

Melt-mineral-fluid interaction in peralkaline silicic intrusions in the Oslo Rift, Southeast Norway. III: Alkali geothermometry based on bulk fluid inclusion content

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Decrepiation-linked ICP analyses of bulk fluid inclusion contents in quartz in 14 samples from the Sande nordmarkite (quartz syenite) and the Eikeren-Skrim ekerite (alkali granite) plutonic complexes yield Na/K ratios which suggest equilibration between aqueous fluid and the host rock at temperatures in the range 240-340°C. This is far below the estimated solidus ($\approx 700^\circ\text{C}$), but can be correlated with the trapping of late, secondary fluid inclusions. The data thus demonstrate the importance of low-temperature sub-solidus fluid interaction processes for the petrogenesis of the Oslo region felsic intrusive rocks.

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Introduction

Peralkaline silicic intrusive rocks (nordmarkite (alkali syenite) - ekerite (alkali granite)) occur in a number of shallow plutons in the Late Paleozoic Oslo Rift, Southeast Norway (Fig. 1). Geochemical studies show that the magmas giving rise to these intrusions formed by a combination of fractional crystallization and crustal contamination processes in the deep crust (Rasmussen et al. 1988). However, anomalously low concentrations of incompatible elements which tend to enter stable halide complexes (e.g. Zr, Hf, Th, Ta, REE) and internal correlations among such elements suggest that interaction between fluid and magma and/or minerals have influenced the geochemistry of these rocks (Dietrich et al. 1965, Dietrich & Heier 1965, Neumann et al. 1990).

To understand the fluid-mineral exchange processes, it is important to obtain an independent estimate for the temperature of maximum intensity of fluid-rock interaction. Such temperature information is important from a geochemical and petrological point of view, e.g. for the interpretation of trace element and stable isotope data, and for the understanding of wall-rock alteration and mineralization processes. This can best be done by applying an appropriate geothermometer (e.g. Truesdell

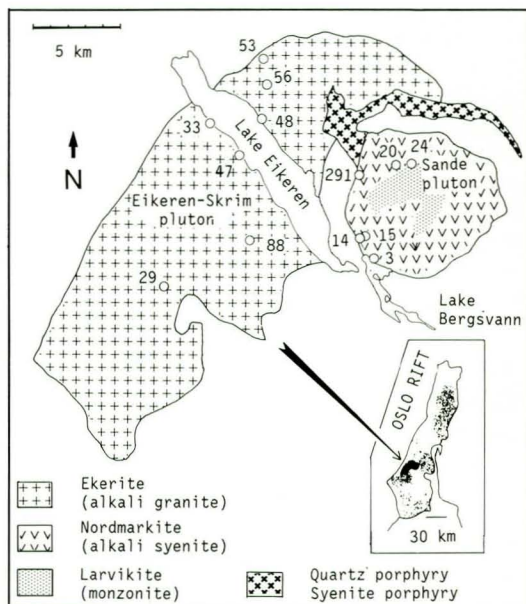


Fig. 1. Simplified geological map of the Sande and Eikeren-Skrim complexes, with sample localities.

1984) to the fluid contained in fluid inclusions in the rock.

Fluid inclusions in minerals in intrusive rocks

represent samples of the fluid phase present in the system at one or more stages of its cooling history (e.g. Roedder 1984). Microscopy and microthermometric analysis of fluid inclusions in quartz in the peralkaline silicic rocks from the Oslo rift show that the magmatic and postmagmatic fluids are predominantly aqueous salt solutions. The history of inclusion trapping is long and complex, extending from the solidus to far sub-solidus temperatures and involving fluids with different salt concentrations and densities (Hansteen 1988, Hansteen & Burke 1990, Andersen 1988, 1990).

The Na/K ratio of an aqueous fluid interacting with feldspathic rocks at solidus or sub-solidus conditions is controlled by equilibria with the feldspar minerals and their alteration products, and is thus a function of temperature (e.g. Orville 1963, Henley 1984). The alkali ion distribution of an inclusion fluid can therefore be used as a geothermometer, defining the temperature at which the fluid last interacted with the feldspathic mineral assemblage, i.e. the trapping temperature of the fluid inclusion(s).

The present note reports the results of a bulk-fluid study of two felsic plutons in the southern part of the Permian Oslo Rift in Southeast Norway (the Sande quartz syenite and Eikeren-Skrim alkali granite plutonic complexes), using the decrepitation-linked ICP method (see below). The fluid evolution of the two intrusive complexes have been studied by microscopy and microthermometry by Andersen (1990) and Hansteen & Burke (1990); the reader is referred to those papers for detailed discussions.

Alkali geothermometry

Several alkali geothermometers have been calibrated, either based on the concentration ratios of dissolved cations in geothermal waters, where interaction temperatures have been measured in wells (see review by Truesdell 1984) or on thermodynamic analysis of experimental data on mineral - solution equilibria (Poty et al. 1974, Lagache & Weisbrod 1977).

In principle, alkali geothermometry can be applied to fluid inclusion waters. There are, however, methodological problems related to (1): the complexity of fluid inclusion assemblages in intrusive igneous rocks (cf. Weisbrod 1981), and (2): the analytical problems in extracting the small amounts of fluid contained in

the inclusions, and measuring the ionic concentration with sufficient accuracy and precision.

The first of these problems, in principle, cannot be eliminated, since most intrusive rocks have complex cooling histories involving fluid interaction at both magmatic and post-magmatic temperatures. The fluid inclusion patterns are therefore complex, referring to several episodes of mineral growth, dissolution or recrystallization. Since the bulk fluid content of a larger sample, rather than single inclusions or generations of inclusions has to be extracted for analysis, the data obtained can only be interpreted in relation to observations from careful microscopy / microthermometry.

The analytical problems have traditionally been solved by crush-leach methods (Roedder 1958) in which dilute solutions of the inclusion fluids are analysed by atomic absorption or other methods (e.g. Shepherd et al. 1985). The dilution procedure increases the analytical error, but cannot be avoided in this type of analysis. The decrepitation-linked inductively coupled plasma spectroscopy (D-ICP) method (Thompson et al. 1980, Rankin et al. 1982, Shepherd et al. 1985) differs from the traditional approach, in that the fluid inclusion content is liberated by decrepitation at high temperature, and transported as an aerosol in an inert gas carrier directly to the site of analysis (the ICP's plasma torch). Thus, the hazard of contamination and loss of material is greatly reduced.

Cathodoluminescence microscopy

We have found it useful to relate our analytical data to observations by cathodoluminescence microscopy, which reveals textures in quartz and feldspars not easily observed by ordinary petrographic microscopy. Cathodoluminescence microscopy is a well established method in sedimentology (e.g. Nickel 1978). More recently, it has also been applied to rocks of igneous and metamorphic origin (e.g. Rae & Chambers 1988). Luminescence effects induced by bombardment of a mineral by electrons (cathodoluminescence) can be generated by point defects in the crystal lattice (e.g. quartz), by trace element substitution in a mineral structure (e.g. carbonates) or by a combination of both (e.g. alkali feldspars, Rae & Chambers 1988). The theory of cathodoluminescence in minerals is discussed by Mariano

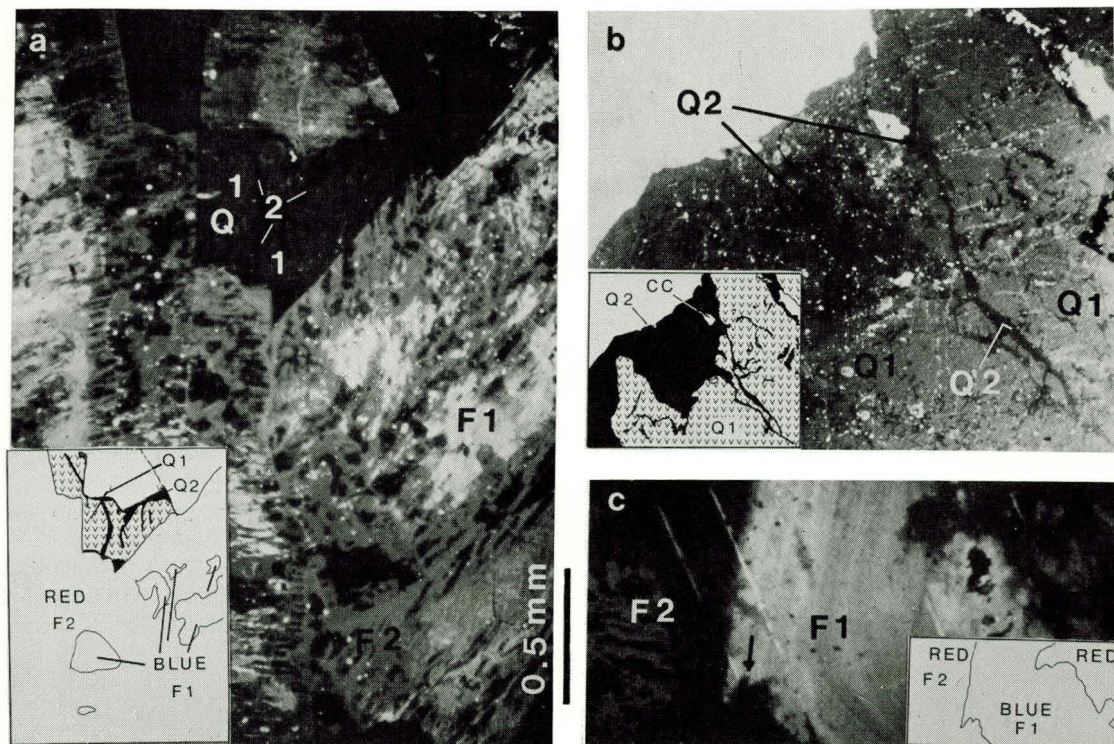


Fig. 2. Cathodoluminescence images of nordmarkite and ekerite. The bar-scale shown is the same for all three images. a: Two generations of quartz and alkali feldspar in nordmarkite, sample A 3, Sande. Light blue luminescing feldspar (F1) is replaced with red-luminescing feldspar (F2). Early interstitial quartz (Q1, bluish luminescence) is penetrated by quartz veins with darker, purplish luminescence (Q2) and high abundance of late secondary fluid inclusions (Andersen 1989). b: Replacement of blue Q1 quartz by late, purplish Q2 quartz along fractures. Ekerite sample TH 58 from the Eikerens-Skrim pluton. The white spots are calcite inclusions (bright yellow luminescence). c: Resorption of a zoned feldspar phenocryst (F1, light blue luminescence colour). The phenocryst shows etching (arrow) and is enclosed in F2 feldspar with red luminescence. Sample TH 69 from the Eikerens-Skrim pluton.

& Ring (1975), Zinkernagel (1978) and Nickel (1978). In plutonic rocks, the cathodoluminescence colours of quartz and alkali feldspars are affected by post-magmatic fluid-mineral interaction processes, making luminescence microscopy a useful method to distinguish between primary magmatic and 'hydrothermally' altered quartz and feldspar domains (e.g. Rae & Chambers 1988).

Geology

As a background for the analytical data, the main features of the geology, petrography and fluid evolution (as derived from microscopy / microthermometry) of the two plutons will be summarized here. More detailed descriptions of these rocks can be found in papers by Andersen (1984a, 1990) and Hansteen & Burke (1990).

The Sande Cauldron (Fig. 1) is one of several cauldron subsidence structures in the Oslo Rift (Oftedahl 1953), and probably represents a deep erosional section through a central volcano (Ramberg & Larsen 1978). Most of the downfaulted cauldron block is presently occupied by younger intrusive rocks, including early monzonite (larvikite) in the central part, and younger, mildly peralkaline quartz syenite (nordmarkite) making up a broad outer sector (Andersen 1984a,b). This study is concerned with the nordmarkite, but one sample of a hybrid rock, intermediate between nordmarkite and larvikite (A 24, Andersen 1984b) has also been included.

The nordmarkite is typically a coarse- to medium-grained alkali syenite with variable quartz content. Mafic silicates (aegirine-augite, Na-Ca amphibole, sphene, zircon, biotite), tita-

nomagnetite, manganiferous ilmenite, quartz and calcite are interstitial phases. Cathodoluminescence images indicate that both quartz and feldspar have gone through complex histories, involving resorption / replacement and reequilibration after primary crystallization (Fig. 2). Secondary calcite is spatially associated with darkly luminescing (i.e. reequilibrated) quartz. The alkali feldspar also shows signs of incipient sericitization.

Three generations of fluid inclusions have been recognized in quartz (Andersen 1989). Primary inclusions (population 1) trapped at or close to the solidus, early secondary inclusions (population 2) and late secondary inclusions (population 3). All three populations are dominated by aqueous solutions, although some CO₂-bearing inclusions have been recognized among population 3. However, aqueous inclusions with a high degree of fill and salinity < 25 wt% NaCl equivalents are most abundant among the latest secondary inclusions (Andersen 1989). There seems to be a rough correlation between a high abundance of late secondary (population 3) inclusions and replacement of primary feldspar (blue luminescence) with secondary, red luminescing feldspar, and deposition of quartz with less intense luminescence (=low-temperature quartz). The samples studied contain all three fluid inclusion populations, with the exception of A 3 which contains population 3 inclusions only.

The *Eikeren-Skrim alkali granite complex* cuts the western margin of the Sande Cauldron. It is the largest peralkaline granite intrusion among the Oslo region felsic plutons, and comprises the type area for ekerite (Brøgger 1906).

The most abundant rock type in the complex is a hypidiomorphic to allotriomorphic granular alkali granite with 20 to 28 vol% quartz. Aegirine and alkali amphibole may occur both interstitially and / or interlocked with alkali feldspar. Other phases comprise magnetite, ilmenite-pyrophanite, apatite, zircon (+ sphene), and less commonly rutile, fluorite, biotite, pyrite, astrophyllite and elpidite. The abundant miarolitic cavities contain all the rock-forming minerals (i.e. perthitic alkali feldspar, quartz, alkali amphibole, aegirine) as well as many accessory phases (Dietrich et al. 1965, Raade 1972). Cathodoluminescence images indicate complex crystallization histories for both feldspar and quartz (Fig. 2). Observed mineral alteration reactions include replacement of

mafic silicates by chlorite, hematite and quartz, and sericitization of alkali feldspar (Hansteen & Burke 1990).

Several generations of aqueous fluid inclusions are recognized (Hansteen & Burke 1990): inclusions derived from magmatic fluids, early postmagmatic sub-solidus inclusions and late, secondary postmagmatic inclusions. All types occur in both rock-forming and miarolitic quartz.

The abundance of aqueous inclusions with moderate salinity and high density increases strongly from the early through the later inclusion generations, although this is less pronounced for the miarolitic quartz (sample TH 88) which contains comparatively few of the latest generation. Only sample TH 58 contains considerable numbers of late, CO₂-rich (type 3) inclusions. As in the Sande nordmarkite, late postmagmatic fluid inclusions are most abundant in samples containing a large proportion of red luminescing feldspar and quartz with weak luminescence (Fig. 2).

Analytical techniques

Mineral separation

The samples studied are not ideally suited for D-ICP studies, because the fluid inclusions are generally small (<20 µm for most samples), and the quartz is intimately intergrown with alkali-bearing minerals (feldspar, alkali pyroxene and amphibole, mica). A finer grain-size and a cleaner mineral separate than commonly used for D-ICP analyses were therefore needed. After crushing to 40-100 mesh (ca. 0.4-0.15 mm) grain-size, the quartz was isolated and purified by a combination of flotation, heavy liquid and magnetic separation methods. The pure quartz separates were washed in alcohol to remove traces of separation reagents, boiled first in concentrated HNO₃, then in distilled water, and finally the separates were cleaned with distilled water in electrolytical cells for several days.

Decrepitation-linked ICP analysis

D-ICP analyses were carried out using an ARL 34000 vacuum emission spectrometer following the procedures outlined by Alderton et al. (1982) and Rankin et al. (1982). A clean pyrex test tube containing a 0.5 g sample of quartz was connected to the plasma source of the ICP via a 50 cm length of silicone tubing. A small electric furnace held at 750° C served as the decrepitation chamber. The sample and sample tube were heated in the furnace for 15 seconds prior to analysis. During this time the temperature had risen to about 150° C. A three-port valve connecting the sample tube to the plasma was then opened and analysis was carried out over the following 45-second interval. Audible decrepitation took place almost entirely within this time interval at an estimated temperature range of between 150° C and 600° C.

Material released from the inclusions during decrepitation is transferred into the ICP via a stream of argon carrier

gas, the flow of which is kept constant so as to avoid the introduction of large (>about 10 μm) fragments of host mineral into the system. A suitable calibration procedure under conditions simulating decrepitation has yet to be achieved. However, calibrations using standard nebulised solutions are quite adequate, at least for the major cations Na and K and moderate salinity fluid inclusions considered here.

The ICP responses for up to 40 elements may be recorded at preset wavelengths as mV responses from the photomultiplier tube by means of a multichannel analyser. In spite of the multielement capability of the D-ICP technique only a limited range of elements gave mV responses which were sufficiently above background values to be meaningful. Of these only sodium and potassium are thought to be derived entirely from the fluid inclusions. In effect, the mV response is directly proportional to the element concentration in the decrepitates; but because the total amount of decrepitate entering the plasma is unknown it is best to present the result as weight ratios (Na:K) rather than attempt to define their absolute concentration units.

Results

Na/K weight ratios from ICP analyses run in duplicate are listed in Table 1, together with temperature estimates. The ratios were calculated from ICP mV readings by calibration with a multielement standard solution. The response for Na ranged from 20 to 200 mV above the background, and 10 to 30 mV above background for K. Poorly reproducible and non-quantifiable readings were obtained for Li and S; other elements did not give responses. Even for Na and K the ICP-response is ca. 1 order of magnitude less than obtained for e.g. quartz from hydrothermally mineralized granites (Alderton et al. 1982, Rankin et al. 1982). Nevertheless, the Na/K-ratios obtained were reproducible to within ± 5 % (1 standard deviation, as judged from repeated runs).

Table 1. ICP-results and temperature estimates

Sample	(Na/K) ppm. wt	T (°C) Fournier	T (°C) Truesdell	T (°C) Lagache and Weisbrod
The Sande nordmarkite				
A 14*	6.21	262	245	320
A 15	5.35	277	267	341
A 20	6.67	254	236	300
A 24	5.95	266	251	322
A 3	5.00	285	277	358
A 4	5.41	276	265	340
R 291	5.35	277	267	341
The Eikeren-Skrim ekerite				
TH 29	5.80	269	255	325
TH 33	5.24	280	270	348
TH 47	7.88	239	215	
TH 53	4.59	294	290	376
TH 56	4.61	294	290	376
TH 48	6.02	265	250	321
TH 88**	3.26	337	351	468

*: Average of 5 runs. **: Quartz crystal from miarolitic cavity.

The reason for the weak signal is only in part a grain-size effect, as the miarolitic quartz from ekerite (sample TH 88) did not give a significantly stronger signal at a 1-2 mm grain-size. Rather, the main reason for the poor response lies with a lower than desired total abundance of fluid, which reflects the moderate average fluid inclusion size in the samples.

The Na/K ratios obtained from the ICP have been recalculated to temperatures, using the empirical geothermometer equations of Fournier (1981) and Truesdell (1976), as listed by Truesdell (1984). The uncertainty in these temperatures resulting from analytical error amounts to + 10° C. The agreement between the two methods is best at T=290° C. At lower T, the Fournier thermometer gives progressively higher temperatures than the Truesdell version; effect is inherent in the formulas used; the present data thus do not tell anything about the relative merit of the two equations.

Poty et al. (1974) and Lagache & Weisbrod (1977) used a thermodynamic analysis of experimental data on alkali feldspar - solution equilibria to derive an expression relating the molar KCl/NaCl ratio of a fluid coexisting with two alkali feldspar phases to temperature. Their results show that the composition of the solution depends upon the composition and structural state of the feldspars; for dilute solutions (<1-2 molal, i.e. <5-8 weight percent NaCl equivalents) the total solute concentration also affects the ionic ratio of the solution (Lagache & Weisbrod 1977, Figs. 6-8).

A general feature of the results are the low temperatures, 239-337° C using the Fournier thermometer (Table 1). The temperatures from rock-forming quartz in the two plutons overlap, but apparently with a slightly larger range for the Eikeren-Skrim ekerite (239-294° C, Table 1) than from the Sande nordmarkite (262-294° C). The miarolitic quartz from ekerite (TH 88) yields a temperature significantly higher than the rock-forming quartz (337° C).

All samples except one have bulk fluid compositions within the range of the calibration of Lagache & Weisbrod (1977). The Lagache - Weisbrod temperatures listed in Table 2 have been determined graphically from their recommended concentration-ratio vs. temperature curve. These temperature estimates are significantly higher than those obtained by the empirical geothermometers, but still lie in the sub-solidus range (T < 470° C).

The difference between temperatures cal-

culated by empirical thermometers and the Lagache - Weisbrod method is probably related to differences in the basic assumptions of the calibrations: in the approach of Lagache & Weisbrod (1977) only feldspar - fluid equilibria are considered, whereas the empirical thermometers include an unspecified contribution from feldspar - sheet silicate - fluid reactions. The latter type of reactions apparently gives a higher K/Na ratio of the fluid phase at any given temperature than do equilibria only involving alkali feldspars. The cathodoluminescence observations suggest that large proportions of the primary feldspar have reacted with the fluid phase. However, minor amounts of secondary sheet silicates (sericite) are undoubtedly present in the samples studied. Since it is not possible to evaluate the relative importance of feldspar-fluid and feldspar-sheet silicate-fluid alkali exchange reactions, a pragmatic view is to regard the Lagache - Weisbrod temperatures as an absolute upper limit for the temperature of postmagmatic fluid interaction processes in the two plutons investigated.

Discussion

The temperatures obtained by bulk fluid alkali geothermometry are far lower than the estimated solidus for syenitic and alkali granitic magmas in the Oslo region ($> 700^{\circ}\text{C}$; Neumann 1976, Andersen 1984a). Data from microthermometry show that the Sande nordmarkite and the Eikeren ekerite have long and complex fluid evolution histories, extending from solidus or near-solidus temperatures to temperatures below 300°C (Andersen 1990, Hansteen & Burke 1990). Regardless of which of the different sets of temperatures in Table 1 is accepted, the present data confirm the importance of the low-temperature fluid interaction processes in the Sande and Eikeren-Skrim plutons, and suggest that important fluid interaction events took place at similar temperatures in the two plutons ($T=240\text{-}300^{\circ}\text{C}$). This event caused the trapping of late postmagmatic fluid inclusions, characterized by low salinities and high densities (Andersen 1989, Hansteen & Burke 1990), and is most probably related to the influx of relatively cool aqueous fluids from a source outside the pluton.

The rock-forming quartz does not show any temperature trends which would allow the internal cooling histories of the plutonic fluid systems to be deduced. The 'high' temperature

of the miarolitic quartz sample (337°C vs. $T < 300^{\circ}\text{C}$ for rock-forming quartz) agrees with the observation that late-postmagmatic fluid inclusions are scarce in this sample.

Aqueous fluid inclusions trapped at temperatures higher than ca. 300°C are definitively present in most of the samples (Andersen 1989, Hansteen & Burke 1989). During microthermometric analysis, a few primary fluid inclusions decrepitated around 600°C , which is equivalent to the maximum temperature experienced by the samples in the decrepitation oven. Most primary and early secondary fluid inclusions survived this temperature. The bulk fluid extracted from the samples therefore only contains a minor component of high-temperature fluid. This would, however, tend to shift the temperature estimates towards slightly higher values, so that the temperature for the maximum intensity of fluid-rock interaction would lie somewhat to the low-temperature side of the values listed in Table 2.

In Fig. 2, a correlation between late secondary fluid inclusions and the low-temperature reequilibration of quartz (low luminosity) was noted. The presence of low-temperature quartz is also correlated with pseudomorphic replacement of an alkali feldspar phase with blue luminescence by one with a characteristic red luminescence (Fig. 2). The present data suggest that these mineralogical changes are due to pervasive fluid interaction at temperatures in the range $200\text{-}300^{\circ}\text{C}$. As the cathodoluminescence properties of feldspar are thought to reflect its trace element chemistry (e.g. Mariano & Ring 1975, Nickel 1978), the changes of luminescence are most likely due to changes in trace element distribution during fluid interaction.

Oxygen-bearing minerals interacting with an aqueous fluid phase at ca. 300°C would acquire an oxygen isotopic signature controlled by the isotopic composition of the fluid and the mineral-fluid fractionation factors for oxygen at the temperature in question (e.g. Hoefs 1980). A fluid phase migrating through the plutonic system at this temperature would most probably contain a significant meteoric component (e.g. Henley & McNabb 1978), and thus have an oxygen isotopic signature different from that of the primary igneous minerals. The quartz and feldspar showing cathodoluminescence indications of low-temperature reequilibration would therefore be expected to differ in oxygen isotopic composition from

the undisturbed quartz and feldspar. If so, the complex intergrowth and replacement structures revealed by cathodoluminescence microscopy (Fig. 2) suggest that these minerals are heterogeneous in oxygen isotopes even on a small (sub-grain) scale. This effect should be taken into consideration when interpreting oxygen isotope data from bulk samples of shallow plutonic rocks like the Oslo region syenites and alkali granites.

Although restricted to two plutonic systems, the findings reported here may have general relevance for the felsic intrusions in the Oslo Rift. Andersen (1990) found that the fluid phase in the Sande pluton during initial sub-solidus cooling was derived from the magma itself, and that it was retained within the rock body down to ca. 300° C. The present data suggest that influx of externally derived fluids and hydrothermal circulation only became important at temperatures lower than this limit. It is interesting to note that this type of fluid evolution differs from what is commonly encountered in porphyry-type systems, where intense fluid-rock interaction and hydrothermal-circulation take place at much higher temperatures, close to the silicate solidus (e.g. Henley & McNabb 1978, Roedder 1984).

Conclusions

Alkali ion geothermometry indicates that the maximum intensity of fluid interaction in the Sande nordmarkite and the Eikeren-Skrim ekerite took place at temperatures between 200 and 300° C, i.e. at temperatures clearly below the solidus (700° C). The temperatures obtained in this study correlate with late, secondary fluid inclusions which have been observed by microscopic examination and microthermometry.

In the interaction with fluids, the feldspar minerals of the intrusive rocks were pseudomorphically replaced by feldspar with different cathodoluminescence properties, and hence different trace element and possibly oxygen isotopic composition.

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References

- Alderton, D.H.M., Thompson, M., Rankin, A.H. & Chryssoulis, S.L. 1982: Developments of the ICP-linked decrepitation-technique for the analysis of fluid inclusions in quartz. *Chem. Geol.* 37, 203–213.
- Andersen, T. 1984a: Crystallization history of a Permian composite monzonite-alkali syenite pluton in the Sande cauldron, Oslo rift, S. Norway. *Lithos* 17, 153–170.
- Andersen, T. 1984b: Hybridization between larvikite and nordmarkite in the Oslo region, S.E. Norway: A case study from the Sande Cauldron central pluton. *Nor. Geol. Tidsskr.* 64, 221–233.
- Andersen, T. 1988: Sub-solidus fluidutvikling i Sande nordmarkitten, Oslo riften, sydøst Norge (abstract) 18. Nordiske Geologiske Vintermøde, København 1988, p. 24.
- Andersen, T. 1990: Melt-mineral-fluid interaction in peralkaline silicic intrusions in the Oslo rift, Southeast Norway. IV: Fluid inclusions in the Sande nordmarkite (quartz syenite). *Nor. geol. unders. Bull.* 417, 41–54.
- Brøgger, W.C. 1906: Eine Sammlung der wichtigsten Typen der Eruptivgesteine des Kristianiagebietes nach ihre geologischen Verwandtschaftsbeziehungen geordnet. *Nyt Mag. f. Naturv.* 44, 117–144.
- Dietrich, R.V. & Heier, K.S. 1965: Differentiation of quartz bearing syenite (nordmarkite) and riebeckite-arfvedsonite granite (ekerite) of the Oslo series. *Geochim. Cosmochim. Acta* 31, 275–280.
- Dietrich, R.V., Heier, K.S. & Taylor, S.R. 1965: Studies on the igneous rock complex of the Oslo region. XX. Petrology and geochemistry of ekerite. *Skr. Norske Vidensk. Akad. i Oslo. I. Mat.-naturv. Kl. Ny Serie* No. 19, 31 pp.
- Fournier, R.O. 1981: Application of water geochemistry to geothermal exploration and reservoir engineering. In Ryback, L. & Muffler, L.J.P. (eds.) *Geothermal Systems: Principles and Case Histories*, John Wiley, New York, 109–143.
- Hansteen, T.H. 1988: Cooling history of the Eikeren-Skrim peralkaline granite complex, the Oslo region, Norway. Evidence from fluid inclusions and mineralogy. Unpubl. Cand. Scient. thesis, University of Oslo. 244 pp.
- Hansteen, T.H. & Burke, E.A.J. 1990: Melt-mineral-fluid interaction in peralkaline silicic intrusions in the Oslo rift, Southeast Norway. II: High temperature fluid inclusions in the Eikeren-Skrim complex. *Nor. geol. unders. Bull.* 417, 15–32.
- Henley, R.W. 1984: Hydrolysis reactions in hydrothermal fluids. *Reviews in Economic Geology* 1, 65–82.
- Henley, R.W. & McNabb, A. 1978: Magmatic vapor plumes and groundwater interaction in porphyry copper emplacement. *Econ. Geol.* 73, 1–20.
- Hoefs, J. 1980: *Stable isotope geochemistry*, 2nd. edition, Springer, Berlin, 208 pp.
- Lagache, M. & Weisbrod, A. 1977: The system: Two alkali feldspars-KCl-NaCl-H₂O at moderate to high temperatures and low pressures. *Contrib. Mineral. Petrol.* 62, 77–101.
- Mariano, A.N. & Ring, P.J. 1975: Europium-activated cathodoluminescence in minerals. *Geochim. Cosmochim. Acta* 39, 649–660.
- Neumann, E.-R. 1976: Compositional relations among pyroxenes, amphiboles and other mafic phases in the Oslo Region plutonic rocks. *Lithos* 9, 85–109.
- Neumann, E.-R., Andersen, T. & Hansteen, T.H. 1990: Melt-mineral-fluid interaction in peralkaline silicic intrusions in the Oslo rift, Southeast Norway. I: Distribution of elements in the Eikeren ekerite. *Nor. geol. unders. Bull.* 417, 1–13.

- Nickel E. 1978: The present status of cathodoluminescence as a tool in sedimentology. *Minerals Sci. Engng.* 10, 2, 73–99.
- Oftedal, C. 1953: Studies on the igneous rock complex of the Oslo region. XIII. The Cauldrons. *Skr. Norske Vidensk. Akad. i Oslo. I. Mat.-naturv. Kl. No. 3*, 108 pp.
- Olsen, K.I. & Griffin, W.L. 1984: Fluid inclusion studies of the Drammen Granite, Oslo Paleorift, Norway. *J. Microthermometry. Contrib. Mineral. Petrol.* 87, 1–14.
- Orville, P.M. 1963: Alkali ion exchange between vapor and feldspar phases. *Am. Jour. Sci.* 261, 201–237.
- Poty, B.P., Stalder, H.A. & Weisbrod, A.M. 1974: Fluid inclusion studies in quartz from fissures of western and central Alps. *Schweiz. min. petr. Mitt.* 54, 717–752.
- Raade, G. 1972: Mineralogy of the miarolitic cavities in the plutonic rocks of the Oslo region, Norway. *Mineral. Record* 3, 7–11.
- Rae, D.A. & Chambers, A.D. 1988: Metasomatism in the North Oroq centre, South Greenland: cathodoluminescence and mineral chemistry of alkali feldspars. *Trans. Royal Soc. Edinburgh: Earth Sci.* 79, 1–12.
- Ramberg, I.B. & Larsen, B.T. 1978: Tectonomagmatic evolution. *In: The Oslo Paleorift, a review and guide to excursions.* *Nor. geol. unders.* 337, 56–73.
- Rankin, A.H., Alderton, D.H.M., Thompson, M. & Goulter, J. 1982: Determination of uranium : carbon ratios in fluid inclusion decrepitate by inductively coupled plasma emission spectroscopy. *Min. Mag.* 46, 179–186.
- Rasmussen, E., Neumann, E.-R., Andersen, T., Sundvoll, B., Fjerdingsstad, V. & Stabel, A. 1988: Petrogenetic processes associated with intermediate and silicic magmatism in the Oslo rift, southeast Norway. *Min. Mag.* 52, 293–307.
- Roedder, E. 1958: Technique for the extraction and partial chemical analysis of fluid filled inclusions from minerals. *Econ. Geol.* 53, 235–269.
- Roedder, E. 1984: Fluid inclusions. *Reviews in Mineralogy* 12, 644 pp.
- Shepherd, T.J., Rankin, A.H. & Alderton, D.H.M. 1985: *A Practical Guide to Fluid Inclusion Studies.* Blackie, Glasgow and London. 239 pp.
- Thompson, M., Rankin, A.H., Walton, S.J., Halls, C & Foo, B.N. 1980: The analysis of fluid inclusion decrepitate by inductively coupled plasma atomic emission spectroscopy: an exploratory study. *Chem. Geol.* 30, 121–133.
- Truesdell, A.H. 1976: GEOTHERM, a geothermometric computer program for hot spring systems: *Proc. 2nd. U.N. Symp. on the Development and Use of Geothermal Resources.* San Francisco, 1975, v.1, 831–836.
- Truesdell, A.H. 1984: Chemical geothermometers for geothermal exploration. *Reviews in Economic Geology* 1, 31–44.
- Weisbrod, A. 1981: Fluid inclusions in shallow intrusives. *Min. Assoc. Canada, Short course handbook* 6, 241–271.
- Zinkernagel, U. 1978: Cathodoluminescence of quartz and its application to sandstone petrology. *Contrib. Sedimentology* 8, 69 pp.