NGU Report 2006.078

The Gullsteinberget and Knøsberget kyanite quartzite deposits

NGU
Norges geologiske undersøkelse
Geological Survey of Norway

Geological Survey of Norway
NO-7441 Trondheim, Norway
Tel.: 47 73 90 40 00
Telefax 47 73 92 16 20

REPORT

Report no.: 2006.078	ISSN 0800-3416	Grading: Confidential until 01.01.2009

Title:
The Gullsteinberget and Knøsberget kyanite quartzite deposits

Authors: Axel Müller, Rolf Lynum, Leif Furuhaug	Client: Norwegian Crystallites
County: Østlandet	Commune: Våler, Åsnes
Map-sheet name (M=1:250.000) Hamar, Torsby	Map-sheet no. and -name (M=1:50.000) 2016 I Kynna, 2016 II Flisa
Deposit name and grid-reference: Gullsteinberget, Knøsberget	Number of pages: Price (NOK): Map enclosures: 5

Fieldwork carried out: June/September 2006	Date of report: 31.12.2006	Project no.: 286100	Person responsible: Are Korneliussen

Summary:

The kyanite quartzite occurrences of Gullsteinberget and Knøsberget in Solør were mapped, sampled and analysed in order to determine the quality and distribution of potential quartz raw material. From the field mapping three potential bodies could be identified: (1) a 50 x 20 m, NE-SW striking body ca. 100 m ESE of the Gullsteinberget top, (2) a 50 x 40 m, NE-SW striking kyanite quartzite lens in the central part of the Gullsteinberget West target area and (3) a 50 x 10 m, NE-SW striking lens at Knøsberget. The average grain size of quartz is 0.5 to 1.3 mm at Gullsteinberget East (body 1), 0.5 – 1.0 mm at Gullsteinberget West (body 2) and 0.2 to 0.4 mm at Knøsberget (body 3). On the basis of these field observations a 400-kg sample were taken from body 2 for a processing test.
The kyanite quartzites contain between 10 and 22 wt.% Al_2O_3 which corresponds to kyanite content of 7 to 15 vol.%. Samples mapped as "good quality" contain maximal 85 wt.% SiO_2 and at least 10 wt.% Al_2O_3. The muscovite content in the rock increase from the central part of the kyanite quartz bodies towards the margin from 0 to 30 vol.%. Common accessory minerals are pyrite, rutile, zircon and apatite and in one case topaz. Rutile forms commonly small (1-20 µm) prismatic inclusions (no needles!) in quartz. The common presence of micro-inclusions of kyanite, rutile, zircon and apatite in quartz may cause problems during processing.
70 LA-ICP-MS analyses on 35 samples were carried out. Concentrations are in the range of 13-44 ppm for Al (average 26 ppm), 4-24 for Ti (average 11 ppm), 1.3-2.7 for Li (average 2.0 ppm), 0.5-1.8 for B (average 1.2 ppm), 0.2-1.3 for Ge (average 0.6 ppm) for the Gullsteinberget East; 15-53 ppm for Al (average 27 ppm), 8-19 for Ti (average 13 ppm), 0.9-2.0 for Li (average 1.5 ppm), 0.7-1.1 for B (average 1.0 ppm), 0.2-1.2 for Ge (average 0.5 ppm) for the Gullsteinberget West and 15-31 ppm for Al (average 22 ppm), 2-5 for Ti (average 4 ppm), 1.2-2.5 for Li (average 1.8 ppm), <0.5-1.3 for B (average 0.9 ppm), <0.1-0.8 for Ge (average 0.5 ppm) for the Knøsberget deposit. The Ti concentration in quartz from the Knøsberget is significant lower than in quartz from the Gullsteinberget. The lower Ti in the Knøsberget quartz is explained by the lower deformation temperature of about 467°C, whereas the Gullsteinberget East and West were deformed at 537°C and 549°C, respectively.
The upper concentration limits of trace elements in high purity quartz are suggested here as follows: Al <25 ppm, Ti <10 ppm, Li <3 ppm, Ge <2 ppm and B <2 ppm. Thus, most of the analyses of the Knøsberget quartz which are not contaminated by foreign mineral inclusions plot in the high purity quartz field. Caused by the higher Ti, quartz of the Gullsteinberget plot mostly in the medium purity field. A number of quartz analyses are contaminated by micro-inclusions of rutile, apatite and kyanite.

Keywords: kyanite quartzite	high purity quartz	industrial minerals
LA-ICP-MS		

Contents

Figures

Tables

Appendix

1. Introduction

In January 2006 Norwegian Crystallites (NC) AS contacted Norges Geologiske Undersøkelse (NGU) in order to start a joint project to evaluate the quartz quality in kyanite quartzite deposits in Solør on the basis of the NGU rapport 2005.039 (Müller et al. 2005). The authors of the NGU rapport found that quartz in Norwegian kyanite quartzites contains very low trace element concentrations and can be considered as high purity quartz. Quartz is designated high purity if it contains less than 50 ppm of impurities (Harben 2002), which mainly comprise structurally bound trace elements (B, Li, Al, Ge, Ti, Fe, Mn, Ca, K, Na, P) in the quartz lattice. The abundance of trace elements in natural quartz differs per element. Al is the most frequent trace element in quartz followed by Ti, Li, K, Na, H, P, Ge, and B, respectively. Therefore it is necessary to assign an upper concentration limit for each element. The upper concentration limits of impurities in high purity quartz are suggested here as follows: Al <25 ppm, Ti <10 ppm, Li <3 ppm, K <5 ppm, Na <5 ppm, P <5 ppm, Ge <2 ppm and B <2 ppm.

The presented project was discussed and decided on the meeting with NC AS and NGU representatives (Are Korneliussen, Peter Ihlen, Jan Egil Wanvik, Maarten Broekmans and Axel Müller) at NGU 26th of January 2006. They agreed to carry out the following investigations:

1) ca. 10 days fieldwork including detailed mapping of relevant deposits and collecting of ca. 50 kyanite quartzite samples
2) ca. 100 laser ablation inductively coupled mass spectrometry (LA-ICP-MS) analyses (2 analyses per sample) of quartz in kyanite quartzites in order to determine the quality of quartz. The analyses included the production of special polished thin sections (500 µm thick)
3) whole rock X-ray fluorescence spectrometry (XRF) analyses of the samples (major and trace elements)
4) grain size analyses of quartz within the kyanite quartzite samples using normal polished thin sections (30 µm thick)

The planned investigations were further discussed during the field meeting of Svein Olerud and Axel Müller at 22nd and 23rd May 2006. After visiting three of the four known kyanite quartzite deposits in Solør – Gullsteinberget, Knøsberget and Sormbrua – it was decided to focus the investigations on Gullsteinberget and Knøsberget deposits. Both deposits seemed to be the most promising deposits regarding location, size and quartz quality. It was further decided to take 9 5-kg samples of kyanite quartzites for processing tests.

Between the 31st May and 2nd June the Gullsteinberget and Knøsberget deposits were mapped in detail by Axel Müller using the maps by Jakobsen and Nielsen (1977) as base. Simultaneously 38 drill cores (diameter 2.1 cm; length ca. 15 cm) and 9 samples (5 kg) were collected by Rolf Lynum (NGU; Appendix 1). The sampling by drilling was necessary due to extreme hardness of the rocks. The XRF and LA-ICP-MS analyses of the 38 drill core samples were performed at NGU. The 5-kg samples were sent to the NC AS processing plant at Drag. The results of this field campaign were summarized in an inofficial interim report and sent to Svein Olerud at 8th July 2006.

At 5th September 2006 Svein Olerud asked NGU to collect a 400 kg kyanite quartzite sample from the Gullsteinberget deposit for a processing test. The sample was taken from Gullsteinberget Vest at 33V 344789/6735582 (corresponding sample point 19) by blasting by Leif Furuhaug and Axel Müller between 18th and 19th September 2006. The sampling was carried out in agreement with the landowner Inger Marie Møllerud (phone 48284867) of gnr92/bnr8 (Åsnes commune). The sample was transported by car to Trondheim and further sent by ship to the Norwegian Crystallites processing plant at Drag. Supplementary mapping was carried out during this field campaign.

2. Deposit locations and geology

2.1 Gullsteinberget

The Gullsteinberget deposit is situated in Åsnes commune (1:50 000 sheet Flisa 2016 II) ca. 35 km SW of Elverum and ca. 15 km NNE of Flisa (Figure 1). It is best accessible via the Kynndalen toll road (bomvei) starting at Øvergard, 3.5 km NE of Sønsterud (state road 206; Figure 2). Following the sign "Gullsteinberget" the toll road ends after 5 km at a turning point situated within the Gullsteinberget deposit (Map 1). The toll road is in good condition.

The deposit was identified and mapped by Jakobsen and Nielsen (1977) in the frame of gold-kyanite exploration by Norsk Hydro AS. It is the largest known kyanite quartzite deposit in this area with a length of 1.8 km and a width of up to 300 m (Map 1). The lens-shaped body strikes NE-SW and forms the mountain ridge of Gullsteinberget (516 m a.s.l.). The lens dips 50 to 60° to NW. The deposit is more heterogeneous than appearing in Figure 2; it comprises strongly layered quartzite with variable kyanite and muscovite contents alternating at millimeter- to meter-scale. The deposit is hosted in Paleaoproterozoic (1800 – 1650 Ma; Nordgulen 1999), medium- to coarse-grained granitic gneisses of the Solør Complex in close relationship with metagabbros and fine-grained amphibolites (hyperites; Figure 1).

The major part of the deposit is covered with forest. The SW end and the middle part of the deposit in the area of Gullsteinmyra (Map 1) the forest has been cleared. 7 weekend houses are located 200 to 500 m W the SW margin of the deposit. The kyanite quartzite is exposed in several outcrops at the top of the Gullsteinberget (515.6 m a.s.l.) and at the hill SW of Gullsteinmyra (460 m a.s.l.). These two areas allowed detailed mapping and were chosen as investigation targets named Gullsteinberget East (Map 2) and Gullsteinberget West (Map 3), respectively. In the following, the two localities are discussed separately.

The geological maps Gullsteinberget East and Gullsteinberget West illustrate the distribution of different types of kyanite quartzites in the sense of raw material quality. The discrimination of the different qualities is based on the muscovite content and average grain size of quartz and is independent of the kyanite content. As shown below the trace element concentrations in quartz show small variations in composition across the deposit and, thus, it has not been considered in the quality mapping. The different qualities comprise:

1) mica-free kyanite quartzite with quartz grain size 0.5 – 1.0 mm
2) strong foliated kyanite quartzite with 1 - 10 vol.% mica and quartz grain size 0.2 – 0.5 mm
3) strong foliated kyanite quartzite with >10 vol.% mica and quartz grain size 0.2 – 0.5 mm

Type 1 can be considered as a good quality quartz raw material.

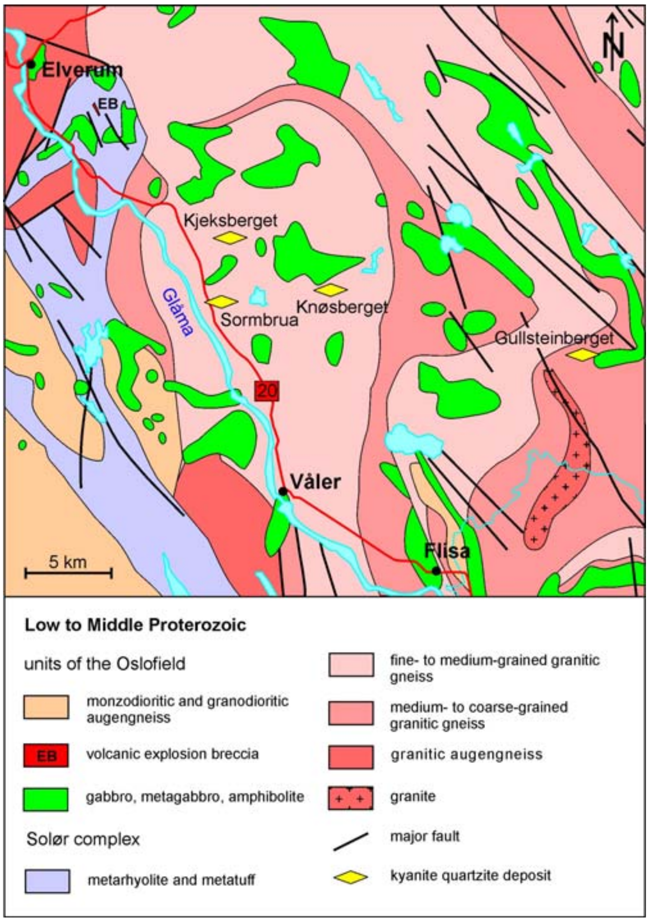

Figure 1. *Simplified geological map of Solør after Nordgulen (1999) and Gvein et al. (1974) with locations of kyanite quartzite deposits.*

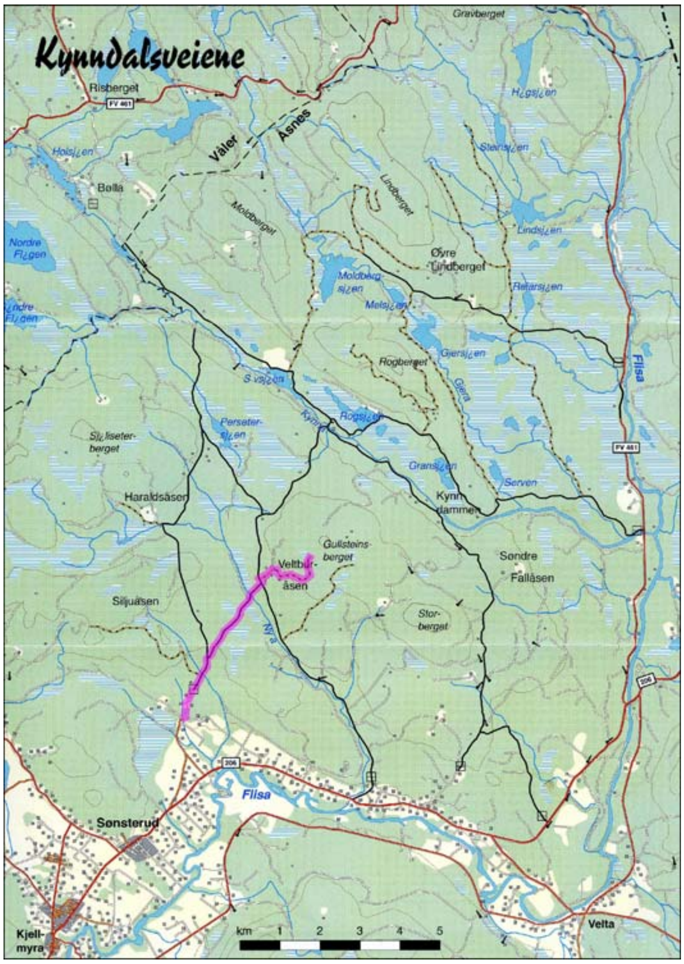

Figure 2. *Topographic map of the toll road net in the Kynndalen area with Gullsteinberget in the centre. The violet line marks the easiest road access to the Gullsteinberget deposit via Sønsterud.*

The target area *Gullsteinberget East* can be reached by a 600-m walk to the top of the Gullsteinberget (65 m difference in altitude) from the end of the toll road (turning point). An old tractor track starts from the turning point in NE direction, which can be followed. It is partially overgrown by small trees. After 500 m the track turns left (N) leading straight to the top of the Gullsteinberget. Ca. 50 outcrops (>1 x 1 m) of kyanite quartzite are exposed SW, E, ESE of the mountain top and at the top itself covering an area of 240 m (E-W) x 140 m (N-S; Map 2).

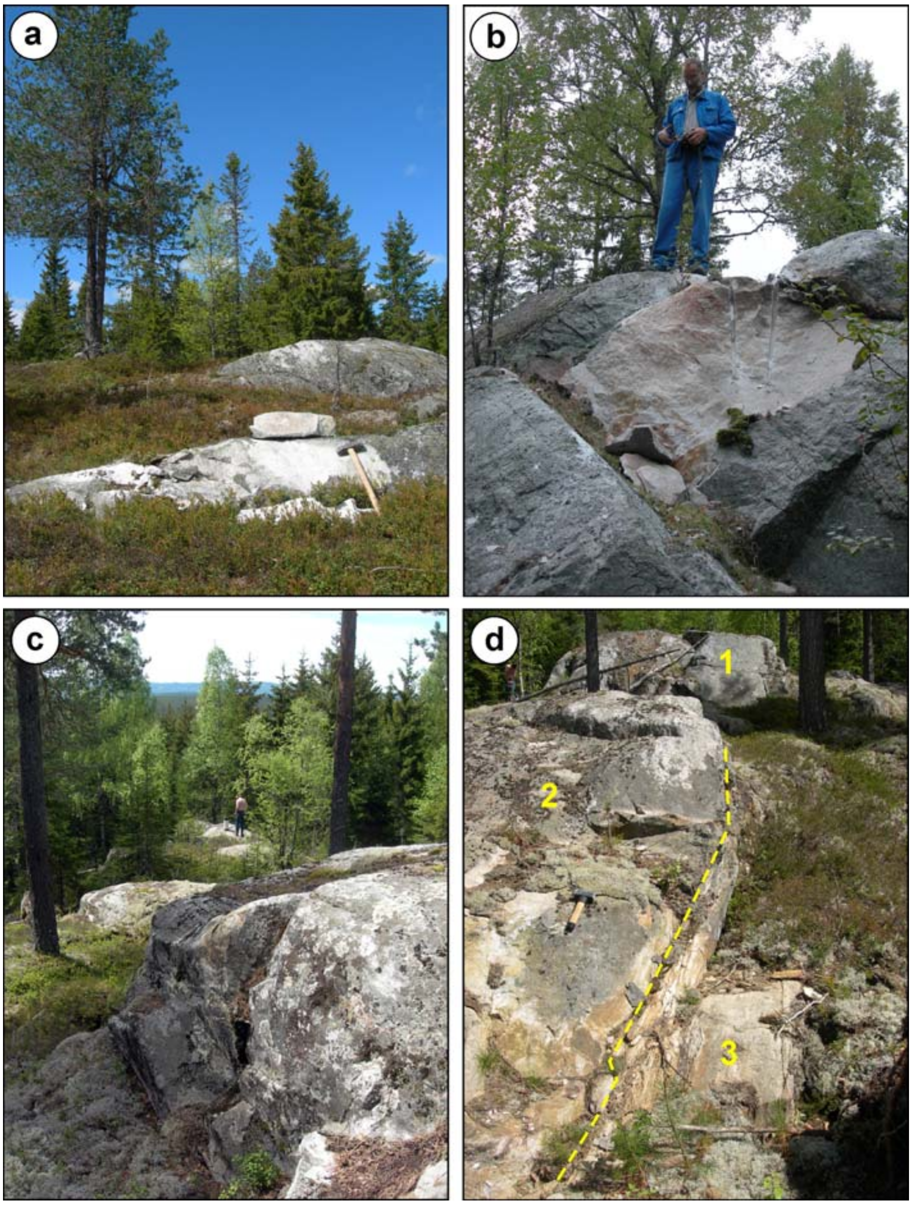

Figure 3. *a – Outcrops of good-quality kyanite quartzite at Gullsteinberget East with sampling point S1 in the foreground. b – Blasting outbreak at sampling point 19 of the Gullsteinberget West deposit. c – Outcrops of moderate-quality kyanite quartzite at Knøsberget, viewed towards the SW from sampling point 30. Drilling at sampling point 38 in the background. d – Section of moderate mylonitised kyanite quartzite (1; background), strongly mylonitised mica-free kyanite quartzite (2) to strongly mylonitised mica-bearing kyanite quartzite (3) at Knøsberget deposit.*

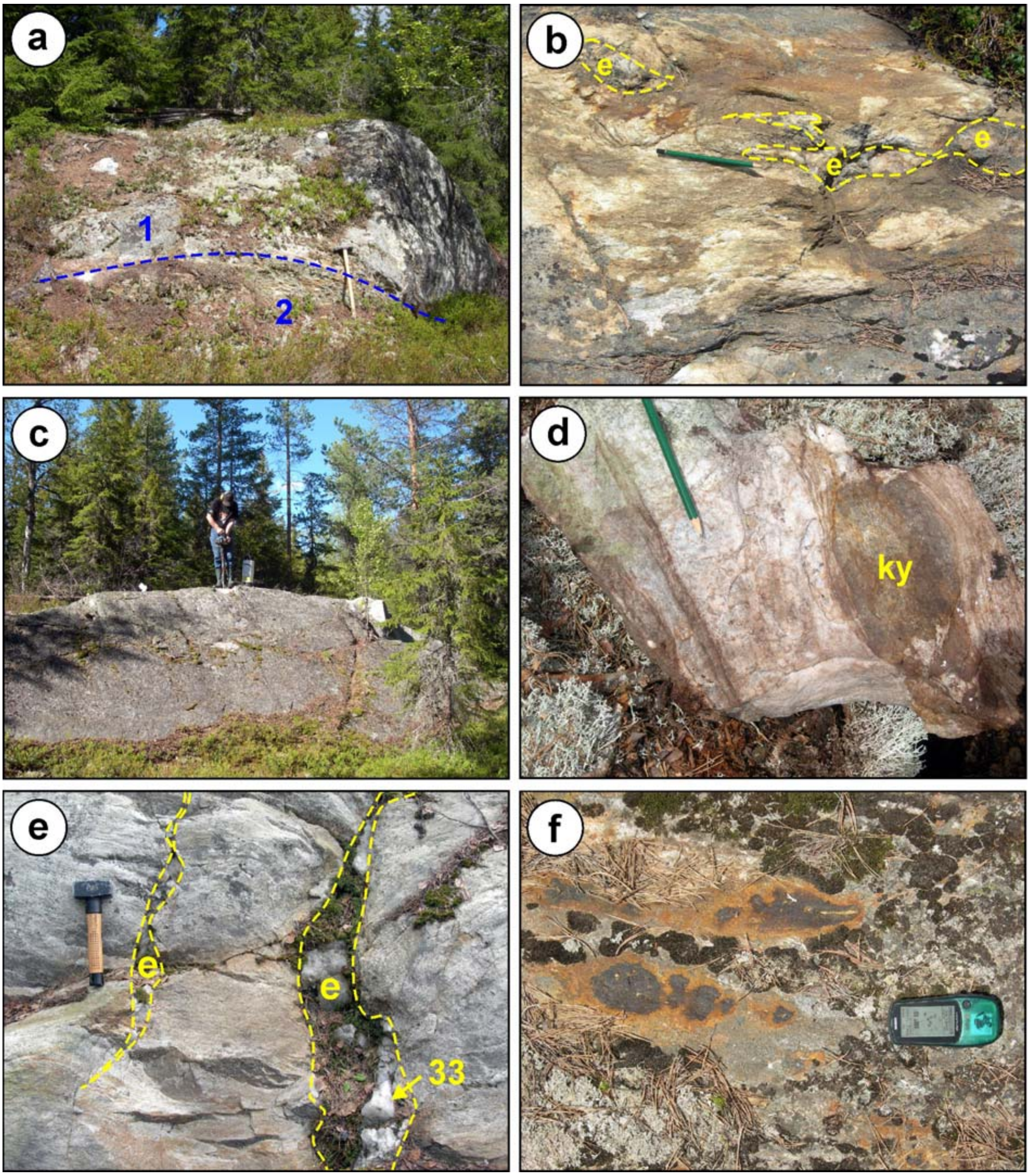

Figure 4. *a – Outcrop near the top of Gullsteinberget (East; sampling points 3 and 4) where the border (blue dashed line) between mica-free kyanite quartzite (1) and mica-rich kyanite quartzite (2) is exposed. b - Mica-rich, tectonised kyanite quartzite with folded quartz segregations (e) at sampling point 15 (Gullsteinberget East). c – Sampling point 19 at Gullsteinberget West representing visually the best quartz raw material quality. d – Mylonitised kyanite quartzite of Knøsberget with kyanite-rich bands (left of the pen) and a almost pure kyanite boudin (ky). Sampling point S8. e – Discordant quartz segregations (e) in mylonitised kyanite quartzite of the Knøsberget with sampling point 33. f – Iron-oxide-rich patina resulting from weathering of pyrite-rich layers within the kyanite quartzite (Knøsberget; sampling point 31).*

Generally, mica-free kyanite quartzite, of promising quality, occurs in the centre of the deposit which becomes richer in mica towards the margin. The kyanite quartzite at the summit is heterogeneous and penetrated by a number of up to 0.5 m wide bands of mica-rich varieties with rotated foliations (Figure 4a). The strike of the main foliation at the summit changes every meter (Map 2). Ca. 70 m SW of the summit occurs an area of 40 x 30 m with mica-free kyanite quartzite having an average quartz grain size of 0.5 – 0.8 mm. The kyanite quartzite with the most promising quartz quality is located ca. 100 m ESE of the top. The high quality body has an extension of at least 50 x 20 m and strikes NE-SW (Figure 3a). The average quartz grain size is here 0.5 – 1.0 mm. The foliation strikes consistently NE-SW and dips 75-85° NW. The reconstructed fold axis dips 30° N (Figure 5a). Figure 4b shows an outcrop (sampling point 15) of mica-rich kyanite quartzite with quartz segregations near the contact to granitic gneiss.

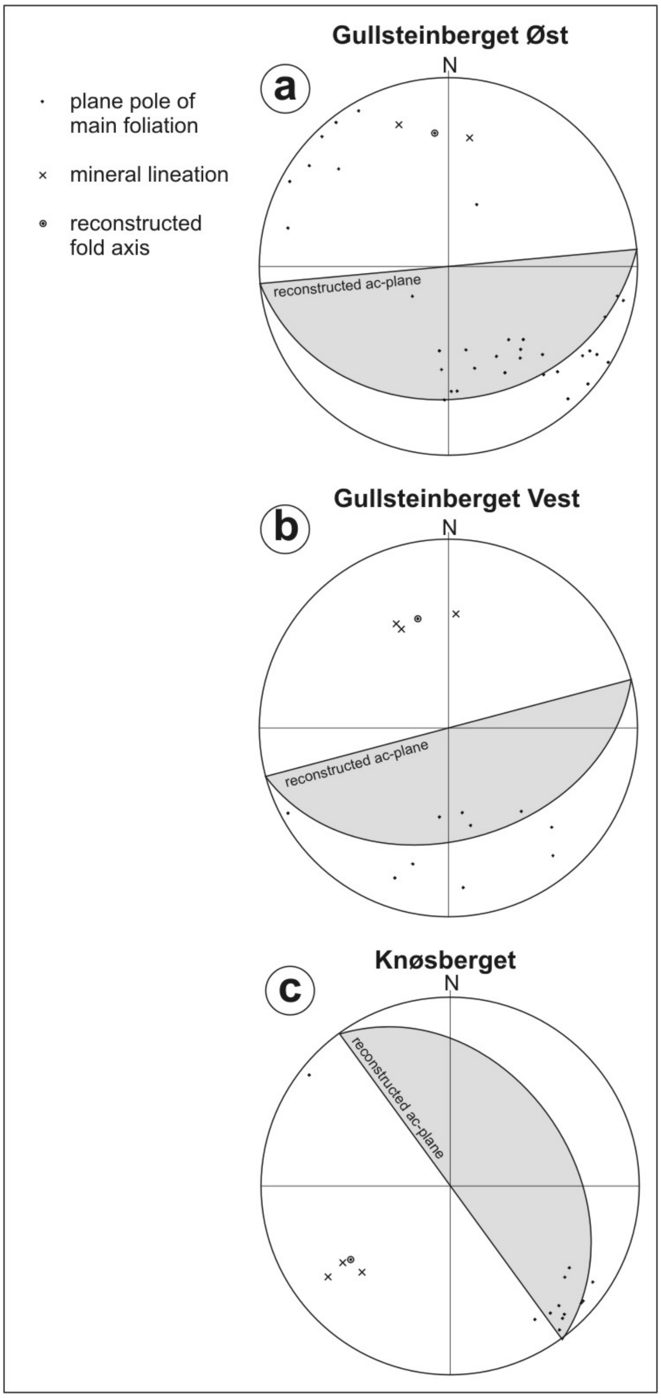

Figure 5. *Schmidt net presentations of measured foliation planes and mineral lineations. The ac-plane and the b axis of the major folding have been reconstructed assuming that the major mineral lineation developed at the foliation plane corresponds to the fold axis of large-scale folds.*

The target area *Gullsteinberget West* can be reached by a 300-m walk along the tractor track starting 200 m SW of the end of the toll road (turning point; Map 1). The tractor track is in poor condition. The kyanite quartzite is here exposed in ca. 60 outcrops (>1 x 1 m) covering an area of 250 (N-S) x 200 (E-W) m. The distance to the nearest weekend house in the W is about 700 m.

A 50 x 40 m large mica-free kyanite quartzite lens of good-quality appearance occurs in the central part of the area (Map 3, Figure 4c). The average quartz grain size is 0.5 to 1.3 mm – the largest grains observed in the deposit. Sampling point 19 lies in the centre of the good-quality body and served as source for the 400-kg sample used in the processing test. The main foliation strikes more or less constantly NE-SW and dips 40-75° NW. The reconstructed fold axis dips 40° NNW (Figure 5b).

2.2 The Knøsberget deposit

The target area of the Knøsberget kyanite quartzite deposit (1:50 000 sheet Kynna 2016I) is best accessible via the private forest road starting N of Knøsen, 6 km NE of Braskereidfoss (Maps 4 and 5). Ca. 500 m N of the farm Knøsen following the private forest road, a tractor track (poor condition) branches off NE-wards from the forest road (Map 4). The target area can be reached by a 700 m long walk from this junction, following the cart track E-wards, turning after 350 m NE-wards and following the marked property border further 350 m (see violet line in Map 4). The forest is dense and it is difficult to orientate in this area.

The Knøsberget deposit is relatively small compared to the Gullsteinberget deposit. The kyanite quartzite is well exposed in the target area in about 20 lumps (>1 x 1 m) covering an area of 80 m (N-S) x 80 m (E-W; Map 5). Here the kyanite quartzite body is much thinner as shown in the map by Jakobsen and Nielsen (1977; Map 4). It is more tectonised (mylonitised) compared to the Gullsteinberget deposit (Figure 4d) resulting, e.g. in more fine-grained quartz (0.2 to 0.6 mm) and kyanite. Pure quartz gash veins (max. 1 m long and 20 cm wide) perpendicular to the main foliation plain are common (Figure 4e). The main foliation strikes NE-SW and dips 65-85° NW. The reconstructed fold axis dips 35° SW (Figure 5c). A lens of moderate mylonitised, mica-free kyanite quartzite of relative high quality (quartz grain size 0.2 to 0.6 mm; marked yellow in Map 5) occurs at the NW contact with biotite gneisses. The lens is about 50 m long and up to 10 m wide. In the other areas the average grain size is 0.2 to 0.4 mm.

Map 5 of the Knøsberget deposit illustrates the distribution of different types of kyanite quartzites in the sense of raw material quality. The discrimination of the different qualities is based on the degree of mylonitisation, average grain size of quartz and muscovite content, but is independent of the kyanite content. The different quality types of the Knøsberget comprise:

4) moderate mylonitised kyanite quartzite with quartz grain size 0.2 – 0.6 mm
5) strong mylonitised kyanite quartzite with quartz grain size 0.2 – 0.4 mm
6) strong mylonitised kyanite quartzite with 1 - 3 vol.% mica and quartz grain size 0.2 mm

Type 1 can be considered as relatively high quality raw material. However, the apparent quartz quality defined by the average quartz grain size and mica content, is not as good as the kyanite quartzites of the Gullsteinberget deposit.

3. Petrography

The kyanite quartzites of Solør are fine-grained, laminated metamorphic rocks containing 70 - 85 vol.% quartz, 10 - 40 vol.% kyanite and occasionally muscovite. The compositional banding of the rock, which parallels the foliation, can be observed on outcrops (meter scale; Figure 4a), in hand specimens (centimetre scale; Figure 4d) and in thin sections (micrometer scale; Figure 6). The visible banding is caused by variations in the kyanite and muscovite contents. The rock can contain up to 40 vol.% kyanite (sample 34), and the average kyanite content is higher in the Knøsberget deposit (ca. 20 vol.%) than in the Gullsteinberget deposit (ca. 15 vol.%). The kyanite is milky white in most of the samples and, therefore, is hardly distinguishable from quartz in hand specimens. Kyanite is greenish in sample 15 only. Homogeneous white, mica-free quartzite samples contain always at least 10 vol.% kyanite! Kyanite plates are commonly 0.1 – 2 mm long and occasionally contain micro inclusion of quartz and/or rutile. The kyanite crystals grew syn-tectonically meaning that they grew parallel to the foliation plane and are partially rotated and broken during subsequent shearing. Examples of kyanite crystal shapes and textures are shown in Figures 6 and 7.

The average grain size of quartz varies between 0.2 and 1.3 mm in the Gullsteinberget and between 0.2 and 0.6 mm in the Knøsberget deposit (Table 1, Figure 8). The distinct difference of the average grain size between the Gullsteinberget and Knøsberget deposit is caused by the more intense deformation (mylonitisation) of the Knøsberget deposit. The Gullsteinberget kyanite quartzite acted more rigidly during deformation due to its larger size. The largest grain sizes of quartz and kyanite occur in the centre of the Gullsteinberget deposit (e.g. samples 2, 3, 9, 11, 19), where the tectonic strain was low. The grain size of quartz in muscovite-bearing samples from Gullsteinberget shows a clear correlation with the muscovite content: High muscovite contents in the rock lead smaller average grain size of quartz (Table 1, Figure 8). The quartz texture with large crystals consists of elongated grains with sutured grain boundaries (Figure 7a). Rock varieties with small crystals form a granobalstic-polygonal texture (Figs. 7c, g).

The kyanite quartzite at Gullsteinberget can contain up to 30 vol.% muscovite (sample 18) whereby the muscovite content tendentiously increases from the centre towards the margin of the kyanite quartzite body. Muscovite-rich samples (>10 vol.%) do not contain kyanite. The Knøsberget kyanite quartzite contains only accessory muscovite up to 3 vol.% (samples 27, 29 and 37) formed during retrograde kyanite alteration. Common accessory minerals are pyrite, rutile zircon and apatite and in one case topaz (sample 19). Pyrite crystals are up to 1 mm in size and most frequent in the Gullsteinberget East deposit (sometimes up to 1 vol.%). Rutile, zircon and apatite are usually not larger than 50 µm and occur as very common inclusions in quartz (Figure 9). Rutile forms small (1-20 µm) prismatic crystals (no needles!) and is the most common inclusion in quartz but also in kyanite (Figure 9). Several ten's of rutile micro inclusions can be found in each thin section. The rutile content riches nearly 1 vol.% in the samples 1-4, 15, 18 (Gullsteinberget East), 28, 34-37 (Knøsberget). Samples from the Gullsteinberget West have generally the lowest rutile content (<0.6 vol.%).

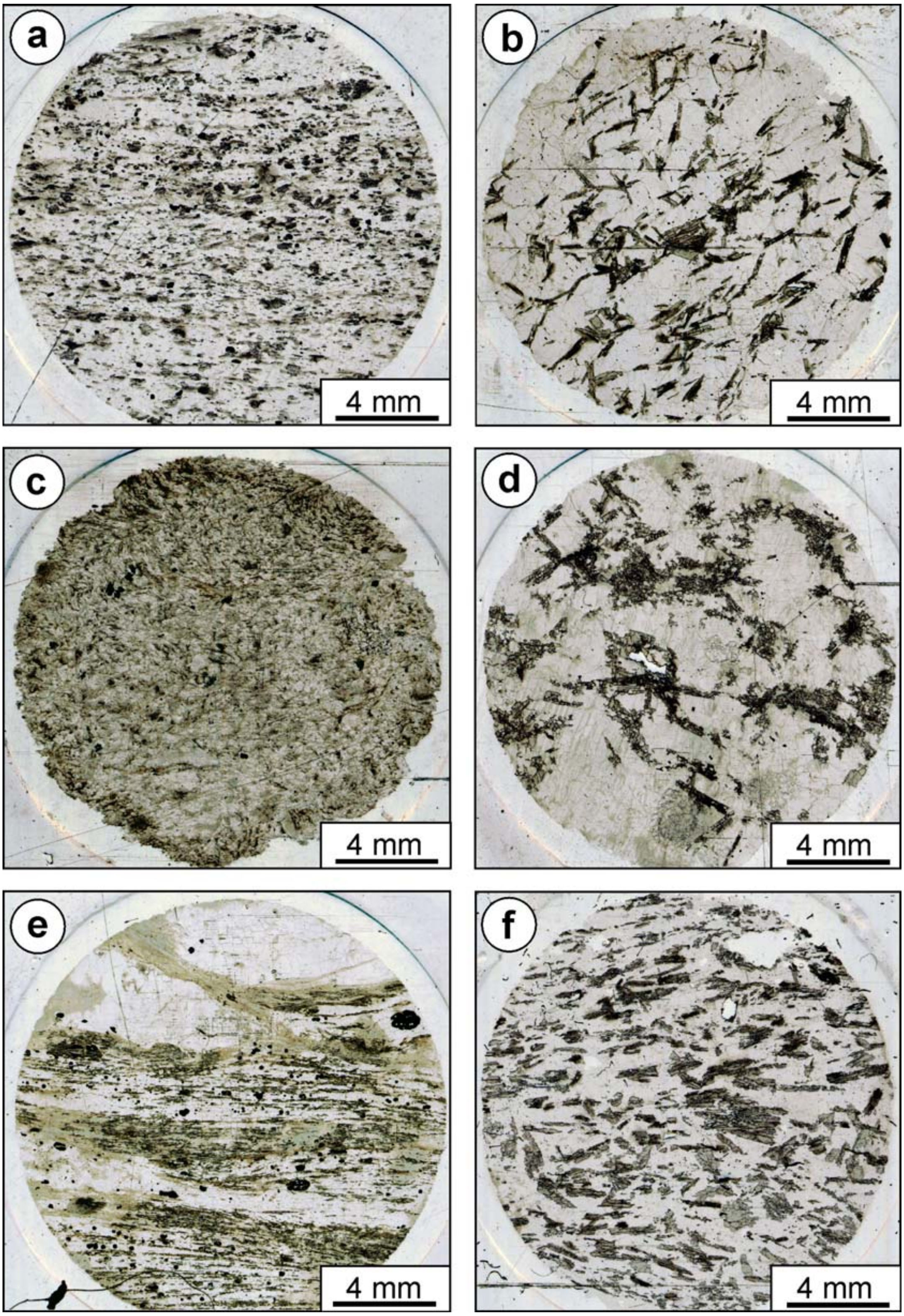

Figure 6. *Thin section scans of kyanite quartzites from Gullsteinberget and Knøsberget. Kyanite appears dark brown, muscovite greenish brown and pyrite black. a – Strongly foliated sample 15 with about 10 vol.% muscovite from Gullsteinberget East. b – Sample 3 considered as good quality rock from Gullsteinberget East. c – Muscovite-rich (ca. 25 vol.%), kyanite-free sample 22 from Gullsteinberget West. d – Good-quality rock of sample 19 with large kyanite crystals from Gullsteinberget West. e – Strongly foliated (mylonite) sample 28 with 2 vol.% pyrite from Knøsberget. f – Typical good-quality rock from Knøsberget (sample 35).*

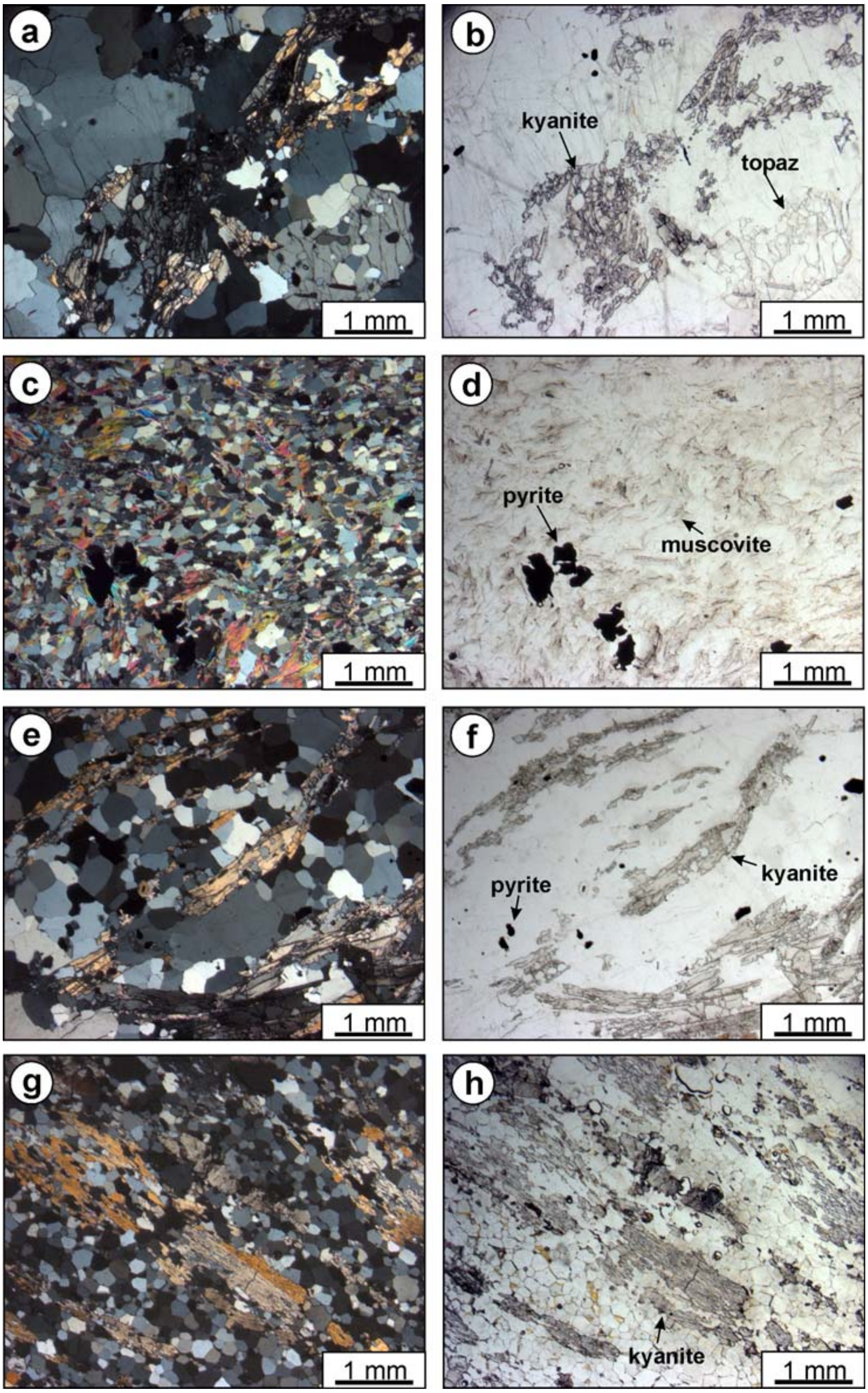

Figure 7. *Thin section photographs of kyanite quartzites.*
a/b – good-quality, mica-free kyanite quartzite (sample 19) from Gullsteinberget West with relative large quartz grains and topaz. The average grain size of quartz in this rock is 1.0 mm. Crossed nicols/Plane light. c/d – Bad-quality, mica-rich (ca. 25 vol.%) kyanite quartzite from Gullsteinberget West with small quartz grains (average grain size is 0.2 mm). The rock is almost free of kyanite. Sample 22. Crossed nicols/Plane light. e/f – Good-quality kyanite, mica-free quartzite (sample 33) from Knøsberget with an average quartz grain size of 0.6 mm. g/h – Low-quality kyanite quartzite (sample 30) from Knøsberget with strong foliation and small quartz grains (average grain size is 0.2 mm).

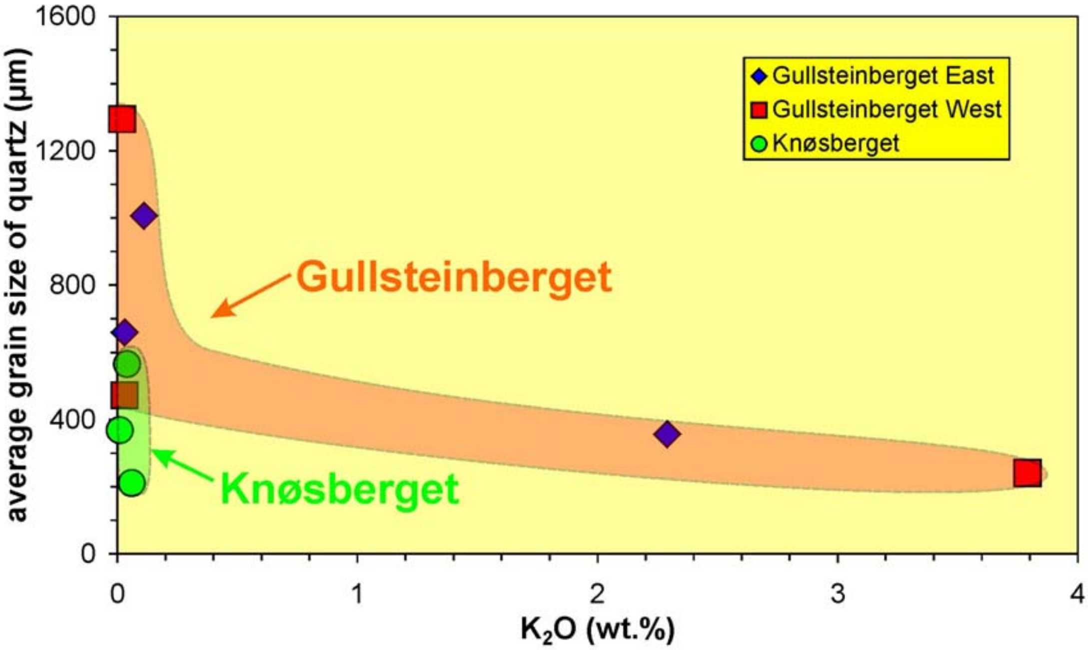

Figure 8. *Plot of the K_2O content of kyanite quartzites versus the average grain size of quartz. K_2O concentration reflects the muscovite content in the rock. Thus, the richer the rock in muscovite, the smaller is the average grain size of quartz. Samples from the Knøsberget deposit are almost free of muscovite but have generally a smaller grain size than quartz from Gullsteinberget due to the higher degree of tectonisation (mylonitisation). The average grain size was determined on samples 9, 15, 16,19, 22, 23, 30, 33 and 35 performing two hundred measurements per sample.*

Table 1. Average grain size of quartz in representative kyanite quartzite samples. The average bases on two hundred grain measurements. Muscovite content was roughly determined by count pointing (100 test points).

deposit	sample nr.	muscovite content (vol.%)	average grain size of quartz (mm)
Gullsteinberget East	09 15 16	<0.1 10 <0.1	1.01 0.36 0.66
Gullsteinberget West	19 22 23	<0.1 25 <0.1	1.30 0.24 0.47
Knøsberget	30 32 35	<0.1 <0.1 <0.1	0.21 0.56 0.37

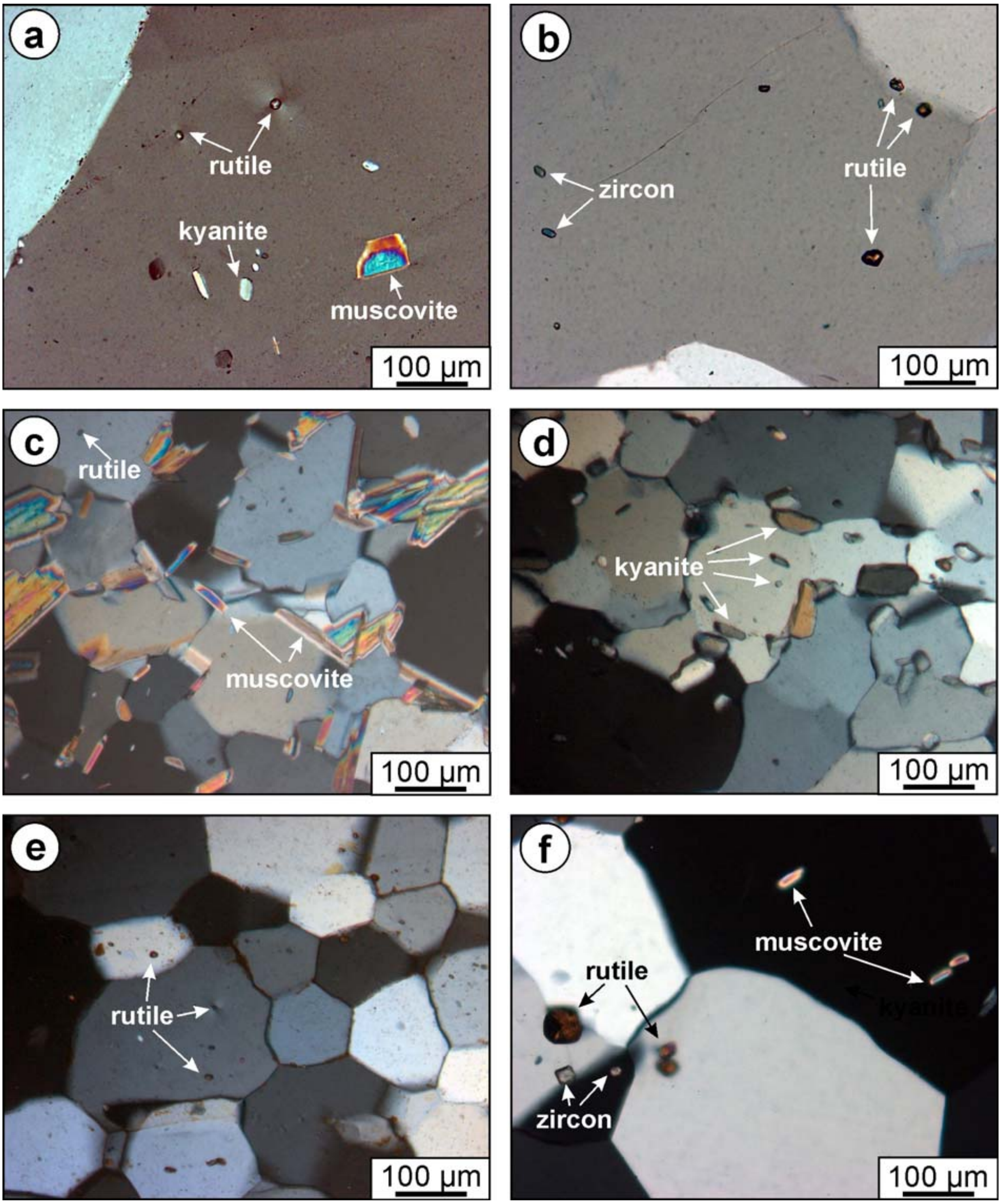

Figure 9. *Thin section micrographs of mineral inclusions in quartz of kyanite quartzite. a – Inclusions in sample 09 from Gullsteinberget East. b – Inclusions in sample 16 from Gullsteinberget East. c – Inclusions in sample 22 from Gullsteinberget West. d – Inclusions in the strongly foliated sample 23 from Gullsteinberget West. e - Inclusions in sample 30 from Knøsberget. f - Inclusions in sample 35 from Knøsberget.*

4. Methods

4.1 Laser ablation inductively coupled mass spectrometry (LA-ICP-MS)

Laser ablation inductively coupled plasma mass spectrometry, LA-ICP-MS, was used for the *in situ* determination of Li, Be, B, Ge, Na, Al, P, K, Ca, Ba, Sr, Pb, Ti, Mn and Fe in quartz grains in the kyanite quartzites. The ICP-MS used in this study is a double focusing sector field instrument (model-ELEMENT-1, Finnigan MAT, Bremen, Germany). The configuration used in this work includes the CD-2 Guard Electrode. A Finnigan MAT, UV laser probe operating at 266 nm with a Gaussian beam profile was used for ablation. A repetition rate of 20 Hz, and pulse energy of 1.5-1.6 mJ with continuous ablation on an area of approximately 140 times 200 µm was used. The laser is not equipped with an aperture, but the laser beam was adjusted to give a spot size of approximately 20 µm. Helium was used as a carrier gas to enhance transport efficiency of ablated material. The helium carrier was mixed with argon as a make-up gas before entering the ICP-MS in order to maintain stable and optimum excitation conditions.

The existence of spectroscopic interferences required the use of variable mass resolutions. Li, Be, B, Ge, Pb, Ba, Sr, and Al were analysed at low mass resolution ($m/\Delta m \approx 300$), while Mn, Na, Ca, P, Ti and Fe required medium mass resolution ($m/\Delta m = 3500$) and K high mass resolution ($m/\Delta m > 8000$). The isotope ^{29}Si, was used as internal standard at low mass resolution, and ^{30}Si at medium and high mass resolution. In addition the argide $^{40}Ar^{40}Ar^+$ was measured in medium and high mass resolution between each analytical measurement and used as lock masses to compensate for time-dependant instrumental mass drift.

External calibration was done using four silicate glass reference materials produced by the National Institute of Standards and Technology (NIST SRM 610, NIST SRM 612, NIST SRM 614, NIST SRM 616). In addition, the standard reference material NIST 1830, soda-lime float glass (0.1 wt.% Al_2O_3) from NIST, the high purity silica BCS 313/1 reference sample from the Bureau of Analysed Samples, UK, the certified reference material "pure substance No. 1" silicon dioxide SiO_2 from the Federal Institute for Material Research and Testing, Berlin, Germany and the Qz-Tu synthetic pure quartz monocrystal provided by Andreas Kronz from the Geowissenschaftliches Zentrum Göttingen (GZG), Germany, were used. Certified, recommended and proposed values for the reference materials are taken from their respective certificates of analysis when available, and if not from Govindaraju (1994), Pearce et al. (1997), Horn et al. (1997), Gao et al. (2002) and Flem and Bedard (2002). Each measurement consists of 15 scans of each isotope, with a measurement time varying from 0.15 s per scan of K in high resolution to 0.024 s per scan of, e.g. Li in low resolution. An Ar-blank was run before each standard and sample measurement. The background signal was subtracted from the instrumental response of the standard before normalisation against the internal standard. This was done to avoid memory effects between samples. A weighted linear regression model including several measurements of the different standard was used for calculation of the calibration curve for each element.

10 successive measurements on the Qz-Tu were used to estimate the limits of detections (LOD; Appendix 4). LOD are based on 3 times standard deviation (3σ) of the 10 measurements divided by the sensitivity S. Flem et al. (2002) gave a more detailed description of the measurement procedure.

5. Results

5.1 Whole rock geochemistry

Whole rock analyses (XRF) of major and trace elements of kyanite quartzites are listed in Appendix 2 and 3, respectively. Generally, kyanite quartzites contain between 10 and 22 wt.% Al_2O_3 which corresponds to kyanite content of 7 to 15 vol.% (Figure 10). Samples 2, 7, 12 and 14 from Gullsteinberget East contain much lower kyanite. Sample 31 from Knøsberget is extreme kyanite rich (ca. 25 vol.%). The average kyanite content of the Knøsberget samples is slightly higher then that of the Gullsteinberget samples. Samples with macroscopic good quality (yellow in Maps 2, 3 and 5) contain maximal 85 wt.% SiO_2 and at least 10 wt.% Al_2O_3 except samples 2, 7, 12 and 14.

Kyanite quartzites are commonly very low in alkalies ($CaO + Na_2O + K_2O$). Samples (4, 8, 13, 15, 22, 25) with a total alkali content >2 wt.% are rich in muscovite and do not contain kyanite. The relative high CaO content in sample 34 (~1 wt.%) from Knøsberget cannot be explained because no Ca-bearing minerals were observed in the thin section.

The TiO_2 concentration reflects the rutile content of the rock. About 0.5 wt.% TiO_2 corresponds to ca. 1 vol.% rutile in the rock. The diagram in Figure 11 shows a clear positive correlation between Ti and Zr content in the rock which indicates that rocks with high rutile content (0.5 – 1 vol.%) are also high in zircon (~0.3 vol.%). Samples from Knøsberget are generally high in zircon and rutile whereas samples from the Gullsteinberget West have the lowest zircon and rutile content.

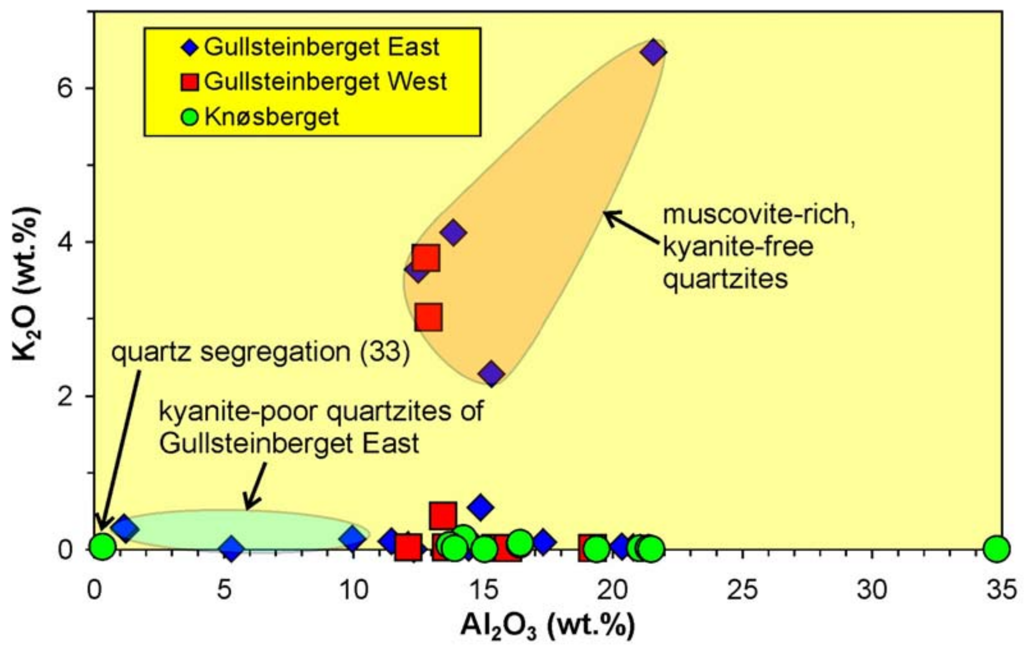

Figure 10. *Al_2O_3 versus alkali plot of XRF whole rock analyses of kyanite quartzites.*

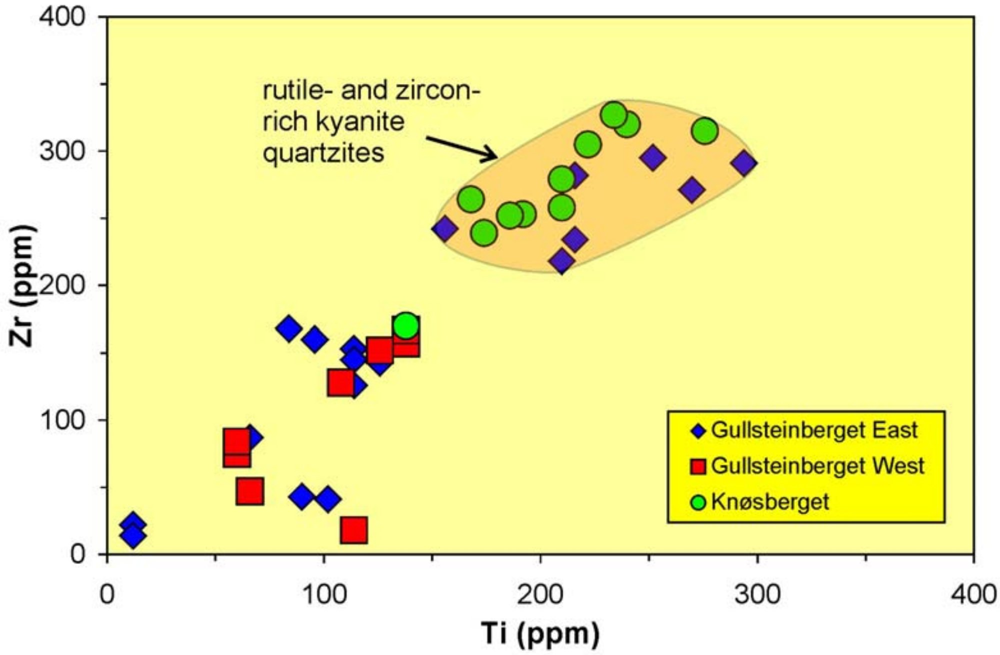

Figure 11. *Ti versus Zr plot of XRF whole rock analyses of kyanite quartzites.*

5.2 Trace elements in quartz

70 LA-ICP-MS analyses on 35 samples were carried out (Appendix 4). Analyses on quartz could not be carried out for three samples: (31056)04 (NGU nr. 37471), (31056)18 (NGU nr. 37485) and (31056)30 (NGU nr. 37497) because the quartz grains are smaller <200 µm in this thin sections. A grain diameter of >200 µm is required because the sampling grid size of the laser is 140 times 200 µm. Sampling grids which cross cut grain boundaries may become contaminated by impurities and minerals occurring along grain boundaries and, thus, the laser grid has to be located within quartz grains. Another analytical problem beside the small quartz grain size is the common presence of micro inclusions of kyanite, rutile, zircon and apatite in quartz. In this study high P and Ca are caused by apatite, high Al (>50 ppm) by kyanite and high Ti (>50 ppm) by rutile (Figure 12).

Concentrations are in the range of 13-44 ppm for Al (average 26 ppm), 4-24 for Ti (average 11 ppm), 1.3-2.7 for Li (average 2.0 ppm), 0.5-1.8 for B (average 1.2 ppm), 0.2-1.3 for Ge (average 0.6 ppm) for the Gullsteinberget East; 15-53 ppm for Al (average 27 ppm), 8-19 for Ti (average 13 ppm), 0.9-2.0 for Li (average 1.5 ppm), 0.7-1.1 for B (average 1.0 ppm), 0.2-1.2 for Ge (average 0.5 ppm) for the Gullsteinberget West and 15-31 ppm for Al (average 22 ppm), 2-5 for Ti (average 4 ppm), 1.2-2.5 for Li (average 1.8 ppm), <0.5-1.3 for B (average 0.9 ppm), <0.1-0.8 for Ge (average 0.5 ppm) for the Knøsberget deposit. Concentrations are similar for the Gullsteinberget East and West. The Ti concentration in quartz from the Knøsberget is significant lower than in quartz from the Gullsteinberget. The lower Ti in the Knøsberget quartz is explained by the lower deformation temperature of about 467°C, whereas the Gullsteinberget East and West were deformed at 537°C and 549°C, respectively, applying the Ti-in-quartz geothermometer (Wark and Watson 2006). Most of the analyses of the Knøsberget quartz which are not contaminated by foreign mineral inclusions plot in the high purity quartz field. Caused by the slightly higher Ti, quartz of the Gullsteinberget plot mostly in the medium purity field.

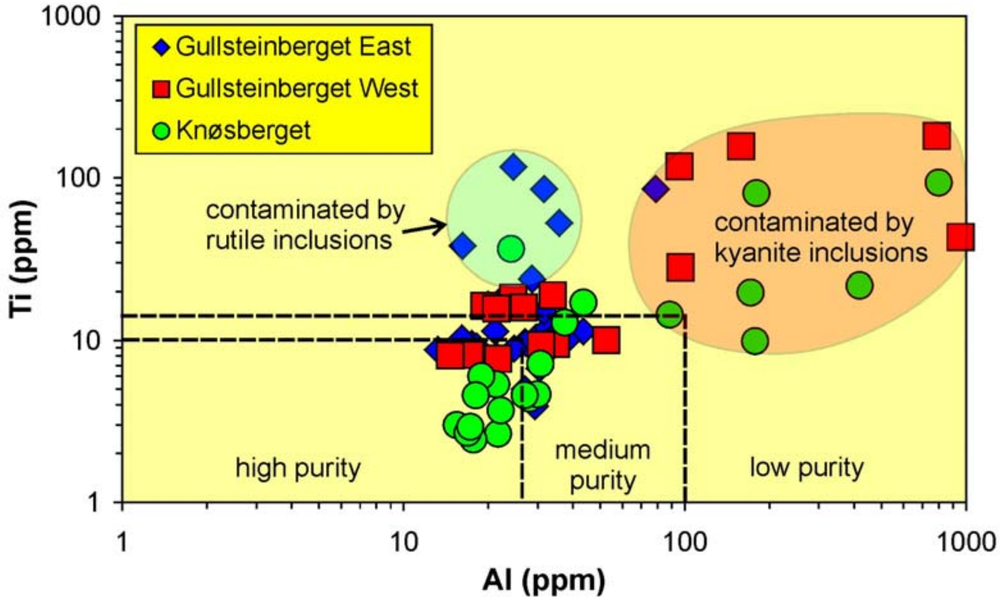

Figure 12. *Al versus Ti in quartz of kyanite quartzites.*
A number of analyses are contaminated by mineral micro inclusions in quartz, such as kyanite and rutile.

6. References

Flem, B., Bedard, L.P. 2002. Determination of trace elements in BCS CRM 313/1 (BAS) and NIST SRM 1830 by inductively coupled plasma-mass spectrometry and instrumental neutron activation analysis. Geostand Newsl. 26: 287-300.

Flem, B., Larsen, R.B., Grimstvedt, A., Mansfeld, J. 2002. In situ analysis of trace elements in quartz by using laser ablation inductively coupled plasma mass spectrometry. Chem. Geol. 182: 237-247.

Gao, S., Liu, X., Yuan, H., Hattendorf, B., Günther, D., Chen, L., Hu, S. 2002. Determination of forty-two major and trace elements in USGS and NIST SRM glasses by laser ablation-inductively coupled plasma-mass spectrometry. Geostand. Newsl. 26: 181-196.

Govindaraju, K. 1994. Compilation of working values and sample description for 383 geostandards. Geostand. Newsl. 18 (Special Issue): 1-158.

Gvein, Ø., Skålvoll, H., Sverdrup, T. 1974. Geologisk kart over Norge, Berggrunnskart Torsby, M 1 : 250.000. Norges Geologiske Undersøkelse.

Harben, P.W. 2002. The industrial mineral handybook – a guide to markets, specifications and prices. Ind. Min. Information, Worcester Park, United Kingdom, 4th ed., p.412.

Horn, I., Hinton, R.W., Jackson, S.E., Longerich, H.P. 1997. Ultra-trace element analysis of NIST SRM 616 and 614 using laser ablation microprobe inductively coupled plasma mass spectrometry (LAM-ICP-MS): a comparison with secondary ion mass spectrometry (SIMS). Geostand. Newsl. 21: 191-203.

Jakobsen, B.M., Nielsen, E. 1977. Kyanite kvartsit projektet 1976-1977. Laboratorienrapport. Endogen Laboratorium. Geologisk Institut Århus Universitet, p.19.

Müller, A., Wanvik, J.E., Kronz, A. 2005. Norwegian kyanite quartzites – potential resources of high purity quartz? Norges Geologiske Undersøkelse, Rapport 2005.039.

Nordgulen, Ø. 1999. Geologisk kart over Norge, Berggrunnskart Hamar, M 1 : 250.000. Norges geologiske undersøkelse.

Pearce, N.J.G., Perkins, W.T., Westgate, J.W., Gorton, M.P., Jackson, S.E., Neal, C.R., Chenery, S.P. 1997. A compilation of new and published major and trace element data for NIST SRM 610 and NIST SRM 612 glass reference materials. Geostand. Newsl. 21: 115-144.

Wark, D.A., Watson, E.B. 2006. TitaniQ: a titanium-in-quartz geothermometer. Contrib. Mineral. Petrol. 152: 743-754.

7. Appendix

Appendix 1. Sample list. Samples (31056)S01-S10 are 5-kg samples for processing tests.

locality	sample nr.	NGU nr.	UTM coordinates			rock
			zone	E	N	
Gullsteinberg øst	(31056)01	37468	33	345436	6736123	kyanite quartzite
Gullsteinberg øst	(31056)02	37469	33	345439	6736125	kyanite quartzite
Gullsteinberg øst	(31056)03	37470	33	345451	6736127	kyanite quartzite
Gullsteinberg øst	(31056)04	37471	33	345448	6736122	kyanite quartzite
Gullsteinberg øst	(31056)05	37472	33	345476	6736124	kyanite quartzite
Gullsteinberg øst	(31056)06	37473	33	345483	6736122	kyanite quartzite
Gullsteinberg øst	(31056)07	37474	33	345490	6736121	kyanite quartzite
Gullsteinberg øst	(31056)08	37475	33	345507	6736095	kyanite quartzite
Gullsteinberg øst	(31056)09	37476	33	345530	6736078	kyanite quartzite
Gullsteinberg øst	(31056)10	37477	33	345525	6736067	kyanite quartzite
Gullsteinberg øst	(31056)11	37478	33	345555	6736084	kyanite quartzite
Gullsteinberg øst	(31056)12	37479	33	345530	6736128	kyanite quartzite
Gullsteinberg øst	(31056)13	37480	33	345422	6736124	kyanite quartzite
Gullsteinberg øst	(31056)14	37481	33	345370	6736085	kyanite quartzite
Gullsteinberg øst	(31056)15	37482	33	345345	6736092	kyanite quartzite
Gullsteinberg øst	(31056)16	37483	33	345405	6736080	kyanite quartzite
Gullsteinberg øst	(31056)17	37484	33	345411	6736083	kyanite quartzite
Gullsteinberg øst	(31056)18	37485	33	345432	6736104	kyanite quartzite
Gullsteinberg øst	(31056)S01		33	345540	6736073	kyanite quartzite
Gullsteinberg øst	(31056)S02		33	345558	6736074	kyanite quartzite
Gullsteinberg øst	(31056)S03		33	345527	6736063	kyanite quartzite
Gullsteinberg vest	(31056)19	37486	33	344789	6735582	kyanite quartzite
Gullsteinberg vest	(31056)20	37487	33	344800	6735634	kyanite quartzite
Gullsteinberg vest	(31056)21	37488	33	344748	6735670	kyanite quartzite
Gullsteinberg vest	(31056)22	37489	33	344760	6735685	kyanite quartzite
Gullsteinberg vest	(31056)23	37490	33	344798	6735566	kyanite quartzite
Gullsteinberg vest	(31056)24	37491	33	344790	6735538	kyanite quartzite
Gullsteinberg vest	(31056)25	37492	33	344815	6735535	kyanite quartzite
Gullsteinberg vest	(31056)26	37493	33	344770	6735505	kyanite quartzite
Gullsteinberg vest	(31056)S05		33	344795	6735632	kyanite quartzite
Gullsteinberg vest	(31056)S06		33	344780	6735578	kyanite quartzite
Gullsteinberg vest	(31056)S07		33	344800	6735580	kyanite quartzite
Knøsberg	(31056)27	37494	32	657321	6740033	kyanite quartzite
Knøsberg	(31056)28	37495	32	657309	6740014	kyanite quartzite
Knøsberg	(31056)29	37496	32	657313	6740005	kyanite quartzite
Knøsberg	(31056)30	37497	32	657289	6740003	kyanite quartzite
Knøsberg	(31056)31	37498	32	657290	6740007	kyanite quartzite
Knøsberg	(31056)32	37499	32	657290	6740014	kyanite quartzite
Knøsberg	(31056)33	37500	32	657293	6740016	exudat quartz
Knøsberg	(31056)34	39591	32	657285	6739994	kyanite quartzite
Knøsberg	(31056)35	39592	32	657283	6739999	kyanite quartzite
Knøsberg	(31056)36	39593	32	657280	6740002	kyanite quartzite
Knøsberg	(31056)37	39594	32	657283	6740009	kyanite quartzite
Knøsberg	(31056)38	39595	32	657267	6739992	kyanite quartzite
Knøsberg	(31056)S08		32	657287	6740003	kyanite quartzite
Knøsberg	(31056)S09		32	657262	6739988	kyanite quartzite
Knøsberg	(31056)S10		32	657283	6740009	kyanite quartzite

Appendix 2. Whole rock analyses (XRF) of major elements of kyanite quartzites. LOD – limits of detection; GE – Gullsteinberget East; GW – Gullsteinberget West; K – Knøsberget.

			SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MgO	CaO	Na_2O	K_2O	MnO	P_2O_5	LOI	SUM
			wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%
		LOD	0.10	0.10	0.01	0.01	0.01	0.01	0.1	0.01	0.01	0.01		
sample nr.	deposit	NGU nr.												
(31056)01	GE	37468	76.54	17.31	2.81	0.45	0.06	<0.01	0.24	0.1	<0.01	0.02	2.35	99.89
(31056)02	GE	37469	89.74	5.29	1.45	0.42	0.05	0.01	0.18	<0.01	<0.01	0.02	0.99	98.17
(31056)03	GE	37470	85.22	12.32	0.14	0.36	0.04	<0.01	0.23	0.01	<0.01	0.03	0.61	98.96
(31056)04	GE	37471	66.75	21.56	1.36	0.49	0.31	<0.01	0.37	6.47	<0.01	0.07	2.9	100.28
(31056)05	GE	37472	84.32	12.1	0.94	0.19	0.03	<0.01	0.27	0.06	<0.01	0.01	1.38	99.32
(31056)06	GE	37473	84.25	14.01	0.1	0.19	0.04	<0.01	0.25	0.04	<0.01	0.02	0.52	99.44
(31056)07	GE	37474	96.97	1.21	0.52	0.19	<0.01	<0.01	0.2	0.26	<0.01	0.01	0.47	99.84
(31056)08	GE	37475	80.78	12.49	0.78	0.11	0.1	<0.01	0.32	3.64	<0.01	0.01	1.7	99.94
(31056)09	GE	37476	83.73	11.46	0.62	0.14	0.05	<0.01	0.23	0.11	<0.01	<0.01	2.36	98.72
(31056)10	GE	37477	78	20.78	0.09	0.02	0.04	0.01	0.21	0.03	<0.01	0.02	1.16	100.36
(31056)11	GE	37478	79.29	20.35	0.03	0.02	0.07	<0.01	0.23	0.04	<0.01	0.03	1.52	101.6
(31056)12	GE	37479	99.56	1.15	0.22	0.21	0.03	<0.01	0.27	0.29	<0.01	<0.01	0.25	102
(31056)13	GE	37480	83.92	14.9	1.03	0.26	0.09	<0.01	0.26	0.55	<0.01	0.04	1.18	102.24
(31056)14	GE	37481	89.22	9.95	0.86	0.17	0.03	0.01	0.25	0.14	<0.01	0.03	1.17	101.84
(31056)15	GE	37482	77.88	15.32	2.39	0.36	0.17	<0.01	0.34	2.29	<0.01	0.04	3.19	101.99
(31056)16	GE	37483	83.37	14.44	0.51	0.15	0.05	<0.01	0.24	0.03	<0.01	0.05	0.61	99.43
(31056)17	GE	37484	83.53	14.55	0.18	0.16	0.04	<0.01	0.24	0.1	<0.01	0.01	0.84	99.65
(31056)18	GE	37485	78.24	13.85	0.59	0.35	0.37	<0.01	0.42	4.12	<0.01	0.04	1.82	99.82
(31056)19	GW	37486	77.96	19.21	0.04	0.19	0.03	<0.01	0.24	0.02	<0.01	0.04	1.19	98.93
(31056)20	GW	37487	82.28	15.46	0.11	0.11	0.03	<0.01	0.2	0.02	<0.01	0.02	0.5	98.73
(31056)21	GW	37488	82.54	13.57	0.96	0.23	0.05	<0.01	0.2	0.03	<0.01	0.01	1.22	98.83
(31056)22	GW	37489	80.02	12.79	0.59	0.23	0.04	<0.01	0.28	3.79	<0.01	0.02	2	99.76
(31056)23	GW	37490	82.21	12.11	1.93	0.21	<0.01	<0.01	0.23	0.03	<0.01	0.01	1.78	98.52
(31056)24	GW	37491	82.18	15.96	0.09	0.1	0.05	<0.01	0.22	0.02	<0.01	0.03	0.36	99.02
(31056)25	GW	37492	79.7	12.89	0.85	0.18	0.09	<0.01	0.43	3.02	<0.01	0.02	2.05	99.24
(31056)26	GW	37493	83.25	13.45	0.48	0.1	0.05	<0.01	0.24	0.44	<0.01	0.03	1.33	99.38
(31056)27	K	37494	75.92	21.05	0.09	0.4	0.06	<0.01	0.25	0.02	<0.01	0.06	1.15	99.01
(31056)28	K	37495	76.78	14.23	2.55	0.35	0.06	0.01	0.18	0.15	<0.01	0.1	4.81	99.23
(31056)29	K	37496	78.78	13.7	1.84	0.28	0.02	<0.01	0.22	0.06	<0.01	0.02	3.11	98.03
(31056)30	K	37497	83.2	13.9	0.73	0.32	0.04	<0.01	0.27	0.02	<0.01	0.08	0.63	99.2
(31056)31	K	37498	62.79	34.8	0.12	0.31	0.06	<0.01	0.21	<0.01	<0.01	0.08	1.14	99.52
(31056)32	K	37499	78.32	19.37	0.25	0.29	0.03	<0.01	0.25	<0.01	<0.01	0.04	0.46	99.02
(31056)33	K	37500	98.36	0.32	0.05	<0.01	<0.01	<0.01	0.24	0.04	<0.01	0.02	0.17	99.22
(31056)34	K	39591	75.77	16.4	1.04	0.46	0.04	0.92	0.2	0.07	<0.01	0.73	2.91	98.53
(31056)35	K	39592	82.09	15.05	0.08	0.35	0.04	<0.01	0.25	0.01	<0.01	0.06	1.06	99
(31056)36	K	39593	76.48	21.38	0.12	0.37	0.06	<0.01	0.25	0.02	<0.01	0.09	0.75	99.54
(31056)37	K	39594	81.15	16.42	0.05	0.39	0.05	<0.01	0.27	0.09	<0.01	0.07	0.45	98.94
(31056)38	K	39595	76.56	21.48	0.04	0.23	0.08	<0.01	0.19	0.01	<0.01	0.03	0.54	99.17

Appendix 3. Whole rock analyses of selected trace elements of kyanite quartzites. Sb, Sn, Cu, Ni, Yb, Co, Nd, Cs, Ta, Pr, Mo, Y, U, V, As, Sc, and Hf are mostly below the limit of detection (LOD) of 5 and 10 ppm, respectively. GE – Gullsteinberget East; GW – Gullsteinberget West; K – Knøsberget.

		Nb	Zr	Sr	Rb	Th	Pb	Cr	Ba	Ga	Zn	Ce	La	W
		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	LOD	5	5	5	5	5	10	10	10	10	5	10	10	10
sample nr.	deposit													
(31056)01	GE	18	271	52	<5	<5	10	26	1583	11	14	21	45	17
(31056)02	GE	17	295	36	<5	<5	14	<10	671	<10	10	<10	25	21
(31056)03	GE	13	234	18	<5	<5	<10	13	41	<10	10	<10	17	27
(31056)04	GE	20	291	7	210	<5	11	63	536	18	35	15	35	18
(31056)05	GE	17	153	<5	<5	<5	<10	<10	72	<10	11	<10	22	22
(31056)06	GE	15	126	23	<5	<5	<10	<10	188	15	11	<10	28	26
(31056)07	GE	21	145	<5	6	5	<10	<10	11	<10	11	<10	20	21
(31056)08	GE	18	87	<5	137	<5	<10	38	75	11	18	<10	17	20
(31056)09	GE	15	168	38	<5	<5	<10	22	23	<10	11	<10	21	25
(31056)10	GE	<5	22	17	<5	<5	<10	148	<10	15	10	<10	11	27
(31056)11	GE	<5	14	28	<5	<5	<10	<10	10	15	11	<10	16	26
(31056)12	GE	16	143	<5	9	7	<10	<10	15	<10	12	<10	21	23
(31056)13	GE	14	242	6	16	<5	<10	82	43	14	16	<10	15	24
(31056)14	GE	14	41	32	<5	<5	<10	<10	526	<10	13	<10	28	23
(31056)15	GE	13	282	43	81	12	21	<10	1119	<10	30	22	33	19
(31056)16	GE	14	43	21	<5	<5	<10	16	277	<10	12	<10	20	24
(31056)17	GE	16	160	<5	<5	<5	<10	<10	36	<10	13	<10	11	26
(31056)18	GE	14	218	<5	141	9	<10	85	431	11	43	64	61	24
(31056)19	GW	12	18	36	<5	<5	<10	37	26	19	10	<10	17	23
(31056)20	GW	17	47	<5	<5	<5	<10	<10	71	12	13	<10	13	22
(31056)21	GW	14	157	<5	<5	<5	<10	<10	25	<10	15	<10	11	19
(31056)22	GW	15	167	9	124	<5	<10	105	490	<10	17	<10	26	22
(31056)23	GW	17	152	<5	<5	<5	<10	53	235	<10	12	<10	21	23
(31056)24	GW	13	75	<5	<5	<5	<10	<10	24	13	10	<10	14	23
(31056)25	GW	22	128	10	142	11	24	<10	227	14	30	21	32	20
(31056)26	GW	16	84	8	10	<5	<10	85	40	<10	10	<10	16	23
(31056)27	K	18	320	89	<5	5	<10	40	1693	17	10	33	46	37
(31056)28	K	14	279	563	<5	<5	<10	33	2109	12	11	52	83	20
(31056)29	K	12	264	76	<5	<5	<10	10	2826	10	8	<10	50	16
(31056)30	K	13	253	192	<5	15	27	13	1456	<10	11	81	79	25
(31056)31	K	26	252	94	<5	8	<10	99	861	33	10	20	44	28
(31056)32	K	13	239	36	<5	12	<10	<10	498	25	9	41	62	23
(31056)33	K	<5	12	148	<5	<5	<10	<10	81	<10	11	<10	18	21
(31056)34	K	15	315	562	<5	<5	12	<10	1601	<10	10	61	85	20
(31056)35	K	20	258	91	<5	9	14	<10	2000	10	11	83	128	29
(31056)36	K	15	305	107	<5	22	<10	21	286	13	9	129	136	31
(31056)37	K	20	327	90	<5	22	<10	42	2690	11	9	98	88	30
(31056)38	K	18	170	28	<5	<5	<10	57	50	28	11	<10	27	28

Appendix 4. Trace element concentrations (ppm) of quartz from kyanite quartzites determined by LA-ICP-MS. Limits for detection (LOD) are shown in the second line. The "A" and "B" measurements of Li have to different detection limits 3 and 1.1 ppm, respectively. Concentrations marked in yellow are considered as high purity quartz (Al <25 ppm, Ti <10 ppm, Li <3 ppm). Analyses contaminated by mineral micro inclusions are marked as follows: Green – contaminated by kyanite; blue – contaminated by rutile; red – contaminated by apatite.

			Li	Be	B	Al	Ge	Sr	Ba	Pb	Na	P	K	Ca	Ti	Mn	Fe
LOD			1.1/3	0.1	0.5	4.3	0.1	0.1	0.1	0.1	9.0	3.0	4.0	31.0	1.2	0.2	0.3
sample nr.	deposit	NGU nr.															
(31056)01	GE	37468-A	<3	<0.1	1.4	28.6	0.4	0.1	<0.1	<0.1	<9	6.3	11.4	<31	23.9	<0.2	2.1
		37468-B	2.2	<0.1	2.0	35.8	0.4	0.1	<0.1	<0.1	9.2	<3	<4	<31	52.7	0.7	1.4
(31056)02	GE	37469-A	<3	<0.1	1.5	43.6	0.3	0.1	<0.1	<0.1	<9	4.1	<4	<31	11.4	<0.2	0.3
		37469-B	1.4	<0.1	1.7	34.3	0.4	0.1	<0.1	<0.1	<9	3.1	<4	<31	12.8	<0.2	<0.3
(31056)03	GE	37470-A	<3	0.1	1.2	21.7	0.4	0.1	<0.1	<0.1	<9	5.5	<4	<31	7.9	<0.2	0.5
		37470-B	2.2	0.1	1.6	29.7	0.4	0.1	<0.1	<0.1	<9	6.0	<4	<31	10.4	<0.2	<0.3
(31056)05	GE	37472-A	<3	<0.1	1.4	31.6	0.4	<0.1	<0.1	<0.1	<9	3.9	<4	<31	85.2	<0.2	1.7
		37472-B	2.2	<0.1	1.8	22.5	0.3	<0.1	<0.1	<0.1	<9	3.7	<4	<31	18.2	<0.2	0.6
(31056)06	GE	37473-A	<3	<0.1	0.9	17.6	0.3	0.1	<0.1	<0.1	<9	<3	6.0	33.0	8.9	<0.2	0.3
		37473-B	2.3	0.1	1.3	32.6	0.3	0.1	<0.1	<0.1	<9	5.6	<4	<31	11.9	<0.2	0.5
(31056)07	GE	37474-A	<3	<0.1	1.5	26.1	0.9	0.1	<0.1	<0.1	<9	6.2	<4	<31	16.9	<0.2	0.6
		37474-B	2.4	0.1	1.5	16.2	0.8	0.1	<0.1	<0.1	<9	3.5	<4	<31	38.0	<0.2	1.0
(31056)08	GE	37475-A	<3	0.1	1.5	29.3	1.2	0.1	<0.1	<0.1	<9	4.1	16.9	<31	3.9	<0.2	0.9
		37475-B	2.7	<0.1	1.1	27.0	1.3	0.1	<0.1	<0.1	<9	3.1	<4	<31	5.0	<0.2	<0.3
(31056)09	GE	37476-A	<3	<0.1	0.8	30.5	0.5	0.1	<0.1	<0.1	<9	<3	<4	<31	6.7	<0.2	<0.3
		37476-B	2.0	<0.1	1.3	30.7	0.5	0.1	<0.1	<0.1	<9	<3	<4	<31	8.2	<0.2	<0.3
(31056)10	GE	37477-A	<3	<0.1	1.1	38.1	0.2	0.1	<0.1	<0.1	<9	<3	<4	<31	10.0	<0.2	0.5
		37477-B	2.0	<0.1	1.3	34.5	0.3	0.1	<0.1	<0.1	<9	<3	<4	<31	10.7	0.2	0.4
(31056)11	GE	37478-A	<3	0.1	0.5	27.0	0.8	0.1	<0.1	<0.1	<9	<3	<4	41.8	9.7	<0.2	0.4
		37478-B	1.9	<0.1	1.4	30.1	0.7	<0.1	0.1	<0.1	<9	<3	<4	<31	8.6	<0.2	0.3
(31056)12	GE	37479-A	<3	0.1	1.2	17.5	0.9	0.1	<0.1	0.2	<9	4.2	<4	<31	9.5	1.3	4.3
		37479-B	1.6	<0.1	0.9	13.2	0.9	0.1	<0.1	<0.1	<9	3.7	<4	<31	8.8	<0.2	<0.3
(31056)13	GE	37480-A	<3	0.1	0.7	27.2	0.7	0.1	<0.1	<0.1	<9	3.7	<4	<31	9.6	<0.2	<0.3
		37480-B	2.5	<0.1	1.4	16.5	0.7	<0.1	<0.1	<0.1	<9	3.0	<4	<31	8.2	<0.2	<0.3
(31056)14	GE	37481-A	<3	<0.1	1.0	16.1	0.3	0.1	<0.1	<0.1	<9	6.8	<4	<31	10.3	<0.2	2.0
		37481-B	1.6	0.1	1.4	31.5	0.4	0.1	<0.1	<0.1	<9	4.6	34.3	<31	15.1	0.2	7.4
(31056)15	GE	37482-A	<3	<0.1	1.3	18.1	0.5	0.1	<0.1	<0.1	<9	0.4	<4	<31	9.2	0.1	<0.3
		37482-B	1.5	<0.1	1.1	24.6	0.7	0.1	<0.1	<0.1	<9	<3	<4	<31	116.9	<0.2	1.4
(31056)16	GE	37483-A	<3	0.1	1.0	21.2	0.4	0.1	<0.1	<0.1	<9	<3	<4	<31	11.4	<0.2	0.4
		37483-B	1.3	0.1	1.2	24.7	0.4	<0.1	<0.1	<0.1	<9	<3	<4	<31	8.9	<0.2	0.6
(31056)17	GE	37484-A	<3	0.1	1.6	20.0	0.2	0.1	0.3	0.1	57.6	25.2	48.4	816.1	16.6	0.5	34.5
		37484-B	1.7	0.1	1.8	78.8	0.3	0.2	0.2	0.5	33.0	4.3	55.3	49.0	85.1	2.2	87.1
(31056)19	GW	37486-A	<3	<0.1	1.1	52.6	0.5	0.1	0.4	0.1	<9	3.2	13.0	<31	10.0	1.0	12.9
		37486-B	0.9	<0.1	1.1	34.7	0.5	0.1	<0.1	<0.1	10.2	<3	<4	<31	9.5	0.2	0.9
(31056)20	GW	37487-A	<3	0.1	0.9	24.5	0.5	0.1	<0.1	<0.1	<9	4.6	<4	<31	18.5	<0.2	<0.3
		37487-B	1.7	<0.1	1.1	96.7	0.5	<0.1	<0.1	<0.1	<9	<3	<4	<31	28.1	<0.2	0.5
(31056)21	GW	37488-A	<3	<0.1	1.5	158.2	0.2	0.1	0.2	0.1	30.3	12.5	173.2	<31	157.2	0.2	43.8
		37488-B	1.5	<0.1	1.1	26.8	0.3	<0.1	<0.1	<0.1	<9	<3	14.4	36.8	16.0	<0.2	<0.3
(31056)22	GW	37489-A	<3	0.1	2.5	788.4	0.6	0.4	1.2	2.3	14.5	17.9	91.1	182.8	181.0	6.9	70.9
		37489-B	1.8	0.2	1.2	95.6	0.8	0.4	0.8	0.2	<9	19.2	102.2	<31	118.0	0.5	36.8

Appendix 4. Continued.

			Li	Be	B	Al	Ge	Sr	Ba	Pb	Na	P	K	Ca	Ti	Mn	Fe
LOD			1.1/3	0.1	0.5	4.3	0.1	0.1	0.1	0.1	9.0	3.0	4.0	31.0	1.2	0.2	0.3
sample nr.	deposit	NGU nr.															
(31056)23	GW	37490-A	<3	0.1	0.9	30.8	0.0	0.1	<0.1	<0.1	<9	<3	<4	<31	9.3	<0.2	0.3
		37490-B	2.0	<0.1	0.7	19.4	0.2	<0.1	<0.1	<0.1	<9	<3	<4	<31	16.4	<0.2	<0.3
(31056)24	GW	37491-A	<3	<0.1	1.1	33.9	0.7	0.1	<0.1	<0.1	<9	3.8	<4	<31	19.0	0.4	0.4
		37491-B	1.5	<0.1	1.0	21.3	0.6	0.1	<0.1	<0.1	<9	<3	<4	<31	15.7	<0.2	<0.3
(31056)25	GW	37492-A	<3	<0.1	0.8	21.7	1.0	0.1	<0.1	<0.1	<9	<3	<4	<31	7.7	<0.2	<0.3
		37492-B	1.6	<0.1	1.0	17.3	1.2	0.1	<0.1	<0.1	<9	3.8	<4	<31	8.1	<0.2	0.4
(31056)26	GW	37493-A	<3	<0.1	0.9	955.7	0.4	0.1	0.1	<0.1	<9	6.5	175.9	<31	43.2	<0.2	8.9
		37493-B	1.3	<0.1	0.7	14.6	0.4	0.1	<0.1	<0.1	<9	<3	<4	<31	8.1	<0.2	0.6
(31056)27	K	37494-A	<3	<0.1	0.9	15.4	<0.1	0.1	<0.1	<0.1	<9	<3	<4	<31	3.0	<0.2	<0.3
		37494-B	1.5	<0.1	0.8	21.6	<0.1	<0.1	<0.1	<0.1	<9	<3	<4	<31	2.7	<0.2	<0.3
(31056)28	K	37495-A	<3	<0.1	0.8	17.7	0.5	0.1	<0.1	<0.1	<9	<3	<4	<31	2.4	<0.2	0.5
		37495-B	1.2	<0.1	0.8	16.9	0.5	0.1	<0.1	<0.1	<9	<3	<4	<31	2.7	<0.2	0.4
(31056)29	K	37496-A	<3	<0.1	0.7	22.2	0.7	0.1	<0.1	<0.1	<9	5.7	<4	<31	3.7	<0.2	0.3
		37496-B	2.5	<0.1	1.3	17.3	0.8	0.1	<0.1	<0.1	<9	<3	<4	31.6	2.9	0.4	1.0
(31056)31	K	37498-A	<3	0.1	0.7	24.1	0.2	0.1	<0.1	<0.1	<9	4.3	<4	53.3	36.5	<0.2	0.9
		37498-B	1.8	0.1	1.0	179.8	0.5	29.8	1.1	2.2	<9	38.7	<4	47.3	80.6	<0.2	1.2
(31056)32	K	37499-A	<3	<0.1	0.8	21.3	0.7	0.1	<0.1	<0.1	10.5	<3	4.2	<31	5.4	0.2	0.7
		37499-B	1.8	<0.1	1.2	30.7	0.5	0.1	<0.1	<0.1	<9	4.1	<4	<31	7.2	<0.2	0.9
(31056)33	K	37500-A	<3	<0.1	0.2	28.0	0.5	0.1	<0.1	<0.1	<9	<3	<4	77.4	4.4	<0.2	<0.3
		37500-B	1.8	0.1	0.7	29.9	0.3	0.1	<0.1	<0.1	<9	<3	<4	<31	4.6	0.3	0.6
(31056)34	K	39591-A	<3	0.1	<0.5	18.9	0.1	0.8	0.5	0.3	<9	61.6	<4	<31	6.0	<0.2	17.5
		39591-B	2.1	<0.1	1.2	27.0	0.2	0.1	0.1	0.1	<9	5.6	<4	<31	4.6	0.2	3.7
(31056)35	K	39592-A	<3	<0.1	0.9	43.6	0.1	0.5	1.3	0.6	9.7	12.0	23.0	338.7	17.1	2.7	167.3
		39592-B	2.0	<0.1	1.6	37.4	0.2	0.8	0.3	0.3	18.4	6.7	10.1	<31	12.9	3.3	20.3
(31056)36	K	39593-A	<3	0.1	0.8	88.3	0.4	14.6	0.5	0.9	<9	38.9	<4	47.5	14.4	<0.2	0.8
		39593-B	1.5	0.1	1.1	418.1	0.4	33.6	17.9	4.8	<9	177.5	<4	105.5	21.8	<0.2	2.2
(31056)37	K	39594-A	<3	0.1	<0.5	18.1	0.3	0.2	0.1	0.1	19.8	<3	5.8	<31	4.6	<0.2	2.0
		39594-B	2.5	<0.1	1.8	799.3	0.8	52.4	5.2	11.5	<9	193.0	<4	201.4	93.7	0.6	15.7
(31056)38	K	39595-A	<3	<0.1	1.3	177.6	0.3	35.5	2.2	2.3	50.4	115.9	22.7	301.3	9.9	1.5	63.4
		39595-B	1.1	0.1	1.3	171.3	0.4	48.1	2.1	4.8	28.2	94.5	36.5	360.3	19.8	0.4	91.7