area was investigated further for more outcrops that did not show on the maps. During this time samples were also collected, both from the quarry and outcrops outside the quarry. Some of these localities had already been sampled by Lindström (2015) and since these samples were available for use in this master's thesis, additional samples were not taken from these localities.

Finally, the geology immediately surrounding the study area was investigated, odd structural measurements were verified, more structural measurements were taken to gather a statistically viable database, and samples were collected from any new outcrops found.

Sample preparation

The samples collected during fieldwork were cut to expose a fresh surface. They were then cut into $\sim 3 \times 1.5 \times 1.5$ cm blocks, exposing the B-side of the rock, i.e. the foliation, were ground on one side with 220-grit SiC, dried at 40°C overnight and then glued using epoxy onto glass slides. Once the epoxy had dried, the blocks were cut down to ~ 1 mm in thickness and then ground down to ~ 0.5 mm, both using a Buehler Petro-Thin thin sectioning system. They were then ground down to proper thin section thickness using a Logitech grinding and polishing system in a number of stages, going from 600 through 1200 μm SiC, and were then polished with 3 μm diamond polish in propanediol.

Samples that contained aluminium phosphates as well as other samples that were brittle were impregnated in epoxy under vacuum and then prepared according to the above method. Aluminium phosphates absorb water and will change volume, and the brittle samples will be unevenly undercut and thus not make good thin sections; both problems can be solved by impregnation with epoxy.

Samples for XRF analysis were ground down to a clay-size powder with a Retsch RS200 vibratory disc mill. Of the ground powder, 5 grams was weighed and put in ceramic cups in an oven and then heated to 105°C for ~10 hours to remove free water in the samples. The samples were then heated to 1000°C for roughly 10 hours to determine bound water and loss on ignition. Following this, the baked sample powder was ground with a mortar and pestle and 2 grams of sample was mixed with 5 grams of flux (lithiumtetraborate and lithiummetaborate). Both measurements had an error allowance of ± 0.0002 grams. The mixture was put in platinum cups and stirred, and then put into a Phoenix VFD 4000 by XRF Scientific to be made into glass discs. The Phoenix VFD 4000 heats the samples to 1100°C while swirling them before pouring them into pre-heated platinum plates. The samples were then cooled quickly enough to form a homogenous glass disc but slowly enough for the discs not to fracture. The discs were mounted in the XRF, a ZSX Primus II by Rigaku, and analysed. Three standards were used and were analysed every five samples.

One of the thin sections made from the rocks in the fault zone at Hålsjöberg, which contained garnets, biotite, amphibole, plagioclase and epidote was coated with carbon and taken to an FE-EMPA electron microprobe model JXA-8530F Jeol Superprobe in Uppsala for analysis. These data were then used for geothermometry using the computer program THERMOCALC by Powell and Holland (1994). THERMOCALC uses thermodynamic datasets to calculate the equilibria for multiple mineral solid solution series to find the P-T where all of these equilibria stability fields overlap. By using multiple solid solution series, the inherent uncertainties of the thermodynamic data can be minimized and a more reliable P-T can be obtained.

Results

Outcrop map

Fig. 1 is the outcrop map produced from the fieldwork. Though there are more than three rock units, due to simplicity, relevance and their small size all rock units apart from metadacite and the kyanite rock has been compiled into a single unit.

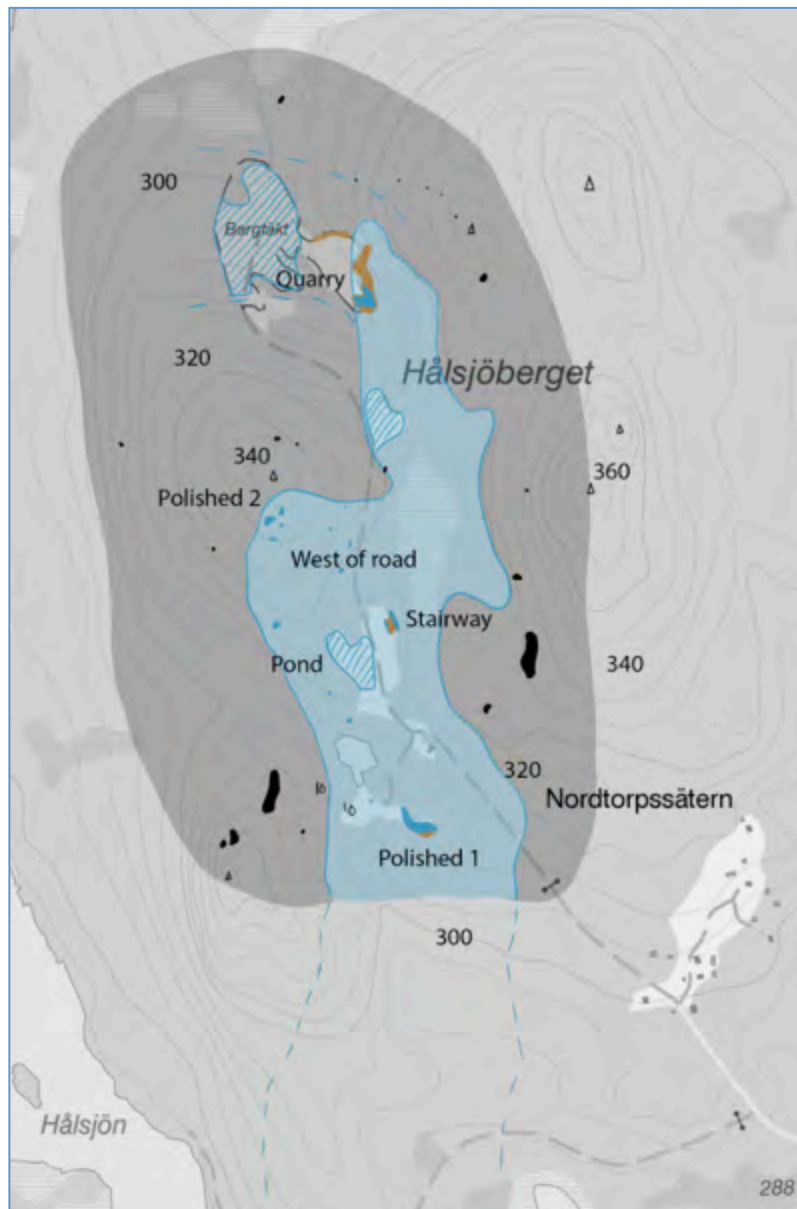


Figure 1: Outcrop map of the study area. Metadacite outcrops are in solid black and extrapolated metadacite is in transparent black. Kyanite rock outcrops is in solid blue and extrapolated kyanite rock is in transparent blue. Outcrops of other rock units are in solid brown, and though not marked on the map can tentatively be assumed to continue as a winding narrow string going through the centre of the kyanite rock area.

Altitude is marked every 5 metres. Data has not been extrapolated outside the boundaries of the study area, though the southward continuation of the kyanite rock unit has been tentatively marked on the map.

Locale naming is based on the following:
Quarry – At a quarry area with plenty of exposed outcrops.
Polished 1 – An area with outcrops polished by LKAB during prospecting.
Polished 2 – Ditto.
Pond – A large pond used for dumping waste rock, with relatively fresh cliffs around it.
Stairway – Another polished outcrop area, reminiscent in shape of a stairway.
West of Road – A number of isolated outcrops west of the road.

A number of cross sections were made to better constrain the geometry of the kyanite rock. They are presented in figure 2.

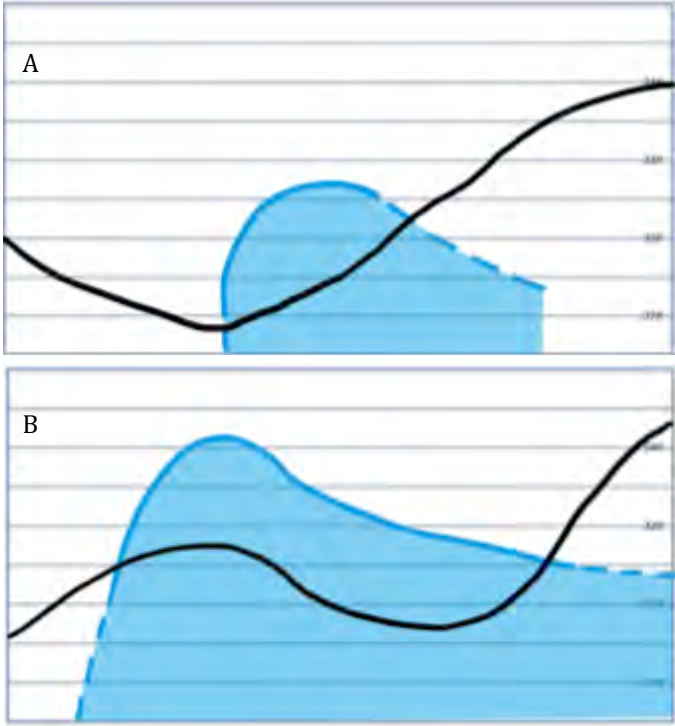


Figure 2: Cross sections A and B. Topography outlined by the black line. Kyanite rock geometry outlined by solid blue line. The dashed blue line indicates extrapolated geometry. Elevation is in meters above sea level.

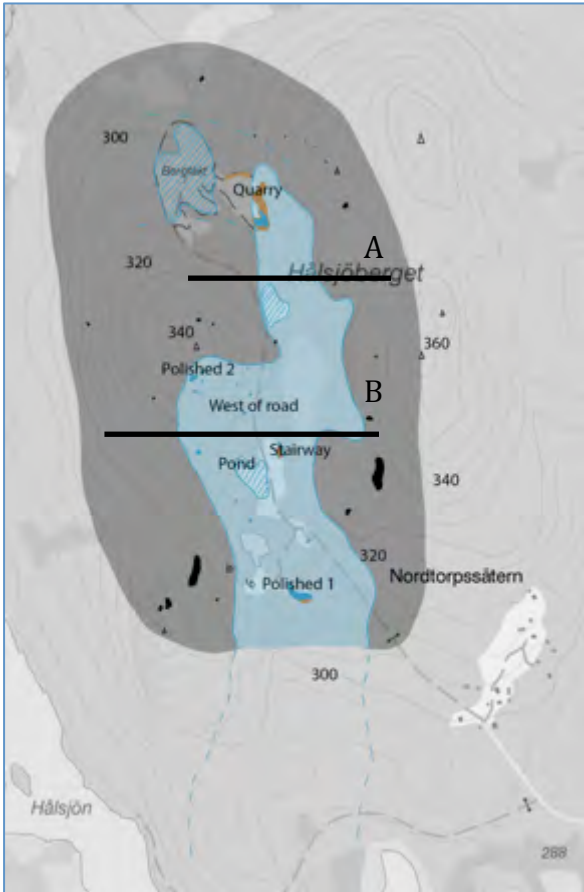


Figure 3: The location of the cross sections shown in fig. 2.

Lithological description

The kyanite rock is rather fine-grained with alternating bands of blue, pink and white. The blue bands are the dominant ones, and contain more kyanite than the other two. Dark-blue Al-phosphates are found in tight clusters throughout the kyanite rock, and are aligned with the banding. A detailed petrographic analysis can be found under the “Thin sections” chapter.

The metadacite has a dark and fine-grained matrix with large clusters of small green and black minerals, presumably amphibole and/or pyroxene. No distinct foliation is visible and there are no signs of bedding or layered. A detailed petrographic analysis can be found under the “Thin sections” chapter.

The other rock units, which for simplicities sake have been compiled into a single unit on the outcrop map (fig. 1) include, from east to west: feldspar porphyry, gneissose granite, garnet-bearing amphibolite, mica schist, mylonite, another unit of gneissose granite, and another unit of mylonite.

The feldspar porphyry has a dark matrix of biotite and possibly muscovite, and contains large clasts of plagioclase. Remains of garnets might be present as yellow specks of rust. It is strongly foliated and appears to be layered. Petrographic analysis reveals that the sample contains mainly K-feldspar, quartz and biotite, but also muscovite, chlorite and epidote. Granoblastic textures can be found and the muscovite indicates the foliation.

The gneissose granite contains large K-feldspar clasts together with quartz that are enveloped by layers of biotite and muscovite. It is foliated and possibly layered as well. Petrographic analysis reveals that the dominant minerals are K-feldspar, quartz and biotite but the sample also contains plagioclase, muscovite, biotite and possibly epidote. The feldspar makes up the majority of the sample, with muscovite and biotite indicating the foliation.

The garnet-bearing amphibolite has a dark matrix of biotite and muscovite with larger clasts of plagioclase. Garnets are present in larger amounts, and of varying hues of red. It is strongly foliated, and also appears to be layered. Petrographic analysis reveals that quartz and amphibole are the two dominant minerals in this sample, with moderate amounts of plagioclase, garnet and biotite present, as well as some minor amounts of epidote. The sample is in general rather fine-grained but the garnets are larger and mostly euhedral to subhedral. Amphibole and biotite indicates the foliation.

The mica schist predominantly contains muscovite and probably quartz and is very brittle. Petrographic analysis reveals that the sample contains quartz and muscovite in larger amounts but also plagioclase and K-feldspar. The sample is banded with some bands composed predominantly of muscovite and others of feldspars. The muscovite indicate the foliation.

The mylonite consists of larger deformed clasts of plagioclase or possibly quartz enveloped by thin layers of biotite, muscovite and a deep red mineral that might possibly be K-feldspar. The entire sample is strongly deformed with wavy foliation. Petrographic analysis reveals that quartz, muscovite and feldspar are the dominant

minerals with minor amounts of garnet and epidote. The foliation is again indicated by muscovite.

The second gneissose granite is similar to the first with large K-feldspar clasts, quartz, muscovite and biotite. The biotite and muscovite form layers that envelope the K-feldspar clasts. The sample is foliated and appears to be layered as well. Petrographic analysis reveals that quartz, plagioclase, K-feldspar, and muscovite are the principal minerals of this sample, with small amounts of biotite present as well. The majority of the sample consists of quartz, plagioclase and K-feldspar, with muscovite indicating the foliation.

Photographs

Structures in the kyanite rock outcrops of possible sedimentary origin were documented with photographs and field sketches. The most compelling ones include cross-bedding, scour-and-fill structures, graded bedding and flaser bedding. Images S1 to S14 show some examples of the structures found.



Image S1: Structures in outcrops, of possible sedimentary origin. Very clear cross-bedding relationship between the green and red beds. The cross-bedding is likely trough cross-bedding, as the contact between the foreset and bottomset laminae is curved and the laminae have a tangential relationship to the contact.

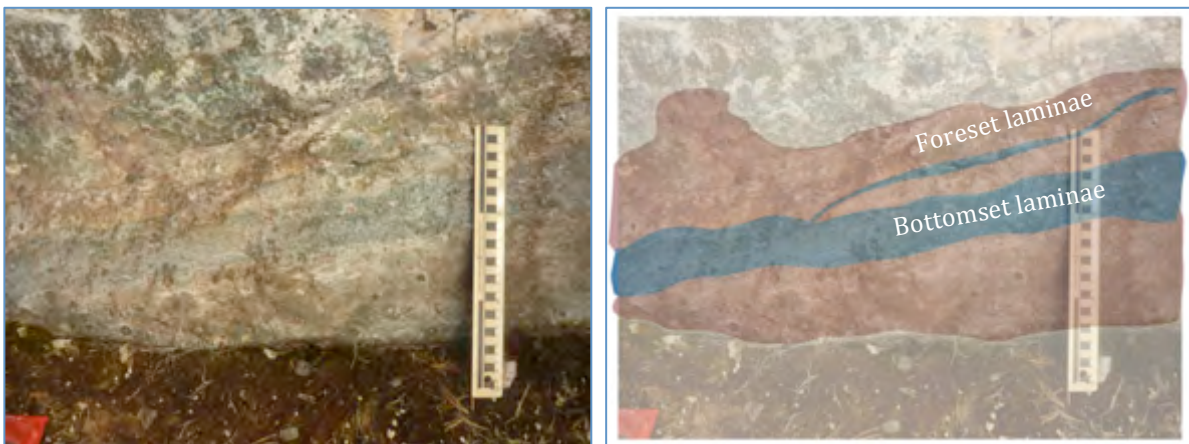


Image S2: Structures in outcrops, of possible sedimentary origin. Possibly cross-bedding, where the foreset laminae meets the bottomset laminae at an angle.

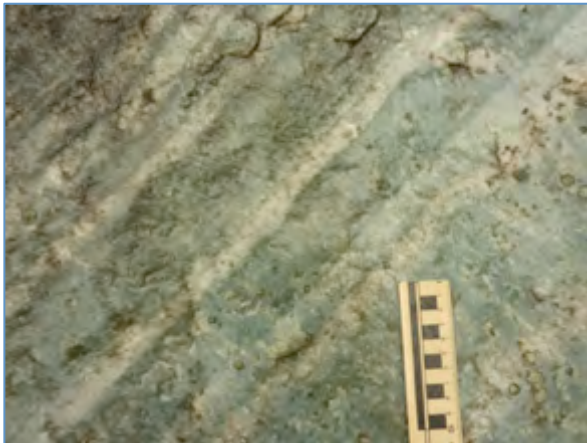


Image S3: Structures in outcrops, of possible sedimentary origin. Repeating graded beds with a coarser grain size transitioning into a finer grain size in each blue layer. The orientation of the beds would suggest reverse grading, but the beds might be tilted and the distinction between normal and reverse grading cannot be made.

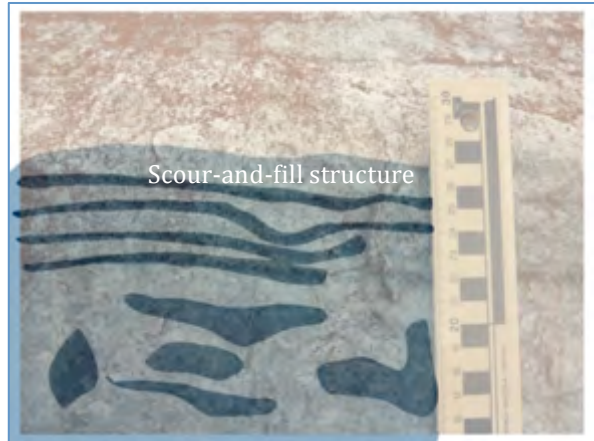
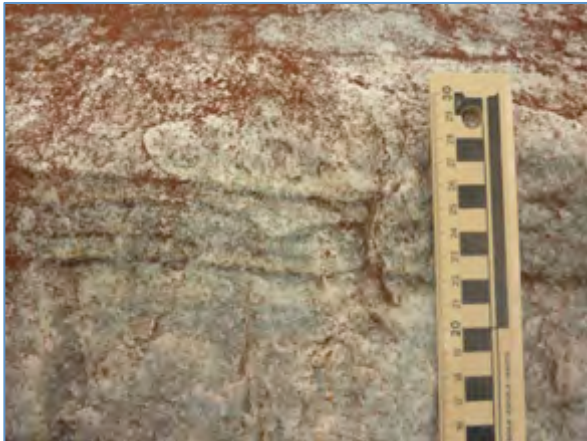


Image S4: Structures in outcrops, of possible sedimentary origin. Scour-and-fill structure clearly defined against the thin dark blue beds directly above and below it.

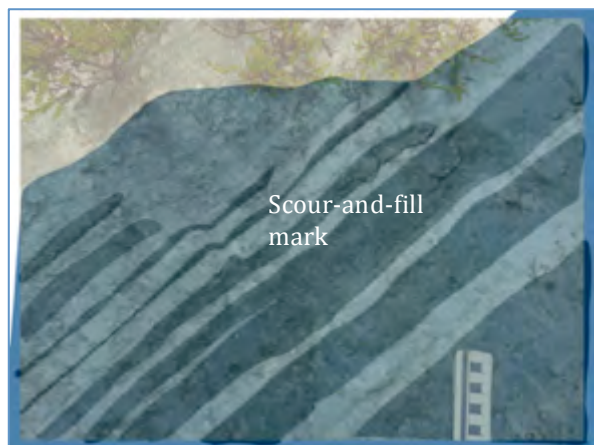
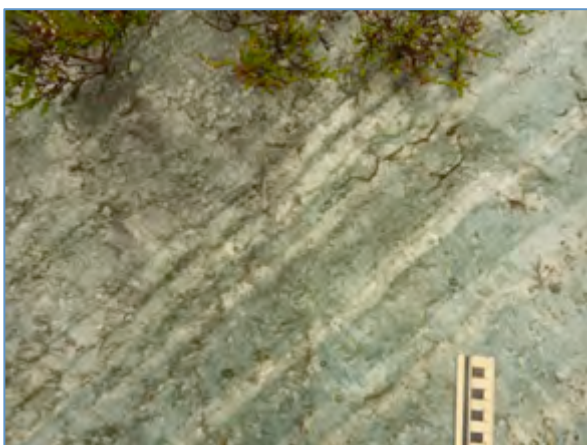


Image S5: Structures in outcrops, of possible sedimentary origin. Possible scour-and-fill structure found to the left of the label. A brush- or prod mark is an alternative to a scour-and-fill structure.



Image S6: Structures in outcrops, of possible sedimentary origin. Possibly cross-bedding.

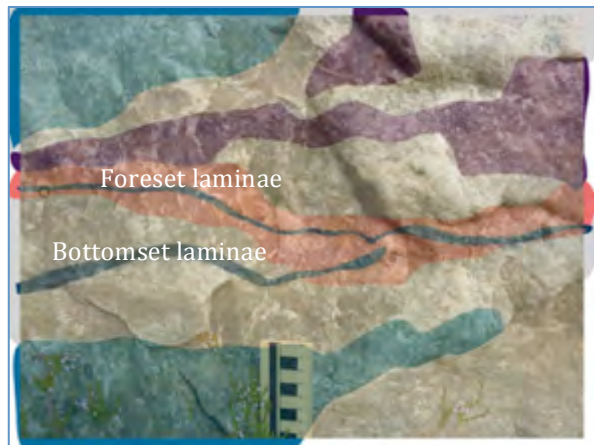


Image S7: Structures in outcrops, of possible sedimentary origin. Possibly cross-bedding.



Image S8: Structures in outcrops, of possible sedimentary origin. Multiple rock units in contact with each other, all exhibiting bedding.



Image S9: Structures in outcrops, of possible sedimentary origin. K-feldspar clasts (shown in red) in gneiss, all aligned in the same direction to indicate foliation. The foliation appears to be more or less parallel to the contacts and the bedding of nearby rock units.

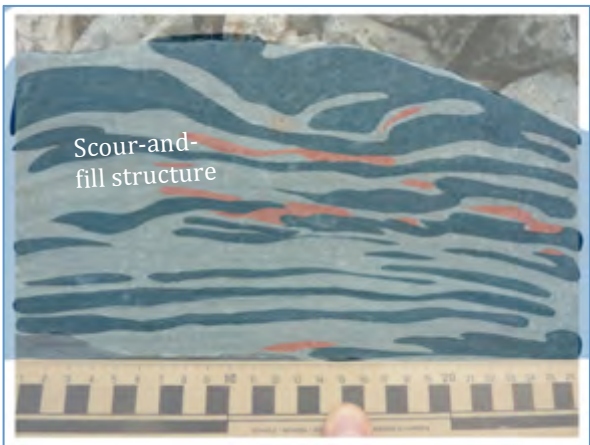


Image S10: Structures in outcrops, of possible sedimentary origin. Possibly flaser bedding or even lenticular bedding. The dark blue layers are presumably more mud-rich than the light blue layers as they are more alumina-rich. Some scour-and-fill structures are also possibly present; the most distinct one can be found below the label.

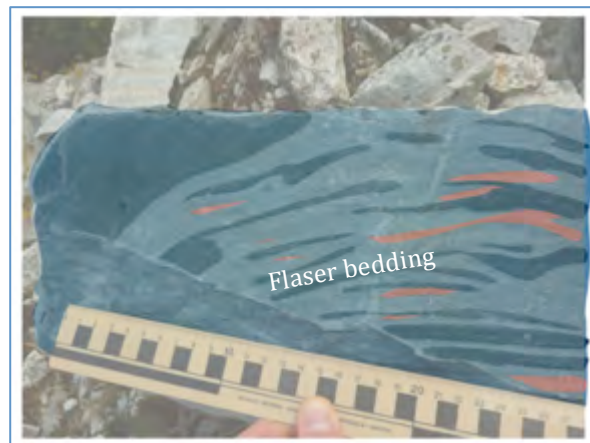
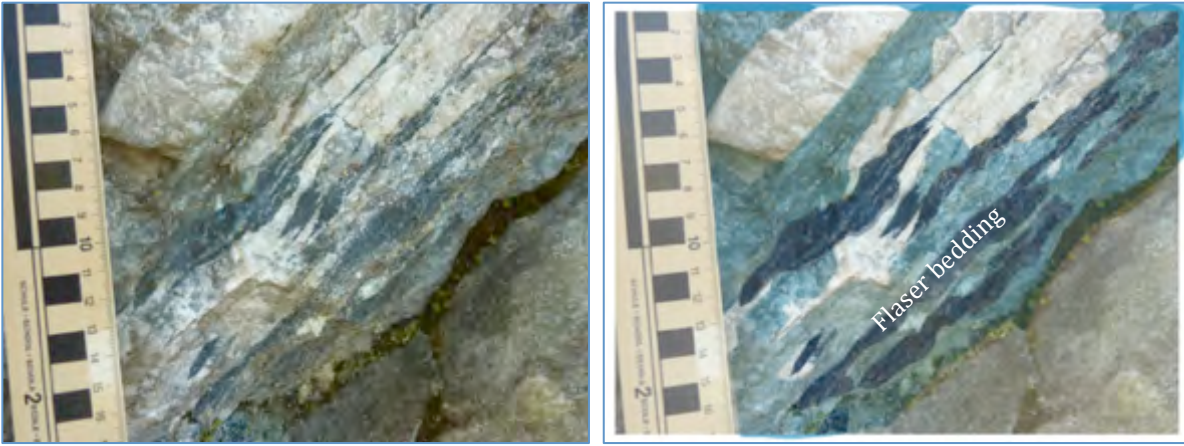
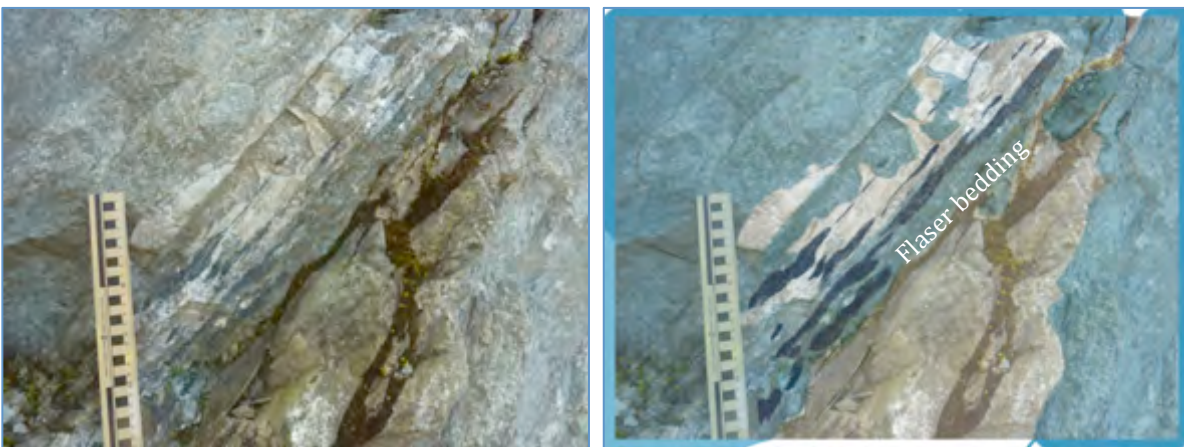


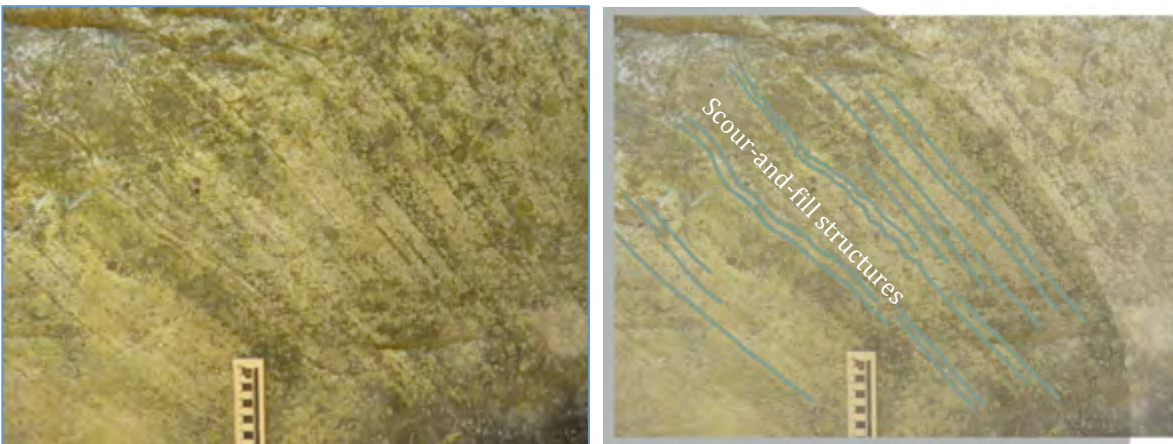
Image S11: Structures in outcrops, of possible sedimentary origin. Possibly flaser bedding.



*Image S12: Structures in outcrops, of possible sedimentary origin.
Possibly flaser bedding or lenticular bedding of Al-phosphate in the kyanite rock.*



*Image S13: Structures in outcrops, of possible sedimentary origin.
Possibly flaser bedding or lenticular bedding of Al-phosphate in the kyanite rock.*



*Image S14: Structures in outcrops, of possible sedimentary origin.
Scour-and-fill structures or alternatively roll- or skip-marks.*

Structural measurements

Structural measurements were collected from all over the study area. The outcrops found in the quarry exhibit layering very reminiscent of bedding. The layering can be found in most of the rock units, and the orientation of the layering is uniform across all the units. The layering is also parallel to the contacts between the rock units. Furthermore, multiple rock units in the quarry exhibit foliation, which appears to be parallel to the layering and the contacts (for instance image S9). Finally, the kyanite rock features alternating bands of blue, red and white. These bands are also more or less parallel to the layering and contacts. This suggests that the layering is indeed bedding. Outside the quarry it could not be verified that the banding of the kyanite was still parallel to the bedding and contacts, so it was assumed to be.

The structural measurements were taken on the bedding and contacts between the rock units, as well as on the banding. Foliation appeared to be very similar to the bedding, but could not be determined accurately and was thus not measured. Fig. 4a and 4b show stereonet plots of the bedding, banding and contacts from all over the study area, and the poles to bedding, respectively.

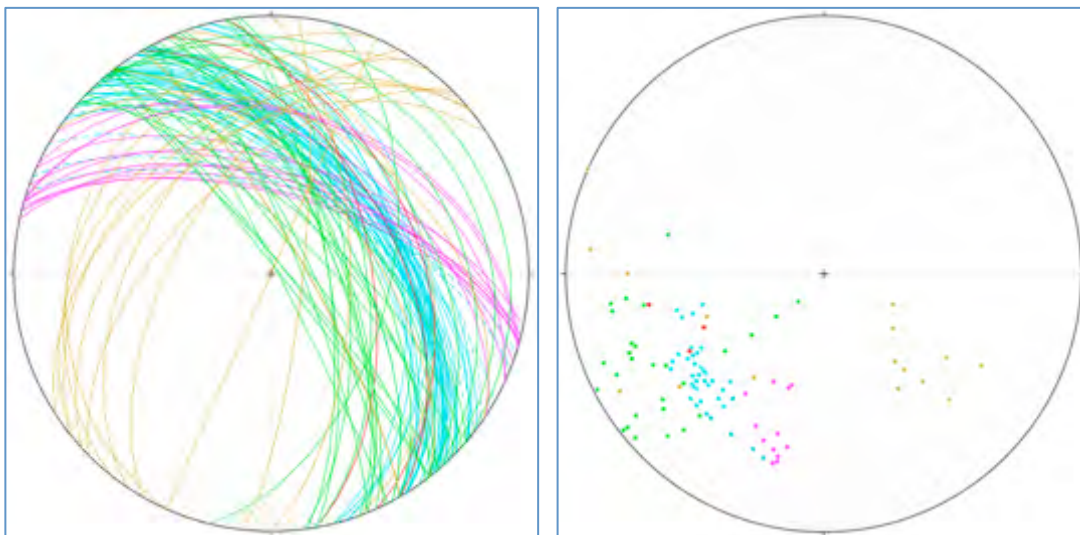


Figure 4a and 4b: Stereonet plots of bedding, bands and contacts of outcrops found throughout the study area (4a). Stereonet plot of poles to bedding for said outcrops (4b). Quarry 1 is in turquoise, Quarry 2 in dashed turquoise, Polished 1 in purple, Pond in red, Stairway in green, West of Road and Polished 2 in yellow.

Thin sections

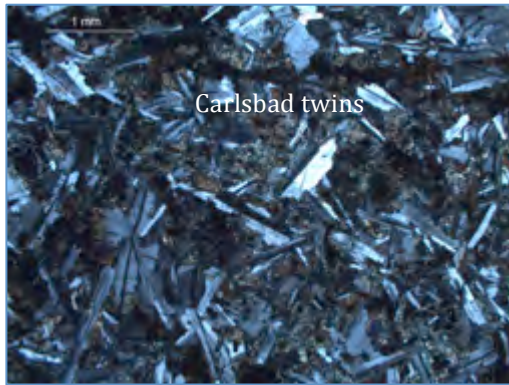
Thin sections from more than thirty samples were described, and the full descriptions can be found in the appendices. A summary of the most important findings is presented below.

Most of the samples around the periphery of the study area contain feldspars, muscovite and biotite, pyroxene, possibly amphibole, and sometimes also chlorite and epidote. They were classified as metadacites based on this mineralogy, as well as based on previous studies such as (Bida, 1983; Lundegårdh, 1980). Composite point counting data from multiple metadacite samples are shown in table 1.

Sample ID	3s1	3s3	3s4	3s7	3s9
<i>Feldspar</i>	255	135	300	223	161
<i>Muscovite</i>	32	109	5	123	79
<i>Chlorite</i>	118	125	87	70	133
<i>Epidote</i>	8	2	53	0	0
<i>CPX</i>	25	21	3	13	2
<i>OPX</i>	23	18	0	6	0
<i>Garnet</i>	1	16	74	10	28
<i>Biotite</i>	20	55	20	40	79
<i>Ilmenite</i>	18	19	39	15	18

Table 1: Composite point counting data of multiple metadacite samples.

The feldspar varies in size and habit between the samples but is often medium to large, subhedral and can often be found interlocking each other. Both plagioclase and K-feldspar is present, in different amounts in different samples. The plagioclase exhibits both albite and Carlsbad twinning, again in various amounts. Both pericline and tartan twinning can be found in some of the K-feldspar crystals, though both types of twinning are rather rare, especially well-developed tartan twinning. Finally, muscovite and sericite is often found replacing the feldspar.



Carlsbad twins



Albite twinning

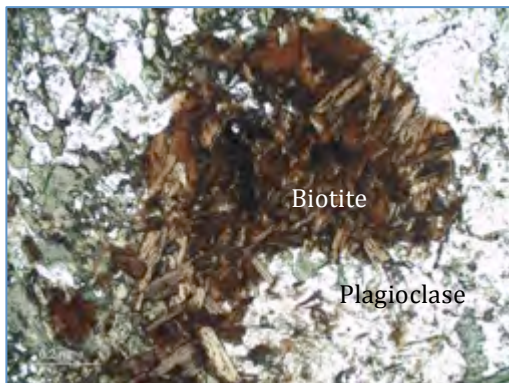


Pericline twinning



Tartan twinning

Image P2: Plagioclase and potassium feldspar. Upper left: Carlsbad twins. Upper right: albite twinning. Lower left: pericline twinning. Lower right: partially developed tartan twinning. Horizontal field of view for the upper left image is 5.6 mm. Horizontal field of view for the other three images is 1.4 mm.



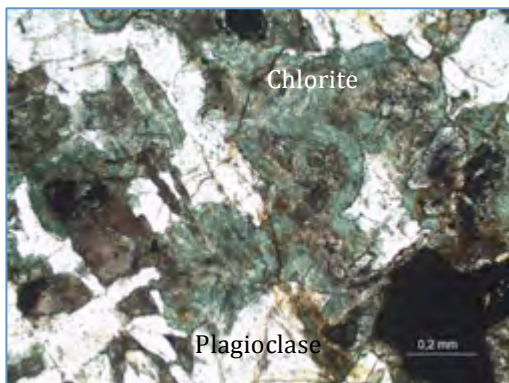
Biotite

Plagioclase



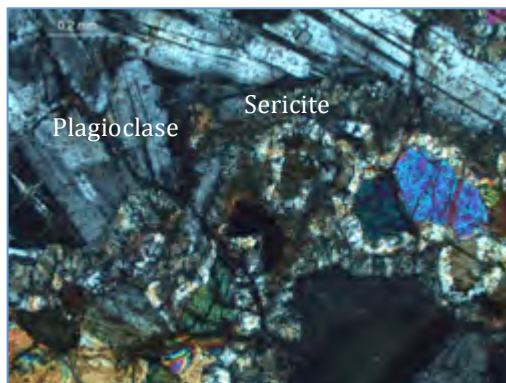
Plagioclase

Epidote



Chlorite

Plagioclase



Plagioclase

Sericite

Image P1: Typical mineralogy of the metadacite. Upper left: biotite. Upper right: epidote. Lower left: chlorite. Lower right: sericite. All surrounded by feldspar. Horizontal field of view for all images is 1.4 mm.

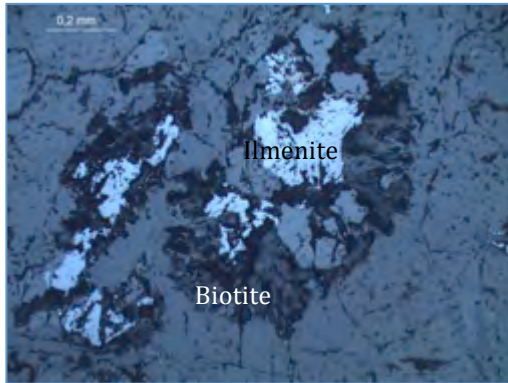
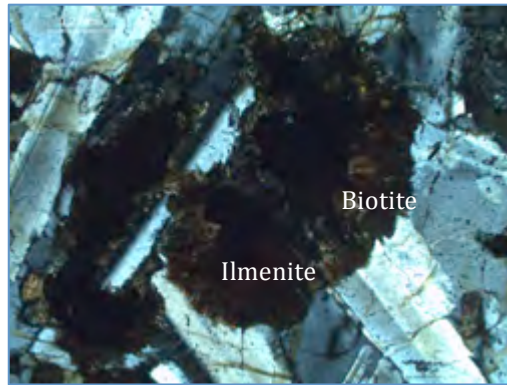
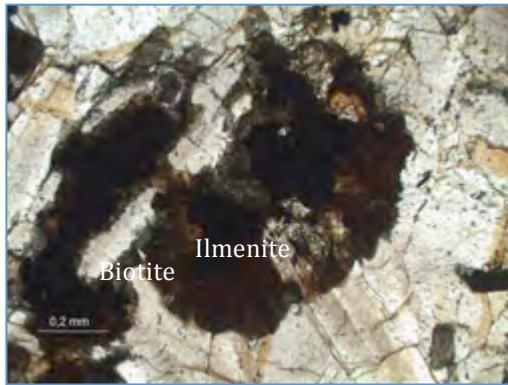


Image P3: Miscellaneous minerals in the metadacite. Upper left and right: biotite growing in radial fans around ilmenite, in plain polarized and cross-polarized light respectively. Lower left: ilmenite in the core of the biotite fan, viewed in reflected light. Horizontal field of view in all images is 1.4 mm.

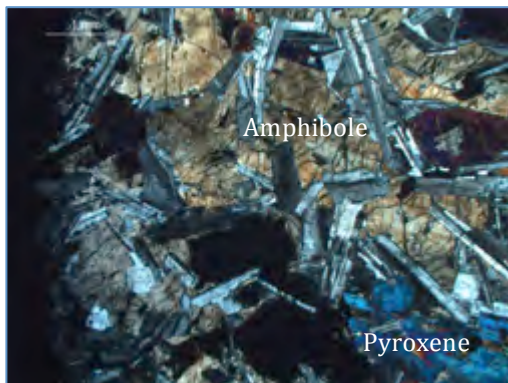
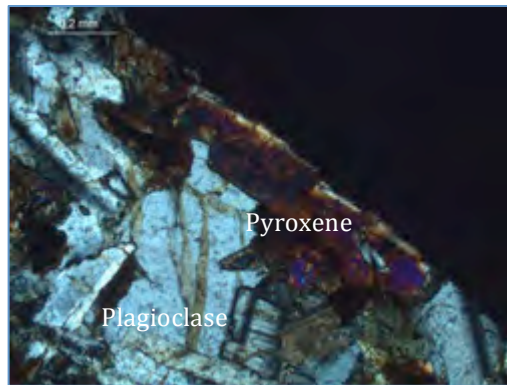
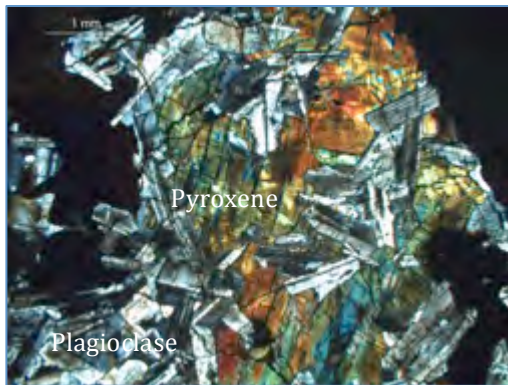


Image P4: Pyroxene and possibly amphibole in the metadacite. Upper left: large pyroxene crystal together with plagioclase. Upper right: smaller and more euhedral pyroxene crystal at edge of sample. Lower left: possibly amphibole crystal(s), with a pyroxene at the lower right edge. Horizontal field of view for the upper- and lower left images is 5.6 mm. Horizontal field of view for the upper right image is 1.4 mm.

Biotite is often present in smaller amounts, and is often found growing in radial fans outward from what appears to be ilmenite, indicating that it is replacing the ilmenite.

Pyroxene and possibly amphibole is also present in most of the samples. The size and habit of the grains vary quite dramatically; in some samples they are very large, euhedral and prominent while in others they are smaller and anhedral or even non-existent. The order of interference and the interference colours of the grains also appear to vary considerably, to the point where identification based on these properties proves difficult. Some grains that would appear to be amphiboles based on their interference colours and order of birefringence can prove to be pyroxenes, and vice versa.

Finally, epidote is present in some samples, and varies in habit and size. The pink colour under plain polarized light suggests that the mineral grain might be piemontite.

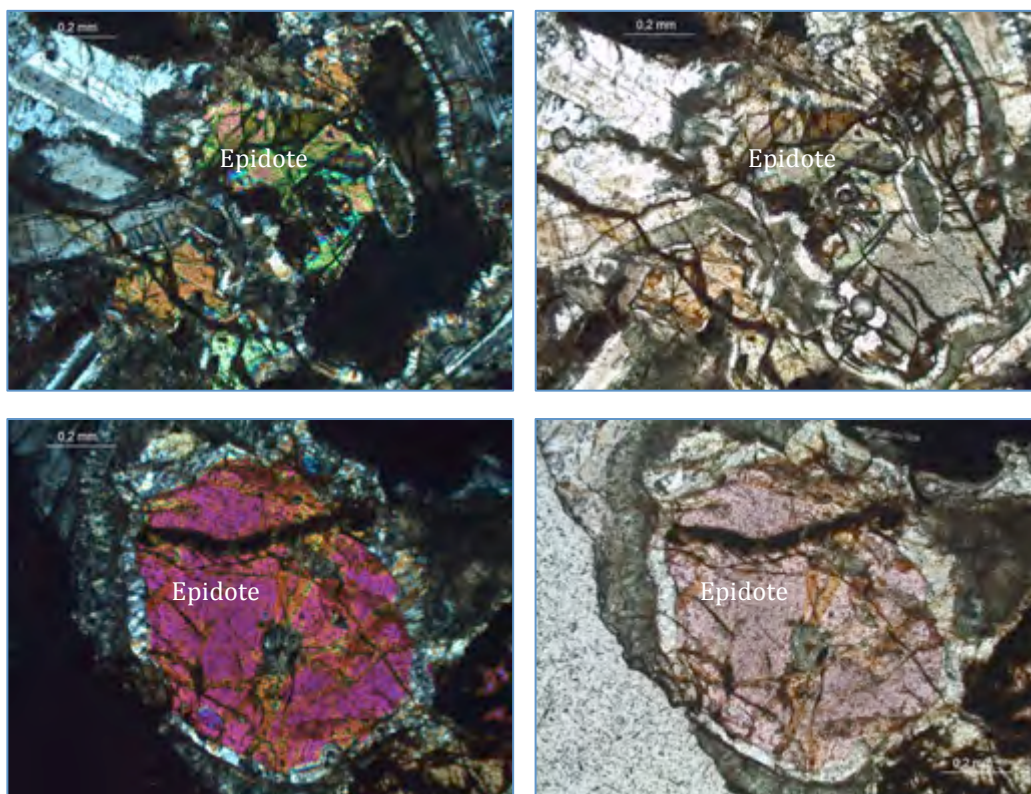


Image P5: Examples of epidote in the metadacite. The upper row shows the same grain in cross-polarized and plain polarized light, respectively. The lower row shows another grain, under the same lighting conditions. The grains are rimmed by chlorite and sericite. Horizontal field of view for all images is 1.4 mm.

The second important rock unit of the study area is the kyanite rock, which is dominated by quartz grains of varying size, habit and abundance. In sections with plenty of quartz crystals, granoblastic texture is common, indicating recrystallization. Kyanite crystals are also present, also of varying shape, habit and abundance. In many of the samples, the kyanite crystals show a preferred orientation and indicate the foliation, sometimes very well and sometimes rather poorly.

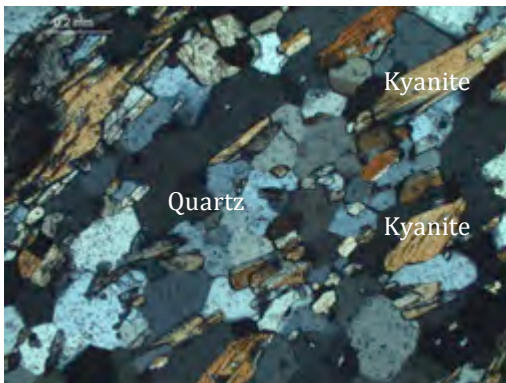
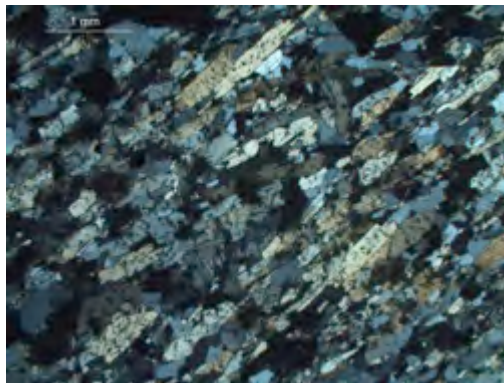
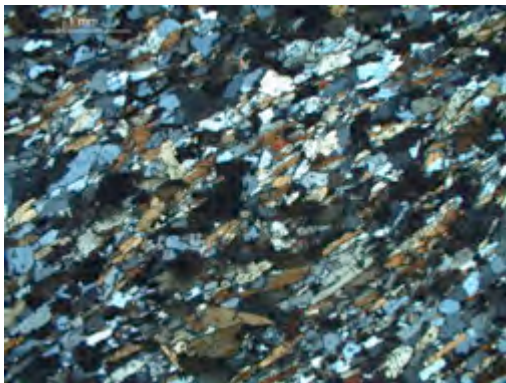


Image P6: Typical mineralogy of the kyanite rock. Upper left and right: examples of kyanite, of varying interference colours. Lower left: close-up of granoblastic texture. Horizontal field of view for the upper images is 5.6 mm. Horizontal field of view for the lower image is 1.4 mm.

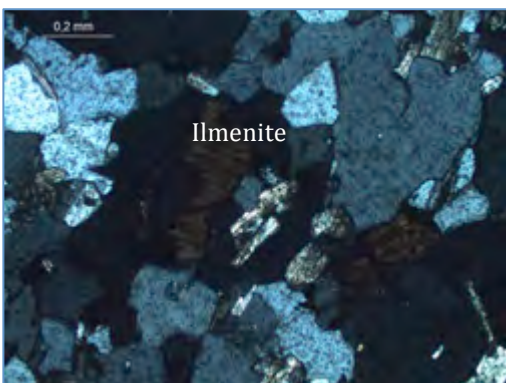
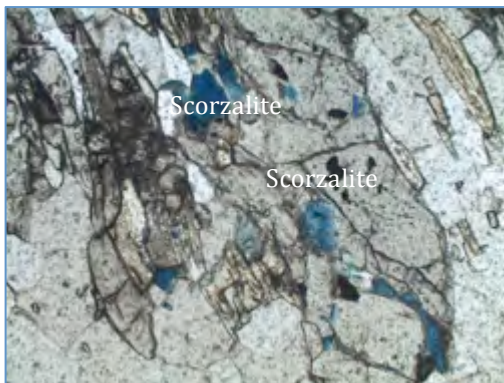
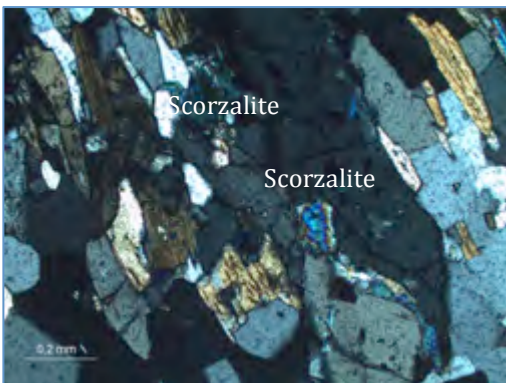


Image P7: Ilmenite and scorzalite (aluminium phosphate) in the kyanite rock. Upper row: scorzalite under cross-polarized and plain polarized light, respectively. Lower row: ilmenite under similar lightning conditions. Horizontal field of view for all images is 1.4 mm.

Garnets of varying size, habit and abundance are also present in some of the samples of the kyanite rock. Rutile, opaques and aluminium phosphates, presumably scorzalite, are also present in small amounts in some of the samples.

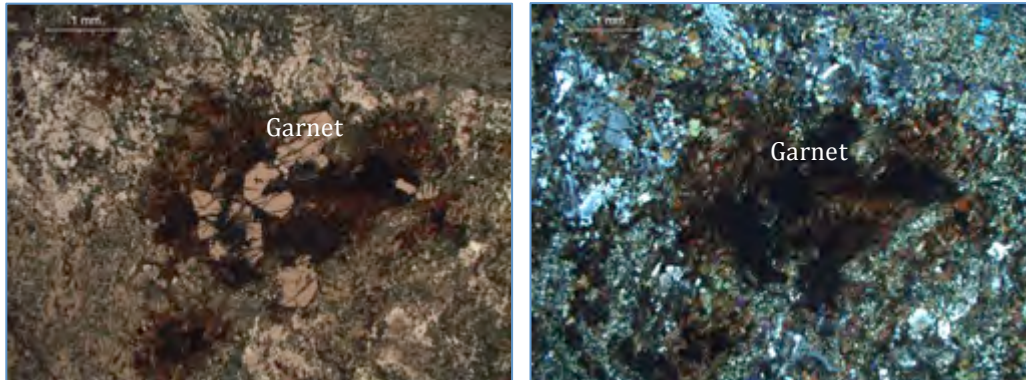


Image P8: Garnets in the kyanite rock. The left image is under cross-polarized light and the right images is under plain polarized light. Horizontal field of view for both images is 5.6 mm.

Major and minor element data

A transect of samples taken from the quarry was analysed with an XRF for major and minor element concentrations. For samples HBCL-5 and HBCL-17, both of which contains at least two markedly different layers or bands, each layer/band was analysed separately. Also, a representative sample of the metadacite was analysed, twice, due to the first sample contractively gaining weight during the LOI stage of the sample preparation. The results are presented in table 2.

		HBCL-1	HBCL-3	HBCL-4	HBCL-5 Ljus	HBCL-5 Moerk	HBCL-6	HBCL-7	HBCL-8	HBCL-9	HBCL-17 Roed	HBCL-17 Blaa	3s7	3s7b
		Feldspar porphyry	Gneissose granite	Amphibolite	Mica schist	Mica schist	Mylonite	Gneissose granite	Mylonite	Mylonite	Kyanite rock	Kyanite rock	Metadacite	Metadacite
SiO ₂	Mass%	61,80	66,05	58,86	73,13	82,91	70,39	50,38	65,61	85,36	88,34	63,48	48,97	48,96
Al ₂ O ₃	Mass%	17,18	17,39	19,07	15,69	5,70	17,44	42,78	19,01	10,16	10,31	35,06	15,09	15,09
CaO	Mass%	3,73	1,96	8,73	0,67	0,35	1,71	0,56	1,90	0,21	0,10	0,09	8,08	8,07
Na ₂ O	Mass%	3,78	3,89	3,20	0,61	0,04	3,18	0,43	6,24	0,03	0,00	0,00	2,60	2,62
K ₂ O	Mass%	3,54	6,01	0,36	4,42	2,11	3,26	2,56	2,08	0,55	0,06	0,05	1,34	1,33
CNK	Mass%	11,04	11,86	12,29	5,71	2,49	8,15	3,56	10,23	0,80	0,16	0,14	12,02	12,02
A/CNK	Ratio	1,56	1,47	1,55	2,75	2,29	2,14	12,03	1,86	12,77	64,01	254,08	1,26	1,25
MgO	Mass%	2,87	0,70	2,55	0,79	1,74	0,60	0,05	0,79	0,00	0,00	0,01	5,51	5,52
Fe ₂ O ₃	Mass%	6,22	3,30	5,94	4,00	5,74	2,81	2,56	3,69	3,19	1,13	1,23	15,97	15,97
MnO	Mass%	0,11	0,07	0,45	0,01	0,09	0,08	0,00	0,08	0,00	0,00	0,00	0,22	0,22
P ₂ O ₅	Mass%	0,14	0,05	0,15	0,15	0,09	0,03	0,20	0,04	0,08	0,00	0,02	0,22	0,22
TiO ₂	Mass%	0,64	0,59	0,69	0,52	1,25	0,49	0,48	0,56	0,41	0,06	0,06	2,01	2,01
		Feldspar porphyry	Gneissose granite	Amphibolite	Mica schist	Mica schist	Mylonite	Gneissose granite	Mylonite	Mylonite	Kyanite rock	Kyanite rock	Metadacite	Metadacite

Table 2: Major and minor element abundances in mass percent for 10 samples, of which three were analysed twice. The sample rock type is included with the sample name.

Chemistry comparison

Mass%	SiO ₂	Al ₂ O ₃	CaO	MgO	MnO	P ₂ O ₅	Fe ₂ O ₃ (total Fe)	Na ₂ O	K ₂ O	TiO ₂	Total	Author
<i>HBCL-17 Blaa</i>	88,341	10,305	0,1	0,004	0	0,003	1,131	0	0,061	0,055	100	
<i>HBCL-17 Roed</i>	63,482	35,063	0,087	0,012	0	0,018	1,227	0	0,051	0,061	100,001	
<i>Whiteschist</i>	48,967	38,0554	0,328	0,329	0	0,1338	0,8406	1,7442	7,66	1,9416	99,9996	<i>Lewerentz (personal communication)</i>
<i>Granitoid (S-type)</i>	70,9	14	1,9	1,2	0,1	0,2	3	2,5	4,1	0,4	98,3	<i>Chappell and White, 1992</i>
<i>Shale</i>	64,1	17,7	1,88	2,65	-	-	6,75	1,91	3,6	0,86	99,45	<i>Shaw, 1956</i>
<i>Sandstone</i>	81,95	8,41	1,89	1,39	0,05	0,12	3,08	1,07	1,71	0,49	100,16	<i>Bhatia, 1983</i>
<i>Sandstone</i>	78,66	4,78	5,52	1,17	-	0,08	1,38	0,45	1,32	0,25	93,61	<i>Clarke, 1924</i>

Table 3: Major and minor element comparison between the kyanite rock and a whistschist, a granitoid S-type, a shale and two sandstones. All of the data except for the kyanite rock data are composite data from various numbers of samples. All data is in mass%.

Analytical errors

Before and after the analysis as well as every five samples, three standards were analysed. The average values, expected values, residual and error of one of these standards, AGV-2, is presented in table 4. The error of the analysis lies within $\pm 4\%$.

	Average (mass%)	Expected (mass%)	Residual (mass%)	Error (percent)
SiO ₂	60,26	60,15	0,11	1,00
Al ₂ O ₃	17,13	17,15	-0,02	1,00
CaO	5,22	5,27	-0,05	0,99
MgO	1,78	1,82	-0,04	0,98
MnO	0,10	0,1	0,00	1,00
P ₂ O ₅	0,51	0,49	0,02	1,04
Fe ₂ O ₃	6,80	6,79	0,01	1,00
Na ₂ O	4,24	4,25	-0,01	1,00
K ₂ O	2,91	2,92	-0,01	1,00
TiO ₂	1,05	1,07	-0,02	0,98

Table 4: Average mass%, expected mass%, residual mass% and the error in percent of standard AGV-2. Residual is the difference between average and expected mass% and Error is the ratio between the two, i.e. the error percentage.

Discussion

The most widely accepted hypothesis that describes the formation of the kyanite rock at Hålsjöberg is hydrolysis and/or acid leaching, possibly in a hot spring or epithermal volcanic environment, followed by amphibolite facies metamorphism (Andréasson and Stanfors, 1988; Ek and Nysten, 1990; Larsson, 2001). The initial stage of hydrolysis is responsible for the addition and/or subtraction of elements, such as phosphorous and aluminium, to/from the protolith rock. Thereafter, amphibolite facies metamorphism produced the current mineralogy. Petrographic analyses and geothermometry using THERMOCALC (Powell and Holland, 1994) confirms that the metamorphism was at amphibolite facies conditions. Chemical analyses of the kyanite rock confirm that it is depleted in most oxides except for silica and alumina, which is consistent with hydrothermal alteration or acid leaching.

A comparison of major and minor element concentrations of the kyanite rock with representative examples of granites, sandstones and shales revealed that a shale might be a possible protolith for the kyanite rock (table 3). Based on the dominance of silica and alumina, the chemistry of the kyanite rock was compared to a whiteschist and they are indeed rather similar compositionally, especially with some degree of alteration due to fluids taken into account. This is not surprising, as a whiteschist is very rich in silica and alumina as a consequence of heavy leaching. This suggests that the protolith might have had a pelitic composition. However, some authors argue that metabasalt and even granite can form whiteschist (Johnson, 2011). The standing hypothesis on the protolith or the paragenesis cannot thus be contradicted at a general level, though a pelitic protolith does provide the more plausible alternative, and the exact specifics of the hypothesised hydrolysis, fluid movement paths and effects on the protolith can be debated. Lindström (2015) questioned the statement by Larsson (2001) that kyanite is metasomatic and formed by replacing muscovite as a result of the hydrolysis during metamorphism. Based on petrographic observations, Lindström (2015) instead suggested that muscovite replaces kyanite as a late-stage, post-metamorphism hydration event, and that the kyanite is not metasomatic but purely metamorphic. Petrographic analysis of the samples collected during this master's thesis did not provide any support for either Larsson (2001) or Lindström (2015), as the samples containing kyanite were very poor in muscovite, and vice versa, and no reaction textures could be found. The petrographic analysis does however confirm previous observations, including the presence of Al-phosphates in the kyanite rock and that the dominating rock type in the area is a metadacite. Photomicrographs of the above are presented in images P1 to P8.

No consensus has been reached regarding the protolith of the kyanite rock. On one hand, authors such as Rodhe and Andréasson (1992) and Larsson (2001) advocate an igneous protolith. On the other hand, authors such as Geijer (1963), Ek and Nysten (1990) and Lundegårdh (1995) suggest a sedimentary protolith. The data used as the basis for their hypotheses regarding the protolith varies, and this discussion will attempt to address this in light of the data acquired during this master's thesis.

The theory laid forth by Rodhe and Andréasson (1992) speculated on a granitoid origin of the kyanite rock based on field observations of a gradual transition between a granite

and the kyanite rock found in Hökensås, where feldspar was replaced by kyanite as the result of hydrothermal alteration. While chemical and petrographic data acquired during this master's thesis cannot fully contradict or disprove that this was also the case in Hålsjöberg, data from Lindström (2015) contradicted this and instead suggested that kyanite was replaced by muscovite, facilitated by fluid-rock interaction along the shear zones, which are defined by mylonite.

The difference in chemistry between the granite and the kyanite rock is significant, and a common protolith seems implausible, especially in light of the data presented by Lindström (2015). A possible explanation to the observed gradual transition found at Hökensås that would accommodate both the distinct difference in chemistry and the gradual transition would be changes in sedimentation. Assuming that the protoliths of both the kyanite rock and the gneissose granite are sedimentary, a change in sedimentation and the chemistry of the sediments deposited could possibly result in the present-day rocks, for instance a change from more sand to more clay.

Larsson (2001) also suggested that the protolith was of granitoid composition, and that it was affected by hydrolysis or metasomatism that formed a chemical zonation within the granitoid. Larsson (2001) further argued that the hydrolysis was the basis for the chemical variation in the area, and that metamorphism formed the mineral assemblages observed today, based on that chemical zonation. If the protolith truly was a single rock unit of granitoid composition, the chemical composition of each "zone" should have a chemistry that can be traced back to the common protolith. This is not the case according to data acquired during this master's thesis; multiple protoliths of varied chemistry is a more plausible explanation.

There are a number of arguments to support this. Firstly, the mass percent of silica is considerably higher in the kyanite rock and mica schist compared to the metadacite, feldspar porphyry and gneissose granite. This would suggest either a higher abundance of quartz in the protoliths of these rock units, or that quartz was added later on. Larsson (2001) claimed that the common protolith of the many rock units found in the quarry had been subjected to mass loss, primarily silica. If there was truly only one protolith however, the silica content should be more or less the same across all the different rock units, regardless of amount of mass lost.

Secondly, there is a difference in silica content between the dark and light layers of the mica schist, and a significant difference between the red and blue bands of the kyanite rock. The blue bands have a considerably lower silica abundance compared to the red ones, and the blue bands are also more abundant in kyanite. This is also difficult to explain with all rock units having a common protolith, again regardless of mass loss.

Larsson (2001) also claimed that there was little or no evidence to support silica being added later on. This makes it even hard to explain the differences in silica concentration, both between different rock units and between different layers or bands, for instance in the kyanite rock. This would entail that silica enrichment, i.e. quartz crystallization, is coupled with the formation of kyanite, or possibly the opposite, i.e. the breakdown of kyanite. This could be accomplished if the kyanite rock was subjected to alteration where kyanite reacts with phosphoric acid to form Al-phosphates and quartz, with the result that the red bands are enriched in silica and Al-phosphates compared to the blue

bands. Alternatively, kyanite can react with quartz, water and potassium to form muscovite, which would suggest that the red bands have used up less kyanite than the blue bands, resulting in a higher concentration of remaining quartz and less muscovite. These two hypotheses are rather unlikely however, as the Al-phosphates in the kyanite rock tend to be concentrated to the blue bands and not the red ones, and the muscovite content is not dramatically different between the red and blue bands. A third alternative would be that alumina has been leached from the kyanite rock, and that the blue bands were originally richer in alumina compared to the red ones, meaning that more alumina remains today. This hypothesis too requires the protolith to be varied compositionally however.

A difference in protolith composition however would indicate that the mineralogy of the protolith of the blue bands was more favourable for kyanite growth than the mineralogy of the red bands; for instance containing greater amounts of plagioclase and other aluminous minerals. This goes well in hand with a sedimentary protolith hypothesis, with the alternation of clayey and sandy layers. The sedimentary protolith hypothesis thus appears to be more plausible than the alternative.

Another important observation regarding the alumina is that the concentration peaks in the gneissose granite in HBCL-7, which almost neighbours the kyanite rock. That a granite is high in alumina is not surprising but a mass percentage of over 40% instead of the average 14% of an S-type granite, coupled with the relatively low concentrations of alumina in the surrounding rock units might suggest that alumina-rich metamorphic fluids might have contributed to an increased alumina concentration. The fluids might have been channelled through the gneissose granite itself and enriched the surrounding rocks, or more likely through the shear zone represented by the mylonite. Lindström (2015) suggested that both of the gneissose granites, i.e. the western one close to the kyanite rock and the eastern one on the other side of the mica schist are related genetically, but that the western one has experienced more intense deformation. If their protoliths were indeed similar or even the same, as Larsson (2001) suggested, their alumina concentrations should reflect this, which they do not as the eastern granite contains 17% alumina compared to the 40% of the western one. Considering that Larsson (2001) did not advocate a focussed channel for the fluids but rather a large-scale movement of fluids related to a shallow magmatic intrusion, a common protolith seems even more far-fetched. The western gneissic granite has over two times the concentration of the eastern one, with the distance between the two measured in metres. This strengthens the hypothesis of alumina-rich fluids being channelled in a focussed way close to or even through the western gneissic granite, enriching it in alumina compared to the eastern one. The western gneissic granite also appears to have a lower concentration of silica, but this is likely a mathematical artefact of the increased alumina.

In an attempt to verify the origins of the gneissose granite found in the quarry at Hålsjöberg, a SIAM diagram was used (White and Chappel, 1983). The mineralogy and major and minor elements suggest that the gneissose granite falls under the S-category, i.e. is derived either from a subduction environment or a supracrustal sedimentary environment. This fits very well with the hypothesis of a sedimentary origin of all rock units found in the quarry in Hålsjöberg. A trace element analysis was not performed on the gneissose granite however, limiting the usage of a SIAM diagram somewhat. Since

the gneissose granite falls under the S-category, the chemistry of a representative S-type granite was used for the major and minor element comparison described above and presented in table 3.

In contrast to Rodhe and Andréasson (1992) and Larsson (2001), Lundegårdh (1995) based his theory of a sedimentary origin on the presence of structures that very likely are sedimentary ones. During the fieldwork for this master's thesis, multiple examples of different structures that are most easily explained as sedimentary were found and documented, and are presented in the Results section.

The most compelling structures for a sedimentary origin found at Hålsjöberg are cross-bedding, scour-and-fill structures and flaser bedding. There are other structures as well that are most likely sedimentary but that can form in igneous or metamorphic environments as well, such as graded bedding, and while they are not conclusive on their own in combination with the more compelling structures they present a strong case for a sedimentary origin.

Image S1 is the most convincing piece of evidence, as the clear cross-bedding relationship is very difficult to attain in any other environment than a sedimentary one. Other cross-bedded structures can be found in images S2, S6 and S7.

Scour-and-fill structures are another example of structures that would be very difficult to form in any other environment than a sedimentary one. Examples of scour-and-fill structures can be found in images S4, S5, S10 and S14. While the structure in image S4 might be interpreted as a sort of "half augen" in a gneissose rock, the lack of deformation around it and the asymmetry of the structure speak against it. In image S14, the scour-and-fill structures are parallel to the metamorphic foliation. The structures could be interpreted as folding, though that would suggest that the folding and the metamorphic foliation are parallel to each other, which is not possible. The asymmetry of the structures also suggests a sedimentary origin.

Graded beds are formed in sedimentary environments as a result of a change in current velocity in a depositional environment. Such structures can be formed in igneous environments as well, for instance through crystallization of minerals in a magma chamber. Repeated graded beds are not as easily explained however, but can be achieved through magma recharge of said chamber. The relatively small difference in bed thickness and the even frequency of the beds hints toward a strongly cyclical depositional environment however, which is associated more intimately with surface sedimentary processes rather than igneous ones. Such structures can be found in images S3.

Structures very reminiscent of flaser bedding or lenticular bedding can also be found, shown in images S10, S11, S12 and S13. Both types of bedding are formed in sedimentary environments where mud or sand is deposited in ripple troughs and become isolated as the ripple crests are eroded and more material is deposited over them. Flaser bedding exhibit isolated lenses and layers of mud while lenticular bedding exhibit isolated sand lenses. The former is more plausible as mud would contain more plagioclase and thus the alumina required for the Al-phosphates, as seen in images S12 and S13. Lenticular bedding cannot be excluded however, as fluid interaction might

transport alumina through the rock and it is unknown if the sandier lenses in lenticular bedding provide a better environment for precipitation of Al-phosphates or the growth of kyanite.

Ek and Nysten (1990), while the intent of their study was not to determine the protolith of the kyanite rock, referred to the rock units at Hålsjöberg as supracrustals, of which some were sedimentary in origin, including the kyanite rock and the mica schist. They further suggest that Al-rich sediment, for example argillic sediments, would provide the proper protolith for the formation of the kyanite rock. Finally, Geijer (1963) also suggested Al-rich sediments as the protolith for the kyanite rock.

Structural measurements taken from all over the study area, presented in fig. 4, indicates a quite uniform orientation throughout the area, with the majority of all measurements dipping approximately to the northeast at an angle around 40°-60°. The exception are the measurements taken in the Polished 2 and West of Road areas, which are located further west compared to most of the samples. These measurements have approximately the same dip, but their orientation tends towards the northwest rather than the northeast. Furthermore, the outcrop map (fig. 1) suggests that the width of the kyanite unit exposed as outcrops is greater in the south compared to the north, and the exposure of kyanite rock at the hill near the Polished 2 area suggests that the kyanite unit is dipping towards the north. These three observations combined points towards a single unit of kyanite, folded into an antiform shape and dipping slightly towards the north, with the antiform hinge located to the east of the hill close to Polished 2 area, but to the west of the Quarry and Stairway areas. The cross sections shown in fig. 2 support this geometry. The kyanite rock unit antiform might also curve towards the west around the Quarry area, based on the presence of an older quarry in that direction. Alternatively, since the quarry is located at a lower altitude, it can cut into a section of the kyanite rock unit that would not have been exposed at the surface, giving the illusion of a curving rock body.

Sources of error

Quantitative errors in the XRF analysis are described under “Analytical errors”. Non-quantitative errors are described below.

Some apparent sources of error include the lack of trace element data to support the SIAM diagram, that the banding in the kyanite rock was assumed to be parallel to bedding throughout the study area, the somewhat limited number of outcrops found in the study area muddling the interpretation of the geology, and that the reaction textures described by Larsson (2001) and Lindström (2015) could not be found. The distinction between S-type and I-type granitoids is also rather hard to make on most granitoids as components from each of the types tend to be mixed into the other type. Also, metamorphism might have affected the granite, rendering the usage of a SIAM diagram invalid. Additional insecurities in the data include minor errors in the structural measurements, the somewhat small number of structural measurements taken, that the orientation of the foliation of rock units in relation to the bedding was not determined, misidentified minerals as a result of difficulties during identification (mainly for pyroxene, amphibole and epidote), and of course human error.

Conclusions

A sedimentary origin of the kyanite rock and surrounding rock units followed by metamorphism and deformation would explain the uniform orientation of the bedding, contacts and banding of the kyanite rock, and how the orientation curves from northeast to northwest over the study area. The outcrops found in the study area support this, and the chemical data, including the SIAM diagram, does not readily support previous hypotheses of a single granitoid protolith, but rather multiple sedimentary protoliths of varying composition. The primary piece of evidence for a sedimentary protolith however is the compelling sedimentary structures, such as cross-bedding, flaser bedding and scour-and-fill structures.

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Appendix

Thin section descriptions

Metadacite

3s1

Sample contains plenty of feldspar, many of which are large, in a partially interlocking pattern. The plagioclase and K-feldspar exhibits all forms of twinning: albite, pericline, tartan and Carlsbad. Muscovite and sericite is replacing the plagioclase. Some biotite is present, often growing in radial fans out from what appears to be ilmenite. Both clinopyroxene and orthopyroxene can be found as well. There is also epidote present, albeit in small amounts and in very poor condition, mostly due to replacement.

3s3

On a large scale the sample consists of intermeshed and criss-crossing swirls and patches consisting of different minerals, however with each swirl composed of a main mineral. Mineralogy is similar to 3s1, but with significantly less large plagioclase, a medium-fine-grained matrix of mainly muscovite and remnant plagioclase, biotite that is often present around ilmenite and that often grows in long narrow needles and what appears to be chlorite. There is also both CPX and OPX present as well as an unidentified high-birefringence mineral, and a second unidentified mineral as well. This latter one has hexagonal crystals, often very euhedral, with a grey or white colour in PPL and low order of interference in XPL. No pleochroism or extinction.

3s4

Sample is dominated by very large plagioclase and K-feldspar crystals forming a partially interlocking grid all over the sample. All four forms of twinning are present. Sericite can be found growing in the spaces between the plagioclase and also on the edges of the feldspar. In some patches the sericite appears to grow in radiating fans around grains of ilmenite. The ilmenite is sometimes in very poor condition, with only a faint patch left of the crystal. Biotite and rutile is often found around these remaining ilmenite grains, but there is rather little present. The sample also features large epidote crystals. CPX is present in minor amounts.

3s5

Sample is dominated by large plagioclase and K-feldspar crystals that form a partially interlocking grid. All four forms of feldspar twinning are present, possibly with the exception of pericline twinning. Other abundant minerals are very large epidote grains, which have been partially replaced by the plagioclase. Some of the epidote grains exhibit what appears to be undulose extinction, though it might be an optical artefact. These grains commonly show lower order interference colours. There are also a few very fractures and ambiguous grains of OPX and what is possibly CPX, but these might be low

interference order epidote crystals. There is also minor amounts of ilmenite, rutile and chlorite, the two latter often growing around the former. Sericitation is very minor.

3s6

Sample is again dominated by large plagioclase and K-feldspar crystals, albeit not as abundantly as previous samples. All four forms of feldspar twinning are present. Present are also very large epidote grains, but again not as abundant as in previous samples. Some of the epidote grains have a dirty appearance, and there is also an unknown mineral that shares many of the characteristics of the epidote, including habit, hardness and size, but instead of having higher order interference colours it has a dirty dark red or brown appearance of lower interference order. There is also plenty of sericitation, and patches of ilmenite, rutile and chlorite.

3s7

Sample is dominated by a network of large partially intermeshed plagioclase and K-feldspar crystals, with all four forms of feldspar twinning represented; possibly with the exception of pericline twinning. Medium to large patches of sericite and some chlorite and biotite are present all over the sample. These patches appear both between groups of feldspar crystals and also partially covering them; the sericite has likely replaced the feldspar. Ilmenite grains surrounded by rutile and biotite are also present. Sections of the sample also feature smaller epidote crystals. Some CPX and very small amounts of OPX can be found. Scattered over the sample are also small irregular grains that might be garnets but are difficult to reliably identify.

3s9

Sample is dominated by large plagioclase and K-feldspar grains that form a partially interlocking grid covering the sample. All four types of feldspar twinning are represented. Chlorite and sericite is very abundant, filling up most of the space between the plagioclase grains. Some sericite/muscovite has grown quite large. Epidote and pyroxene are non-existent. Ilmenite crystals of varying size, up to quite large, are also rather common, and biotite commonly grows around them, often in radiating patterns. Rutile is very rare if not missing altogether.

4s9

The sample is dominated by large plagioclase crystals and epidote crystals, of which some are in poor condition, sometimes even as segments of an otherwise fresh grain. Ilmenite crystals of varying size, up to quite large, are also present, and is often associated with chlorite. Sericite and muscovite also appears as twisting narrow bands, often close to the ilmenite, but sericite also appears as irregular patches next to plagioclase crystals.

Additional metadacite samples were only briefly analysed to confirm that they shared the general mineralogy of the above samples.

Kyanite-bearing rock

4s3

Sample is dominated by medium to large quartz grains, with granoblastic textures being common but not overly abundant, and by kyanite crystals, most being rather large and subhedral to euhedral. The kyanite crystals indicate the foliation through preferred orientation. Apart from quartz and kyanite there is a significant amount of garnet. The size of the garnets varies greatly, but all are anhedral. Other minerals present include small amounts of rutile, opaque minerals (most likely ilmenite). There are also trace amounts of a clear blue Al-phosphate mineral, presumably scorzalite.

4s2

Similar base mineralogy to 4s3 but with markedly more muscovite and less kyanite. The muscovite crystals are larger and the kyanite crystals are smaller than in 4s3. Both muscovite and kyanite show preferred orientation, with no undulation in their direction throughout the sample. Muscovite and kyanite dominate the sample along with quartz, commonly with granoblastic texture where there is enough space for several grains to touch each other in clusters. Apart from quartz, muscovite and kyanite there are moderate amounts of opaques and small amounts of garnet. No rutile or Al-phosphate is present.

4s10

Similar base mineralogy to the regular kyanite rock but with quartz dominating the sample alone. Granoblastic texture is common. Kyanite is still present in large amounts, but the crystals are smaller, less euhedral and not as prominent as in other samples. Apart from quartz and kyanite there are small to moderate amounts of garnet, mostly anhedral medium-sized grains, small amounts of rutile, and minor amounts of muscovite, of which some is sericite. The sericite is found along a fracture, and appear to post-date all other minerals, which might be an effect from the fracture or actual replacement. There are no Al-phosphates present, nor any opaques. The kyanite and opaques show somewhat of a preferred orientation, but not nearly as well as in most other samples.

4s4

Again the same base mineralogy, and this sample is also very similar in appearance to sample 4s3, which is not surprising considering their proximity. Quartz of varying size but in general quite large, with granoblastic textures being common, dominate the sample along with kyanite crystals, which are rather euhedral and large. The kyanite crystals show preferred orientation along the foliation. Unlike sample 4s3 however, rutile is rare, and opaques are more or less non-existent. Muscovite is present in minor amounts, as are garnets, which are mostly small and anhedral. Al-phosphates however are rather common.

4s20

This sample is also very similar to samples 4s3 and 4s4, with quartz and kyanite dominating the sample. The quartz grains are mostly large grains however, and there are thus fewer of them. Granoblastic textures are common, and around $\frac{1}{4}$ to $\frac{1}{5}$ of the sample is made up almost exclusively of large quartz grains. The kyanite crystals are rather euhedral and large, but the size does vary. They don't show a preferred orientation as strongly as in other samples. Muscovite and garnet appears in minor amounts, but the muscovite is not aligned with the kyanite. There are only trace amounts of opaques and Al-phosphates, no rutile, and the Al-phosphates are clustered in the section of the thin section dominated by quartz only.

What few minerals can be found inside the quartz-dominated section, including the Al-phosphates, seem to be located in fractures. The complete lack of Al-phosphates in the quartz of that section and their clustering in the fractures where other minerals, mainly kyanite, is present would suggest that the Al-phosphates are secondary and require kyanite to form: in other samples it has always been found growing on or beside kyanite.

Some of the kyanite has twinning similar to albite twinning, and some of the kyanite has a rather dark red interference colour reminiscent of pyroxene. It still has the other characteristics of kyanite however, and is thus assumed to be kyanite.

4s14

Similar base mineralogy, with quartz and kyanite dominating. The quartz is in general small-grained and kyanite medium- to small-grained. The sample seems to be in somewhat poor condition and is pitted. Kyanite shows preferred orientation but not very strongly. Garnet is common and often rather large. Minor amounts of Al-phosphate and muscovite. Trace amounts of opaques, and no rutile. A large part of one edge of the sample has a much lower concentration of kyanite, for unknown reasons.

4s15

Similar base mineralogy but in this sample quartz is the dominant mineral followed by rutile. The quartz grains are of medium size and with only small variations in size, with abundant granoblastic textures. The sample also seems to be in poor condition and is pitted. Rutile is common and appears as a loose swirl in the core of the sample. Kyanite and muscovite are present in rather large amounts but the crystals are small and evenly dispersed throughout the sample. They indicate the foliation through preferred orientation. The sample also has minor amounts of Al-phosphates, clustered into a few small areas. Garnet appears in minor amounts, often as smaller grains similar in size to the quartz. There are no opaque minerals.

4s18

Quartz and kyanite dominate the sample, both as rather large grains, and both appear to be in poor condition. There is no preferred orientation of mineral grains in the sample, and some grains are even bent. Apart from quartz and kyanite there are moderate amount of garnet, most of which is located along a fracture running through the sample.

There are other garnets in the sample however, of varying size. There are also small amounts of muscovite, mostly as rather small crystals, and also rutile. Al-phosphates are present in trace amounts, as well as minor amounts of opaques.

4s17

The sample is much more fine-grained than most other samples, and is dominated by small- to medium-sized quartz grains, with abundant granoblastic textures, and small- to very small-grained kyanite and muscovite. Garnets in sizes varying from large to small are also quite common. The muscovite and kyanite exhibit preferred orientation. Again, the garnet is the main mineral in fractures. There are only trace amounts of rutile, and no Al-phosphates or opaques.

2.3-1

Medium-sized quartz grains of very homogenous size and habit dominates the sample, with abundant granoblastic textures. There is also plenty of kyanite and a lot of muscovite, both rather homogenous in terms of grains size and habit. Both indicate the foliation through preferred orientation. There is not a lot of garnet in the sample, most of it being a single very large oblong grain, and the rest dispersed as grains of the same size as the quartz grains. There are trace amounts of Al-phosphates, rutile and opaques. In this way, the sample is very homogenous, but at the same time the sample can be divided into parallel bands, with different combinations of muscovite and kyanite amounts. Some bands have almost no muscovite but plenty of kyanite, and others the opposite.

4s11

This sample is different from the regular kyanite quartzite samples in that it has plenty of feldspar mixed in with the quartz and kyanite. The feldspar has little or no twinning, and can sometimes be mixed up with the quartz, especially if the feldspars are anhedral. Feldspar, quartz and kyanite thus dominate the sample almost completely. Garnets are present, mostly as rather large grains. There are only minor amounts of opaques and rutile present, but no muscovite or Al-phosphates. There are also minor amounts of what appears to be epidote present, but that might be strange-looking muscovite.

2.3-2

The sample is similar to sample 2.3-1 in that the sample is dominated by quartz, although with a bit more variation in size and shape, and by muscovite and kyanite, although the grains in general larger and with more variation in size and shape. The muscovite and kyanite show preferred orientation. It is also similar in that there are bands of varying amount and ratio of kyanite and muscovite: some bands have abundant kyanite, some abundant muscovite, and so on. Unlike sample 2.3-1 however the bands grade into each other, and in general the sample is less structured and chaotic. There are minor amounts of Al-phosphates and opaques, but only trace amounts of rutile. Garnets are present but most of it as a few very large oblong grains. The rest appear as large grains, and around the edges of the sample.

Other

4s16 – Likely mica schist

Sample is dominated by quartz, muscovite and biotite, of which the latter two show preferred orientation throughout the sample. Both the muscovite and biotite appear as rather large but narrow crystals, and are euhedral. Other minerals present include garnets, but they are rather small and often clustered into groups. There are no opaques, rutile, Al-phosphate or other minerals apart from the four mentioned above.

3s8 – Possibly metadacite

The sample is dominated by a fine-grained matrix consisting of plagioclase, calcite, muscovite, chlorite and ilmenite. The sample matrix is divided into three roughly equal bands, of which the inner one is composed of even finer grains. Present are also a few larger grains of ilmenite, with the associated hematite, plagioclase, an amphibole-esque mineral with somewhat high order birefringence and pleochroism but no extinction.

4s13 – Possibly kyanite

The sample is dominated by feldspar and sericite. Most of the feldspars are plagioclase with albite and Carlsbad twinning, but minor amounts of K-feldspars with tartan and pericline twinning is also present. The feldspar is in bad condition, replacement by sericite having progressed far. Apart from the feldspar and the sericite there is some biotite, small-grained garnets, some rutile and opaques. There is no quartz, pyroxene or kyanite present.

4s12 – Possibly metadacite

On a large scale the sample is made up of several undulating and whirly bands, each different in thickness and composition. The main minerals in these bands are feldspars, either distinct grains in very bad condition or just areas of largely dissolved and fine-grained feldspar remains; sericite; small muscovite or alternatively large sericite crystals; biotite; garnet, often small and in clusters; opaques; minor amounts of chlorite; and minor amounts of rutile. There might be some single grains of pyroxene, but they are in extremely poor condition and might just be clusters of muscovite. The bands are mostly dominated by feldspar and sericite, biotite and opaques, or muscovite and sericite. Larger feldspar grains are most common in the feldspar and sericite bands.

4s5 – Granite

The sample is rather massive, homogenous and is mostly large-grained. Quartz and K-feldspars dominate the sample, with tartan and pericline twinning being common, but there are a few grains of plagioclase that exhibit albite twinning, but no Carlsbad twins. The quartz and feldspars are rather large-grained and granoblastic textures are common. Other minerals present include large and euhedral biotite crystals, medium and small and somewhat euhedral muscovite crystals, a few large opaques that look like

pyrite or something equally white and high-reflectance under reflected light. There are a few fractures, which are filled with small-grained muscovite and biotite mainly, but a few calcite grains can also be found. The sample is in very good condition: no sericite replacement has occurred. The biotite and muscovite show preferred orientation.

4s1 – Granite

The sample is very similar to sample 4s5 in that it is rather massive, homogenous and large-grained, and in that it is dominated by K-feldspar, quartz, biotite and muscovite. The difference is that muscovite is much more abundant, and that both the muscovite and biotite crystals are much larger, longer and prominent. They also indicate foliation through preferred orientation.. Apart from that and that the sample is in a little more poor condition the sample is very similar to sample 4s5.

4s6 – Possibly metadacite

The sample consists of a few very large feldspar crystals in rather poor condition inside a fine-grained matrix primarily made up of feldspar (though some could be quartz), muscovite and biotite. Other minerals present, which are present both inside (or having replaced) the feldspar crystals and inside the matrix, include sericite, some chlorite, and minor amounts of pyroxene and epidote. There is also an opaque mineral very similar to the one found in 4s5.

Structural measurements

Quarry		
Sample #	Dip direction	Dip
1	076	40
2	041	46
3	046	52
4	060	50
5	053	50
6	052	50
7	050	50
8	050	50
9	050	54
10	048	52
11	044	60
12	048	56
13	041	50
14	037	54
15	058	52
16	052	54
17	047	60
18	044	58
19	044	58
20	050	56
21	040	53
22	051	50
23	061	54
24	046	50
25	051	52
26	061	49
27	062	64
28	058	52
29	058	50
30	060	57
31	058	59
32	049	56
33	055	51
34	076	49
35	073	48
36	058	48
37	059	46
38	073	44

Quarry 2		
Sample #	Dip direction	Dip
1	022	62
2	036	50
3	018	64
4	030	61
5	038	60
6	022	62
7	040	60

West of road and Polished 2		
Sample #	Dip direction	Dip
1	320	40
2	300	60
3	308	28
4	321	36
5	327	44
6	294	24
7	315	58
8	317	47
9	304	48
10	034	40
11	070	40
12	114	90
13	090	65
14	096	80
15	060	80
16	060	80
17	052	60

Polished 1		
Sample #	Dip direction	Dip
1	016	60
2	014	64
3	016	60
4	024	54
5	016	37
6	015	65
7	020	58
8	025	38
9	017	38
10	014	62
11	012	58
12	033	46
13	016	54

Pond		
Sample #	Dip direction	Dip
1	060	50
2	080	58
3	066	42

Stairway		
Sample #	Dip direction	Dip
1	060	60
2	050	30
3	052	40
4	042	12
5	048	20
6	070	68
7	068	70
8	053	80
9	052	86
10	052	58
11	060	80
12	066	70
13	050	70
14	068	81
15	041	62
16	049	86
17	052	88
18	052	68
19	042	70
20	062	64
21	064	78
22	063	88
23	044	76
24	069	67
25	080	60
26	104	52
27	080	72
28	083	66
29	082	72