

# Granite pegmatite quartz from Evje-Iveland: trace element chemistry and implications for the formation of high-purity quartz

RUNE B. LARSEN, MIREILLE POLVÉ & GUNNAR JUVE

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Previous studies imply that granite pegmatites and hydrothermal quartz veins are the most promising igneous repositories of high-purity quartz. This is because quartz from higher temperature geological settings (granites, monzonites, diorites, etc.) accommodates higher concentrations of impurities in its atomic structure. Systematic studies of granite pegmatites from Evje-Iveland, South Norway, show a marked relationship between petrogenesis and the distribution of structural impurities. Accordingly, less fractionated pegmatites feature relatively high concentrations of Ti, Mg, Ca and Cr whereas more fractionated pegmatites contain higher concentrations of Fe, Li and B, and the total concentration of structural impurities rises with the degree of differentiation. Therefore, detailed knowledge of a pegmatite field, if combined with quartz analyses from a few carefully selected localities, may drastically reduce the area in which prospecting for high-purity quartz resources is feasible.

Rune B. Larsen, Geological Survey of Norway, N-7491 Trondheim, Norway.

Mireille Polvé, UMR 5563. Université Paul Sabatier, 38 Rue des 36 Ponts, 31400 Toulouse, France.

Gunnar Juve, Geological Survey of Norway, Oslo Office, P.O.Box 5348 Majorstuen, N-0304 Oslo, Norway.

## Introduction

High-purity quartz is common quartz that is characterised by exceptionally low concentrations of elements other than silicon and oxygen. Untreated, naturally occurring quartz with less than 50 ppm of impurities qualifies as high-purity quartz; however, quartz with as much as 500 ppm total impurities may suffice if industrially feasible dressing techniques succeed in lowering the impurity level to less than 50 ppm. Given these specifications, prices in excess of 1000 US\$ /ton may be obtained in a market which, according to a 1992 Roskill report "*The Economics of Quartz*", is stipulated to increase by 5-8 % per annum. The *USGS Minerals Information* (ref.: <http://minerals.usgs.gov/minerals/pubs/commodity/>) also forecasts solid growth in the demand for high-purity quartz, not least as a result of continued expansion in the production of silicon oxide wafers for semi-conductor technology. High-purity quartz is largely used to manufacture *silica glass*, which is formed by melting processed crystalline quartz at temperatures between 1750 and 2000°C. The final product contains > 99.995% SiO<sub>2</sub> and, because of its outstanding chemical and physical properties, silica glass is the only single-component glass that has wide commercial applications (Fanderlik 1991). The most important properties of silica glass are resistance to extreme fluctuations in temperature, chemical durability in acidic environments and its ability of transmitting light from near ultraviolet to infrared parts of the spectrum. Therefore, silica glass has found wide applications in the metallurgical, chemical and optical industries, as well as in communication technology for the manufacture of optical wave-guides. An exciting application is as a

raw material in the development of high-performance solar panels for energy production.

Because the trace-element chemistry of quartz is only cursorily evaluated in most literature, the first part of this communication summarises the appearance and character of impurities in quartz and defines the principle features of high-purity quartz. This section is followed by a case history from Evje-Iveland in South Norway where the quality of igneous quartz in a closely related suite of granite pegmatites has been studied. This case history does not report on the discovery of new high-purity quartz occurrences in Norway; in fact, given our present knowledge it is unlikely that the Evje-Iveland area contains any promising targets. Rather, we refer to this area as providing an illustration of the principles and strategies that may be applied in future prospecting for industrially feasible quartz deposits in granite pegmatite provinces.

## Geology of quartz

The following outline is primarily extracted from work by Dennen (1964, 1967), Dennen et al. (1970), Lehmann & Bam-bauer (1973), Fanderlik (1991), Jung (1992), Perny et al. (1992), Deer et al. (1997) and Watt et al. (1997). Other sources are cited in the text.

In evaluating the quality of quartz, distinguishing between structural impurities, solid and liquid inclusions (Fig 1), is imperative. Solid and liquid inclusions are evaluated only briefly at the end of this section because, to a large extent, they are removed during the processing of quartz unless they are small and/or very abundant. Structural impurity elements, on the contrary, can only be partially removed

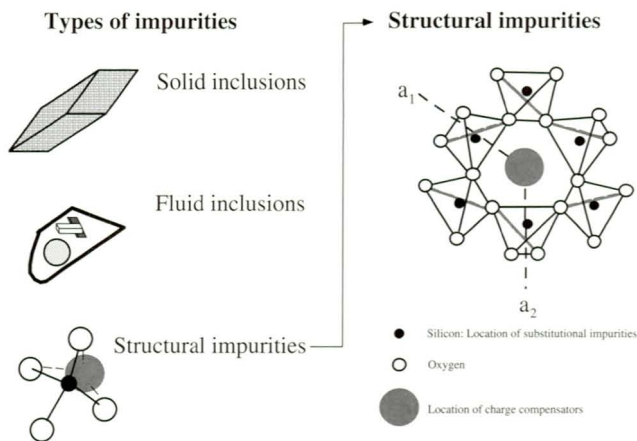


Fig.1. This figure illustrates the types of impurities that are common in quartz. The left part of the figure illustrates different types of impurities, i.e. solid inclusions, fluid inclusions and structural impurities. The right hand figure shows types of structural impurities. Locations of structural impurities (fig. to the right) are shown for  $\alpha$ -quartz which is the most common type of quartz at the Earth's surface and is the only type of quartz found in the Evje-lveland area. Also to the right, the atomic configurations of silicon and oxygen are viewed in a section perpendicular to the crystallographic c-axis.  $a_1$  and  $a_2$  denotes crystallographic axes. Basement geology after Pedersen (1981), Falkum (1982) and Padgett (1994).

by time-consuming and expensive dressing techniques. Therefore, it is the concentration of these elements that ultimately distinguishes high-purity quartz deposits from inferior quality occurrences.

The speciation and character of impurities in quartz are non-obvious features which complicate prospecting for high-purity quartz resources. For example, quartz, which at first glance appears clear and inclusion-free, may contain thousands of ppm of structural impurities. On the contrary, dark smoky quartz with many solid and liquid inclusions may provide an excellent raw material for certain applications if the inclusions can be removed through affordable industrial dressing methods. This is because the smoky colour of quartz is caused by low levels of ionising radiation induced by the decay of radioactive elements in neighbouring minerals (e.g.  $^{40}\text{K}$  in alkali feldspar), whereas the quartz itself may contain only a few ppm of structurally bound impurities that, however, are confined to colour centres in the atomic lattice, hence inducing the smoky colour. Other colour variations may indeed be signs of abundant structural impurities, such as in amethyst, for example, that owes its colour to structurally bound Fe (e.g. Cohen & Hassan 1974, Cohen 1985, Aines & Rossmann 1986, Adekeye & Cohen 1986); and rose quartz colours which, according to some studies, are due to high concentrations of structurally bound Fe and Ti (e.g. Hassan & Cohen 1974, Cohen & Makar 1984, 1985), Al-P substitutions (Maschmeyer & Lehmann 1983) and/or, according to recent studies, are caused by inclusions of submicroscopic dumortierite  $[\text{Al}_7(\text{BO}_3)(\text{SiO}_4)\text{O}_3]$  fibres (Julia Goreva, unpublished).

Quartz has an exceptionally strong atomic configuration of Si-O bonds that allows only a minimum of other elements into its structure. However, minute amounts of substitutional and interstitial impurities may be incorporated into the

atomic lattice and these elements are classified as structural impurities. Elements that are most commonly identified as structural impurities encompass Al, B, Ca, Cr, Cu, Fe, Ge, H, K, Li, Mg, Mn, Na, P, Pb, Rb, Ti and U. Not all studies agree with this list of elements. Jung (1992) suggested that only Al, B, Ge, Fe, H, K, Li, Na, P and Ti may be regarded as true structural impurities, whereas Ca, Cr, Cu, Mg, Mn, Pb, Rb and U are the results of contamination by microscopic solid and liquid inclusions which were not entirely removed before analysis. Another reason for this apparent controversy may be the fact that certain elements, e.g. the alkali metals, tend to form minute atomic clusters adsorbed at specific growth directions i.e. the 0001 surface (Brouard et al. 1995). Forming adsorbed clusters, they hardly classify as conventional structural impurities. However, being strictly confined to one growth direction, the incorporation of atomic clusters is dependent on the physics and hence on the atomic lattice properties of specific crystallographic orientations. As they are not so strongly arrested in the quartz structure as compared with conventional structural impurities, atomic clusters may be more exposed to acid leach and, therefore, may be partially or fully removed during processing of the quartz raw material.

Substitutional impurities compete with  $\text{Si}^{4+}$  in the Si-O tetrahedron composing the quartz lattice (Fig. 1), whereas interstitial impurities mostly include small monovalent ions that fit into structural channels running parallel to the c-axis and function as charge compensators balancing substitutional impurities (Fig 1).  $\text{Al}^{3+}$ , for example, is a common substitutional impurity whereas  $\text{Li}^+$  or  $\text{Na}^+$ , in the structural channels, is balancing the missing positive charge. Next to aluminium, Ti, Fe(III) and Ge are common substitutions for Si whereas H, Li, Na and also K (e.g. Watt et al. 1997) include most charge compensators. However, H is rare in magmatic quartz, whereas it dominates over the other common charge compensators in quartz that formed from dilute aqueous solutions, e.g. in alpine-type quartz veins. This latter type of quartz, occasionally featuring lamellar growth structures, is also known for highly asymmetric distributions of structural impurities giving rise to sectoral or concentric zonation patterns brought about by selective accumulation along specific growth orientations of certain elements (e.g. Paquette & Reeder 1995). In single crystals of some lamellar quartz, for example, the concentration of Al may experience an abrupt increase from 20 ppm in one growth sector to 620 ppm in a neighbouring growth sector of the same crystal.

Highly uneven distributions of impurities are limited to lamellar hydrothermal vein quartz, whereas structural impurities in igneous and metamorphic quartz are more evenly distributed throughout individual crystals.

It is challenging to try to forecast the specific geological environment that most favours the genesis of high-purity quartz. Traditionally, high-purity quartz is recovered from quartz veins and granite pegmatites. Brazil and Madagascar, in particular, were leading producers of vein-type high-purity quartz whereas, today, the Spruce Pine pegmatite district in North America is almost the solitary world supplier. Recently, the production of high-purity quartz from Drag, North Nor-

way, recommenced after a near 10-year period of inactivity and quartz production from the Drag granite pegmatites has now been in operation for more than 3 years.

In most minerals, there is a crude positive correlation between temperature and the concentration of structural impurities, and this relationship also applies to structural impurities in quartz. Accordingly, if silica-oversaturated igneous rocks and their derivatives from granodiorites through granites to pegmatites and to hydrothermal veins are considered, the best qualities are mostly present in pegmatites and hydrothermal veins. Indeed, experience has shown that high-temperature igneous rocks produce poor-quality quartz in terms of structural impurities, whereas many pegmatites and some hydrothermal vein deposits, in general, produce better qualities. However, it is also clear that the concentration of impurities in igneous, hydrothermal and pegmatite quartz varies over several orders of magnitude and, therefore, other parameters than temperature also influence the incorporation of trace elements into the quartz-crystal structure. These other parameters are rarely addressed in the literature; however, the incorporation of Fe, for example, partially depends upon the oxidation state and hence the oxygen fugacity of the quartz-forming environment. The activity of other minerals may also influence the availability of some elements that may potentially be incorporated into the quartz-crystal structure. Finally, the trace

element distribution in igneous quartz may follow the petrogenetic history of the quartz-forming melt, as is documented in the present study.

## Composition of pegmatitic quartz at Evje-Iveland

In an approach to evaluating the parameters that influence the incorporation of impurities into igneous quartz, granite pegmatites were sampled from the Evje-Iveland, Glemsland and Froland areas in South Norway (Fig 2). These particular areas were chosen because detailed mineralogical investigations throughout the 20<sup>th</sup> century have shown this to be the most well studied granite pegmatite province in Norway and, arguably, in the entire Fennoscandian Shield (e.g., Bjørlykke 1935, 1937, 1939, Pedersen 1973, 1975, 1981, 1988, Juve & Bergstøl 1990, Fought 1993, Stockmarr 1994, Hansen et al. 1996, Bingen & van Breemen 1998).

Although pegmatites were sampled in all three areas (Fig 2), the present preliminary study will concentrate on Evje-Iveland where earlier activity had documented a closely related suite of granites and pegmatites that probably formed from a limited parental source during a protracted igneous event in the Upper Proterozoic (Bjørlykke 1935, 1937; Frigstad 1968, 1999; Fought 1993, Pedersen and Konnerup-Madsen, 1994, Stockmarr 1994).

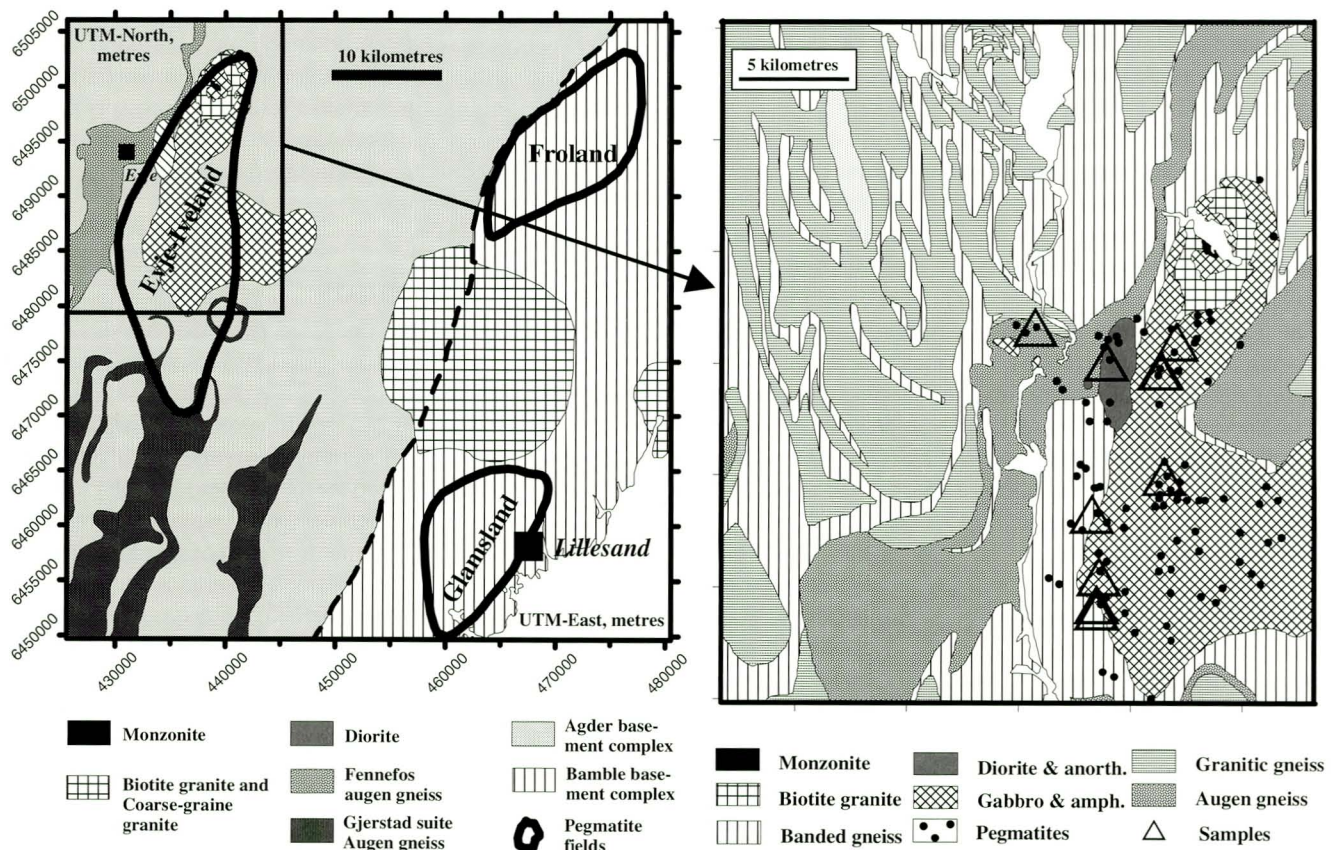


Fig. 2. Geology and sample sites for pegmatitic quartz addressed in the present study. The figure to the left is a general geological outline of Southwest Norway and shows the most important pegmatite fields in the region. The right-hand figure is a detailed map of the framed area to the left and shows pegmatites, sample localities and the geological setting of the studied area. See legend and main text for more details. Geology after Pedersen (1981) and Pedersen and Konnerup-Madsen (1994).

## Geological outline of the Evje-Iveland area

The granite pegmatites of the Evje-Iveland area are located in the southwestern part of the Mesoproterozoic Sveconorwegian/Grenvillian province of South Norway (Pedersen 1981). In contrast to many other parts of Norway, the Early Palaeozoic Caledonian orogenic event had a minimal effect on the basement lithologies; hence, the Sveconorwegian orogeny comprises the youngest pervasive deformation recorded in the region. The Evje-Iveland area is dominated by a suite of granitic and mafic plutonic rocks (Fig 2) that formed over a period of 450–500 million years beginning with intrusion of coarse-grained, granitic augen gneisses yielding whole-rock Rb/Sr maximum ages of ca. 1290 Ma (e.g. Pedersen & Konnerup-Madsen 1994). This suite of igneous rocks is also known as the Gjesdal Suite Augen Gneisses, for which U/Pb sphene dating provided a minimum age of 1166 +66/-21 Ma (Bingen & van Bremen 1998). Recent U/Pb zircon geochronology of the prominent Iveland-Gautestad Norite (Fig 2) gave an age of 1278 +/-2 Ma and, accordingly, suggests that mafic igneous rocks also characterised the initial magmatic activity in the Evje-Iveland area (Pedersen 1981, S. Pedersen, pers. comm. 1997). However, large-scale igneous crustal amalgamation did not begin before 1150–1100 Ma (or even later) when acid plutonism gave rise to widespread emplacement of granites (Fig 2). At 1034 +/-2 Ma (Bingen and van Bremen, 1998) the large Fennefoss augen gneiss was generated and, at 985 +/-1 Ma (Pedersen 1981, S. Pedersen, pers comm. 1998) was followed by emplacement of the Evje diorite.

This long, discontinuous, plutonic history come to an end with the emplacement of the Høvringsvatnet granite-monzonite complex at 950–900 Ma (Fig 2) (Pedersen 1981), a body that may be compared to the inferred parent magma of the granite pegmatites addressed in the present study (Fought 1993, Pedersen & Konnerup-Madsen 1994, Stockmarr 1994). The Høvringsvatnet bimodal complex comprises ring-shaped masses of monzonite and granite that are intersected by a cone-sheet system of later monzonites and granites (Pedersen 1981, Pedersen & Konnerup-Madsen 1994). All granitic intrusions are characterised by relatively high concentrations of K, Ti, Ba, Sr, Zr, P and REE, a small or absent Eu anomaly and a fairly juvenile  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.7040–0.7045 (Pedersen 1988).

Granite pegmatites occur in a 5 km-wide belt extending southwards from the Høvringsvatnet complex (Fig 2). Along this belt, several thousand pegmatites are scattered over a distance of ca. 25 kilometres. Recent studies of the pegmatites in the northern part of the area have shown that they were probably derived from the same source as the monzonites in the Høvringsvatnet complex (Fought 1993, Stockmarr 1994). In agreement with this origin, the pegmatites were considered to have formed from relatively primitive granitic melts and inherently have a low  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of 0.7063. As previously emphasised by Bjørlykke (1935, 1947) and Barth (1947), most of the pegmatites were emplaced into the Iveland-Gautestad norite along subvertical dykes that

pass into subhorizontal sills and solidified as strongly zoned chamber pegmatites. Well-exposed bodies display both wall-, intermediate- and core-zones and some examples may also develop a relatively fine-grained contact-zone. In general, the geometry and distribution of the zones are symmetrical with the wall-zone enveloping the intermediate- and core-zones. However, several core-zones may develop inside the intermediate-zone in different parts of the same pegmatite. As it was concluded in earlier works (Bjørlykke 1935, Frigstad 1968, 1999, Fought 1993, Stockmarr 1994) and supported by the strict zonal evolution, most pegmatites formed from a single batch of igneous melt. Some pegmatites, however, display magmatic erosion features and a repetitive evolution of the intermediate zone, i.e. features that may imply replenishment of silicate melt before the pegmatite was completely solidified.

Where present, the contact-zone is an assemblage of relatively fine-grained, perthitic K-feldspar, plagioclase, quartz and biotite. The wall-zone contains decimetre size crystals of plagioclase, perthitic feldspar, quartz, biotite and white mica and in places shows examples of graphic feldspar and quartz intergrowth. Spectacular examples of graphic granite are common in the intermediate-zone where metre-size crystals of quartz and feldspar are intergrown with some biotite and muscovite interspersed throughout the zone. Finally, the core-zone may be composed entirely of quartz but mostly contains a few rafts of plagioclase and perthitic feldspar floating in the quartz matrix. Biotite is the dominant mica and generally occurs as blades radiating from a common nucleation point. Other than the major minerals previously mentioned, the pegmatites contain a wealth of accessory phases that are summarised in Bjørlykke (1935, 1937), the most common being magnetite, spessartite garnet, monazite, beryl, xenotime and gadolinite.

## Analytical methods

Samples of quartz were collected from the margins of the intermediate zone from 10 pegmatites in a profile extending over a distance of 12 kilometres (Fig 2). They were crushed and sieved to the 150–250  $\mu\text{m}$  fraction, then subjected to magnetic separation followed by acid leach and, finally, were hand-picked and inspected for mineral impurities by binocular microscopy. Trace impurities, which were measured after these preparations, will primarily represent structural impurities, adsorbed atomic clusters or elements associated with dislocations, or other atomic lattice defects or elements dissolved in fluid inclusions. Grains were again cleaned with acetone and deionized water in a clean room, then dissolved by ultra-pure concentrated HF using the combined efficiency of an ultrasonic bath and a microwave oven. After evaporation to dryness, which allows Si to escape as volatile  $\text{SiF}_6$ , residue was recovered with 5ml of 2% distilled  $\text{HNO}_3$ . Solutions were analysed by ICP-MS at Université Paul Sabatier (France) on a Perkin-Elmer ELAN 5000, using In and Re as internal standards and SARM49 for quality control. This standard is only certified for a few of the elements we analysed, whereas most elements are listed as recommended values; however,

at the time of analysis, certified trace element standards for quartz were difficult to obtain. A suite of 33 elements comprising Li, Be, B, Mg, Ca, Sc, Ti, V, Cr, Fe, Co, Ni, Cu, Zn, Ga, Rb, Sr, Y, Zr, Nb, Mo, Cs, Ba, La, Ce, Nd, Sm, Eu, W, Au, Pb, Th and U were included in the analytical programme. Results of the final analysis are listed in Table 1; however, elements giving insignificant concentrations are omitted.

## Habit of quartz

Quartz is common throughout the pegmatites and, in quantity, is inferior only to K-feldspar. Most of the quartz is transparent although in places it may be milky-white due to high abundances of microfractures or, in rare cases, to high densities of fluid inclusions. Pale grey smoky quartz is particularly common throughout the wall and intermediate zones and always occurs in 10-15 cm-wide rims enclosing feldspar. Quartz that occurs at distances greater than 15 cm from feldspar is milky-white or transparent. Accordingly, it is implied that the smoky colour of quartz is a result of  $\gamma$ -radiation from decaying radioactive elements in feldspars, rather than being

a consequence of radiogenic elements from structural or solid inclusions incorporated in the quartz.

Microscopic examination of quartz shows that solid inclusions other than rutile are rare, although magnetite may be present in some of the pegmatites. Rutile is common in intermediate-zone quartz but rare in the core-zone and occurs as minute micrometre to sub-micrometre thick needles that are evenly dispersed throughout the quartz. Primary fluid inclusions are common and vary strongly in proportion and size but are subhedral and consistently classify as H<sub>2</sub>O-CO<sub>2</sub>-NaCl type inclusions. The intermediate-zone is characterised by low- to medium-salinity (in NaCl equivalents) H<sub>2</sub>O-CO<sub>2</sub>-NaCl inclusions with 10-15 vol% CO<sub>2</sub> whereas the core-zone is characterised by low-salinity H<sub>2</sub>O-CO<sub>2</sub>-NaCl inclusions with 5 – 10 vol% CO<sub>2</sub>. From the microthermometric behaviour of ice (Larsen et al. 1998a & b) it is implied that the dominant electrolytes in the aqueous phase were Cl<sup>-</sup> and Na<sup>+</sup>. Secondary inclusions mostly have the same composition as primary inclusions in the inspected samples, but in places show evidence of liquid immiscibility with phase separation of a carbonic and an aqueous phase, respectively. A separate manu-

Table 1. Composition of quartz from the intermediate zone of the granite pegmatites. Concentrations in ppb. Presumed structural impurities in bold letters. UTM-N and UTM-E: Location of samples in metres and according to the UTM system.

	RBL96004	RBL96006	RBL96008	RBL96010	RBL96012	RBL96014	RBL96016	RBL96017	RBL96021	RBL96022
UTM-E	436400	436300	437050	436500	433275	433500	433500	433600	430750	433925
UTM-N	6494700	6494700	6496000	6489950	6488275	6483975	6484250	6485500	6496650	6495100
B	225	50	163	570	734	2984	369	2164	243	95
Ba	60	14	31	300	23	403	64	157	307	762
Be	56	141	129	223	85	374	154	237	182	84
Ca	4198	12073	6379	4252	3200	13375	4786	31230	2798	8074
Ce	1	2	4	6	2	10	1	22	1	10
Cr	1591	69	2288	3276	391	1279	679	567	312	1113
Cs	10	45	64	39	391	290	781	263	126	37
Cu	71	102	23	18	15	157	49	81	26	64
Fe	3344	2461	3978	5079	3075	9339	5982	6956	2447	8840
Ga	254	263	222	286	328	243	409	556	145	314
La	1	1	2	3	1	5	0	10	0	5
Li	1053	774	644	6652	5062	852	4252	6471	2702	811
Mg	942	1651	331	374	963	1188	355	1874	1451	901
Nb	3	5	9	4	8	65	15	22	6	61
Pb	59	279	58	44	114	351	25	50	22	282
Rb	106	168	359	285	437	3779	1129	782	215	1025
Sr	130	479	257	148	133	618	137	791	76	750
Ti	26131	25197	25111	26170	23131	12334	3348	31906	8772	23557
U	1	2	6	1	3	4	17	6	1	27
V	15	7	12	17	2	93	12	51	3	15
W	12	4	9	11	11	22	3	19	11	12
Y	2	7	7	11	4	7	17	21	3	11
Zn	16	35	27	43	32	269	43	83	33	77

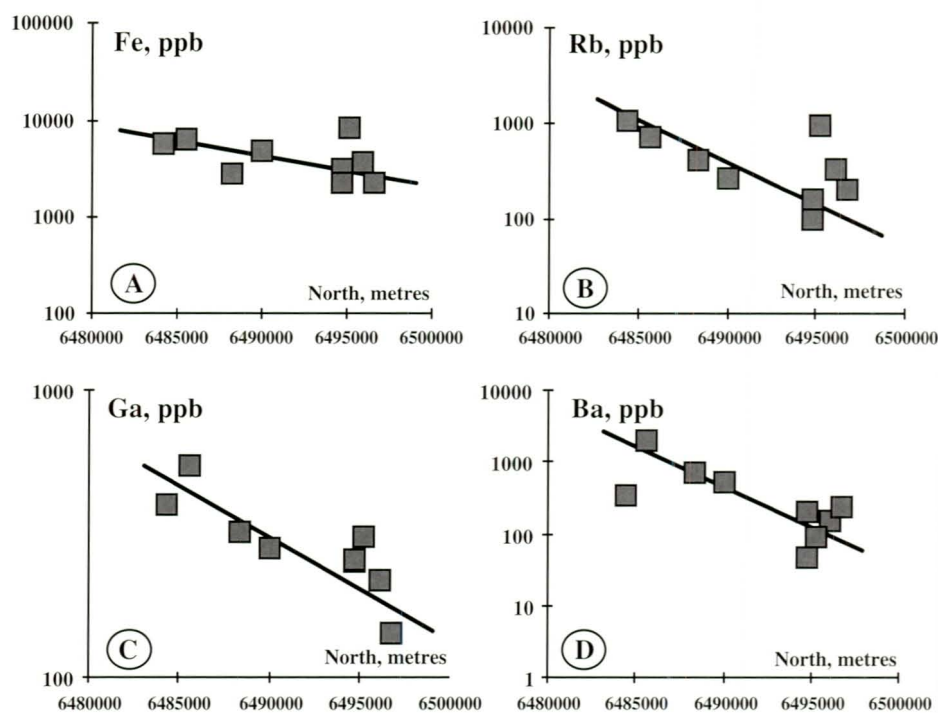


Fig.3. Concentrations of structural impurities in quartz from the intermediate-zone of granite pegmatites at Evje-lveland in a profile running from south to north in the studied area.

script, which addresses the chemistry, composition and distribution of fluid inclusions, is in preparation.

Among the elements analysed by ICP-MS (Table 1), only B, Ca, Cr, Fe, Ga, Li, Mg, Pb, Rb, Sr, Ti and U are commonly accepted as true structural impurities (e.g., Fanderlik 1991, Perny et al. 1992, Hemming et al. 1994, Watt et al. 1997). Indeed, these elements constitute more than 95% of the trace impurities (Table 1) detected in analysing the quartz samples. Because Ti is occasionally represented in minute rutile needles, the exact amount of this element can only be quantified in rutile-free specimens.

In decreasing order of concentration Ti, Ca, Fe and Li are the most abundant elements and mostly are present at the ppm level. Cr, Mg, Rb, B, Sr, Ga and Pb consistently yield hundreds of ppb and in a few cases exceed one ppm in concentration. Finally, the U concentration is lower than 20 ppb. Among the other analysed elements that normally are not regarded as structural impurities, only Ba, Cs and Be are present in any abundance although the concentrations vary inconsistently from tens to hundreds of ppb. On the average, quartz shows the following distribution of structural impurities (in ppm and in decreasing order of abundance), Ti(21), Ca(9.0), Fe(5.2), Li(2.9), Cr(1.2), Mg(1.0), Rb(0.83), B(0.76), Sr(0.35), Ga(0.30), Pb(0.13), U(0.007) (See also Table 1).

On a regional scale, the total concentration of impurities varies considerably from only 20 ppm in RBL96021 to 84 ppm in RBL96017 (Table 1). These abundances are only advisory as Al, K, and Na are not included and in some cases (in particular Al) constitute a large part of the structural impurities.

Certain elements show conspicuous regional trends in their concentrations throughout the studied area. Seen together, the concentration of many elements experiences a gradual southward increase as exemplified by Fe, Rb, Ga and B (Fig 3). Not all structural impurities show such regular trends but the overall pattern is that quartz in the south con-

tains higher concentrations of impurities. Fig. 4, which shows the regional distribution pattern of Li and Cr, illustrates this trend.

## Discussion and conclusions

Studies of quartz from granite pegmatites at Evje-lveland, South Norway, have shown that the quartz has a relatively high purity, although the absence of Al, Na and K analyses precludes any firm conclusions. None of the granite pegmatites so far studied in the Evje-lveland provide feasible targets for industrial exploitation, and in particular Ti, Fe and Li exceed the concentrations preferred for high-purity quartz. With this conclusion in mind, it should be stressed that the present study embraces only a fraction of the pegmatites and the geochemical patterns imply that better qualities of quartz may be found in the northern parts of the studied area.

Structural impurities that normally would be expected in quartz also constituted most of the impurities found in the present study. However, Ba, Cs and Be also yielded significant concentrations during ICP-MS analysis and it is not clear if these elements occur as sub-microscopic inclusions, are confined to dislocations or other areas with significant lattice defects, or if they may be dissolved in the aqueous solutions forming the fluid inclusions. Feldspar would be the prime suspect if Ba and Cs came from sub-microscopic inclusions but the lack of correlation between Ba, Cs, Rb and Sr rules out this possibility. However, given the highly irregular distribution of these elements when comparing different pegmatites, either of these options or a combination of the three may explain the origin of the Ba, Cs and Be concentrations.

Regarding petrogenetic patterns, a systematic distribution of trace elements in the quartz implies that there is a strong connection between granite pegmatite genesis and

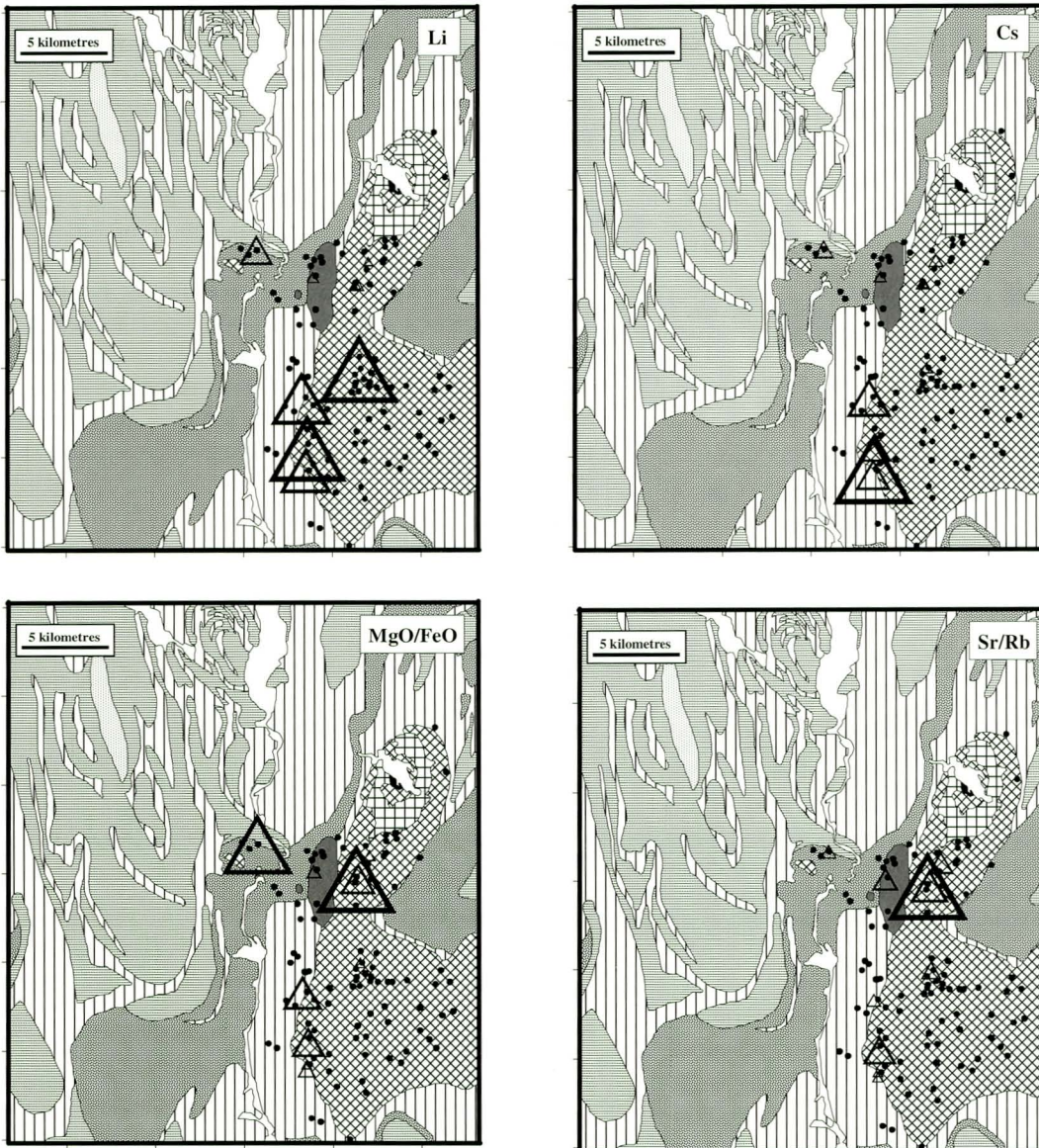


Fig.4. Areal distribution of structural impurities in quartz. In the two upper figures, sizes of triangles are proportional to the concentrations of Li and Cs, respectively. In the two lower diagrams, sizes of triangles are proportional to the MgO/FeO and Sr/Rb ratios, respectively. The legend to the geology is shown in Fig. 2.

the distribution of structural impurities in quartz. Petrogenetically significant element ratios demonstrate a conspicuous pattern when evaluated on a regional scale. Accordingly, the MgO/FeO and the Sr/Rb ratios of quartz show consistent northward increases (Fig 4) whereas the total concentration of Nb+Y (Fig 5) is falling toward the north. In whole-rock analysis, and in the analysis of specific igneous minerals in granitic rocks, these ratios would indicate the degree of magmatic differentiation, and, at Evje-lveland, the distribution of these elements implies that the pegmatites towards the south formed from progressively more differentiated, i.e. evolved, granite melts. Although quartz has not previously been used in this context, this conclusion is supported by the analysis of K-feldspar from the intermediate zone of the pegmatite in which the Sr/Rb (Fig 5) and the CaO/(K<sub>2</sub>O+Na<sub>2</sub>O) ratios of the K-feldspar show a consistent increase towards the north (Larsen, in review).

In conclusion, the present study shows that the total concentration of trace elements in pegmatitic quartz correlates with the degree of fractionation of the pegmatite-forming

melts. This relationship is in fine agreement with the fact that an igneous melt becomes progressively more saturated with incompatible elements as differentiation proceeds, and the ratio between the compatible and the incompatible elements decreases. From the present work, it may be concluded that the chemistry of quartz reflects the chemical evolution of a granite melt as it differentiates towards more evolved compositions. It may seem contradictory that quartz that formed from more differentiated pegmatitic melts, hence solidified at a lower temperature, shows higher impurity levels than quartz from pegmatites which crystallised at higher temperatures from more pristine pegmatitic melts. Apparently, the observed chemistry of quartz contradicts what is expected from the crystal chemistry of quartz that was outlined in the first section of this article. Accordingly, the concentration of impurities in quartz should be proportional to the crystallisation temperature, i.e., quartz that crystallised from more differentiated granitic melts should include fewer structural impurities because they formed at lower temperatures. A possible explanation for this contra-

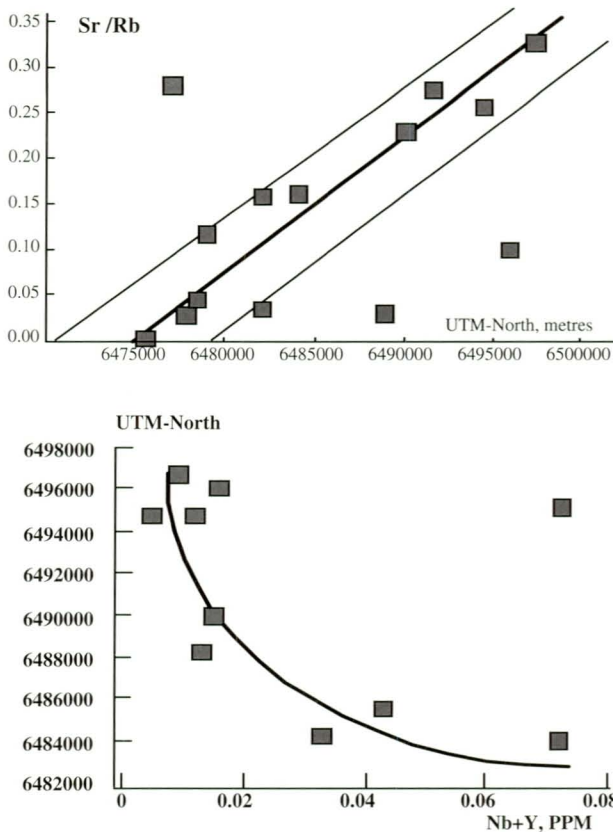


Fig.5. Lower figure - the concentration of Nb+Y in quartz as a function of distance (in metres) towards north along a N-S profile through the studied area. Upper figure - the Sr/Rb ratio of potassic feldspar from the intermediate-zone of granite pegmatites along the same profile as in the lower figure.

diction may be that crystallisation of granite pegmatites occurs under conditions of strong disequilibrium, i.e., far below the liquidus temperature (e.g. Jahns 1959, London 1992). Therefore, as with most of the other major mineral species composing a granite pegmatite, the pegmatitic melt rapidly reaches a level of strong oversaturation. The crystallisation of quartz then becomes a function of diffusion rates and the availability of nutrients for crystal growth, rather than strictly a function of temperature. Following this argument, pegmatitic quartz in the south, although forming from more differentiated melts, could have formed at nearly the same temperatures as quartz in the northern area; and the concentration of structural impurities becomes a function of the total concentration of impurities in the pegmatitic melts during quartz growth (see also Larsen et al. 1998a & b, 1999).

In advocating for specific strategies in future prospecting for pegmatitic high-purity quartz in Norway, more data are required before we may reach any firm conclusions. Detailed studies of well zoned pegmatites which were sampled under the auspices of the present project (by the third author and F. Fontan) may provide important information on the chemical evolution of quartz from contact to core zone and may further elucidate how the chemistry of quartz depends on the fractional crystallisation of granite pegmatites. A parallel development of *in situ* analysis of quartz by LA-HR-ICP-MS

(Laser Ablation High Resolution Inductively Coupled Plasma Mass Spectrometry) at NGU will also be conducive to efficiently characterising the spatial distribution of structural impurities in quartz, and will introduce a rapid method that may partially replace conventional and very time-consuming quartz analysis techniques. However, for the moment, it may be concluded that the regional sampling of a pegmatite province has indeed provided valuable information about the overall distribution of impurities in quartz and, more importantly, demonstrates the relationship between the purity of quartz and the history of pegmatite genesis. In doing so, detailed knowledge about the genetic history of a particular pegmatite province, combined with the analysis of a few carefully selected quartz samples, may drastically reduce the size of the area where detailed prospecting is feasible.

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