Cathodoluminescence and microporosity in alkali feldspars from the Blå Måne Sø perthosite, South Greenland

ADRIAN A. FINCH* AND F. DAVID L. WALKER

Department of Geology and Geophysics, University of Edinburgh, West Mains Road, Edinburgh EH9 3JW, U.K.

Abstract

Samples from a traverse across the Blå Måne Sø perthosite unit in the Tugtutôq Central Complex of the Gardar province, South Greenland have been examined for cathodoluminescence characteristics, microporosity and $\delta^{18}O$ isotopic values. Reddening of cathodoluminescence colours in alkali feldspars (normally blue) from the unit may be correlated with increased microporosity of the feldspars as determined using scanning electron microscopy. $\delta^{18}O$ values of all samples lie within the range of values expected of juvenile fluids, independent of the level of alteration indicated by cathodoluminescence studies.

Observations are consistent with previous suggestions that levels of alkali feldspar microporosity and levels of fluid alteration (as determined by cathodoluminescence of alkali feldspars) are related phenomena. Oxygen isotope ratios suggest that the fluid is largely juvenile in origin, with, perhaps, some meteoric (low $\delta^{18}O$) component.

KEYWORDS: cathodoluminescence, microporosity, alkali feldspars, perthosite, Greenland.

Introduction

THE association of alkaline magmatism with evidence for the presence of a hydrothermal fluid phase has been noted by many authors (e.g. Andersen, 1989, and refs therein). This fluid is enriched in many elements and may bring about secondary alteration of both the envelope rocks of alkaline intrusions, and of the consolidated rocks of the intrusions themselves (autometasomatism). This process of alteration is variously known as *fenitisation* or *alkali metasomatism*. Some disagreement about the use of these terms has appeared in the literature. Most petrologists (e.g. Andersen, 1989) consider the term 'metasomatism' (i.e. change of body) to imply some major bulk chemical change as a result of alteration. However, in some instances (e.g. Stephenson, 1976) alteration as a result of the fluid is largely isochemical, with only textures and trace element concentrations being altered. The process described in the present study is a process of textural change with most likely only minor changes in chemistry. This process does not represent another type of alteration; rather that the rock and fluid are close to equilibrium and hence chemical changes are subtle. No one term encompasses without ambiguity either major chemical, trace element, or textural change as a result of subsolidus interaction with a fluid phase. The term *alkali metasomatism* has been used to describe the alteration process in the present paper. The term 'metasomatic' is considered justified since it is assumed that observed textural changes are associated with at least trace element chemical changes.

Many recent studies have used alkali feldspar microtextures as indicators of fluid interaction with evolved rocks. As reviewed by Parsons and Brown (1984), coherency is lost during exsolution of alkali feldspars if a hydrous phase is present at elevated temperatures. The presence of coarsely exsolved perthites is therefore taken to indicate that a rock has been subjected to deuteric alteration. Despite the obvious importance of alkali feldspars in studies of alkaline rocks, no study has yet attempted to link the hydrothermal

* Present address: Department of Chemistry, University of Aberdeen, Meston Walk, Old Aberdeen AB9 2UE, U.K.

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alteration implied by feldspar microtextures and the observation of fluid-rock interaction on a large scale in and around evolved alkaline rocks.

Cathodoluminescence (CL) characteristics of alkali feldspars may be changed drastically by fluid interaction including alkali metasomatic alteration (e.g. Mariano, 1988), and this textural change may be used as a first-order gauge of the amount of fluid interaction a sample has undergone. The process of change in the alkali feldspar luminescence characteristics appears from studies of altered and unaltered rocks (Finch, 1990) to be isochemical, yet texturally it can be clearly related to the actions of a fluid phase, associated with, and probably evolving from, an alkaline igneous body. In addition to this, alkali feldspars, when deuterically altered, develop intragrain microporosity, associated with the formation of subgrains (Worden *et al.*, 1990). In the present paper, an attempt has been made to compare the small-scale microporosity of alkali feldspars and the pluton-wide observation of fluid interaction as determined by CL-studies.

The Blå Måne Sø ('Blue Moon Lake') perthosite is an ovoid stock approximately 1.2 km across its longest diameter, and represents the last intrusive event of the Tugtutôq Central Complex (TCC) (Upton, 1964; Upton *et al.*, 1991). The TCC is part of the mid-Proterozoic Gardar province of South Greenland, as reviewed by Emeleus and Upton (1976) and Upton and Emeleus (1987). The perthosite is a pink or chalky white syenite, composed largely of coarsely perthitic alkali feldspar with very small amounts of other minerals. Ferruginous staining sometimes occurs on the cleavages and between the feldspar laths. Occasional apatites, amphiboles and biotites are found. In thin section, the feldspars are seen to be coarsely exsolved patch perthites, although some relicts of braid perthite still remain. Very occasionally, optically homogeneous cryptoperthitic feldspar relicts occur. The Blå Måne Sø stock was chosen for this study since it is undisturbed by later igneous activity, and therefore preserves evidence for movement of fluids directly associated with the intrusion of the stock around and within the unit. In addition, the monotonous mineralogy of the unit removes the possibility that changes in modal percentages of key minerals will effect the appearance of fluid alteration in the sample.

A traverse was made across approximately two thirds of the stock in regular intervals along a sighted line (Fig. 1). In total, 24 samples were collected, including two from the basement Julianehåb granite adjacent to the contact (BM21 and BM22), and one from a trachyte dyke emplaced along the contact between the stock and its envelope (BM20A). BM9A is a sample of a pegmatite adjacent to the location of sample BM9.

Cathodoluminescence

Cathodoluminescence characteristics of alkali feldspars have been studied by several authors since the work of Smith and Stenstrom (1965). Mariano (1976) first used these characteristics to study alkali metasomatism, noting that metasomatised feldspars luminesced red, whereas those which had escaped alteration were blue. This provides clear visual criterion by which levels of alteration by late-stage fluids in syenites can be judged. The causes of the different luminescence colours have been the subject of some disagreement. Mariano suggested that the blue luminescence colour was due to trace amounts of Ti, although Rae and Chambers (1988) could find no correlation between the height of the blue peak and Ti-content. An alternative suggestion was presented by De St. Jorre and Smith (1988), who linked deep blue luminescence in feldspars from the Thor Lake deposit, Quebec, to gallium contents. The gallium contents of red and blue luminescing alkali feldspar variants of the Klokken quartz syenite aplite unit (Sample GGU 43729) (Parsons, 1979), which we consider analogous to the Blå Måne Sø feldspars, have been compared. The Ga-levels were measured using a Cameca ims-4f ion-microprobe using a 15 keV O^- primary beam and measuring secondary positive ion intensities. Measurements were made at approximately 8000 mass resolution without energy filtering, and molecular interferences were fully resolved. Ion yields were assumed to be the same as for NBS 610 glass standard (500 ppm Ga). Ga levels were measured by normalising the counts of $^{69}Ga^+$ to those of the $^{30}Si^+$ species. The core gave concentrations of about 20 ppm Ga, and the rim contained approximately 50 ppm Ga. These values were far below the highly enriched Ga-levels of the Thor Lake feldspars (300–600 ppm). Since *increases* in gallium content from the blue luminescing core to the red luminescent rim have been observed, Ga is unlikely to be a critical factor in determining blue luminescence in the Blå Måne Sø rocks. By analogy with the deductions of Sigel (1973), who studied the blue luminescence of quartz, Geake *et al.* (1977) have suggested that the blue feldspar luminescence results from E′-defects in the structure, a theory supported by Rae and Chambers. Such an interpretation is difficult to prove without detailed TEM work.

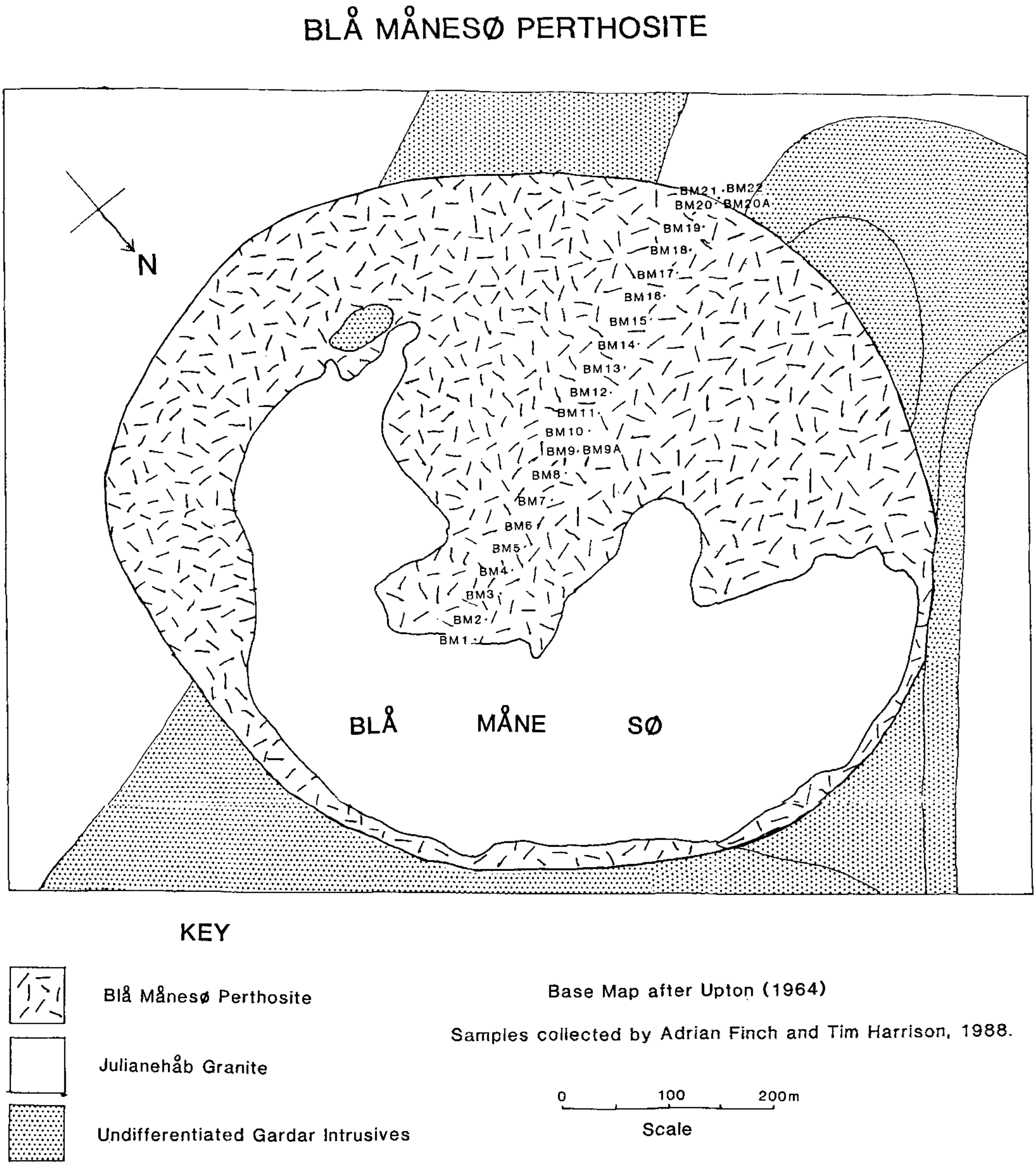

FIG. 1. Sample localities of Blå Måne Sø traverse. The centre of the intrusion lies at approximately 60°51′N, 46°22′W.

Red luminescence in feldspars was first observed by Smith and Stenstrom (1965) in a microcline. Mariano (1976, 1979) suggested that the red colour in alkaline environments was due to enrichment of the feldspars in Fe^{3+} from a metasomatic fluid. Textural evidence strongly suggests that the reddening of luminescence of originally blue-luminescing feldspars is as a direct result of the action of a fluid phase. However, Rae and Chambers (1988) found that the red peak was also present in blue luminescing feldspars, but was masked by the dominant blue colour. The observation of red luminescence in altered feldspar, therefore, relies not only on the amplification of the red luminescence band, but also on the suppression of the original blue colour.

Rae and Chambers did however show that the red luminescence peak was increased in strength during progressive action of the fluid phase, and that the strength of the peak could be related to Fe-contents. These authors also noted the presence of purple luminescing alkali feldspars, where, presumably, the suppression of the blue luminescence peak was incomplete.

As part of the present study, the ratio of blue to red luminescing alkali feldspar in a rock has been used as a gauge of the amount of alteration to which a sample has been subjected. An index of this alteration (*feldspar luminescence index*, f.l.i.) is defined as the percentage of metasomatised alkali feldspar divided by the sum of the metasomatised (red luminescing) and magmatic (blue luminescing) feldspar present [f.l.i = %red/(total feldspar)]. Determination of f.l.i. for the Blå Måne Sø samples was carried out by point counting (200 points) on colour photographs of representative areas (usually two) in the sample.

The samples of the perthosite studied show f.l. indices ranging from 48% to 96%, and are therefore highly altered rocks (Table 1). The greatest fluid interaction as indicated by CL was found near the centre of the intrusion and near the edge, with a localised increase associated with the pegmatite along the traverse (BM9A) (Fig. 2). Small grains of yellow luminescent calcite were found in sample BM19, adjacent to the contact with the Julianehåb granite and in samples of the basement. Other metasomatic minerals which are known from other units of the TCC, such as fluorite (Upton *et al.*, 1991), were absent. Orange luminescing apatites were unzoned. This evidence suggests that volatiles both collected in the centre and passed around the edge of the intrusion during cooling. The presence of a line of weakness between the stock and its envelope is implied by the presence of a small trachyte dyke (BM20A), emplaced along the contact.

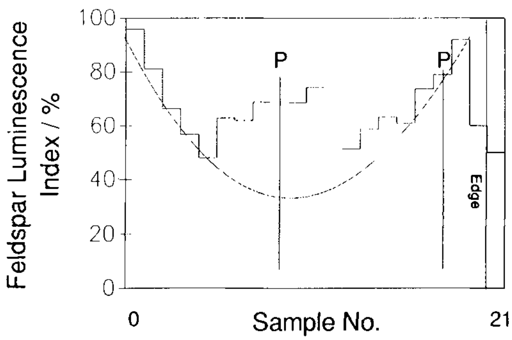

FIG. 2. Variation of f.l.i. across the Blå Måne Sø traverse. Pegmatites are marked by the letter P. The curve represents a possible variation of f.l.i. across the traverse before the intrusion of the pegmatites.

Microporosity

Alkali feldspars in plutonic igneous rocks have often undergone fluid alteration which results in the formation of coarse irregular deuteric perthites in place of fine-scale regular strain-controlled micro- to crypto-perthites (Parsons and Brown, 1984). The regular perthites are termed 'strain-controlled' since their morphology is controlled by elastic strain between the K- and Na-rich phases within the perthite at the time of initial cooling. It has also been noted (Parsons, 1978, 1980; Parsons and Brown, 1984) that there is a general connection between the development of deuteric feldspars and optical turbidity in the perthites. Recent work (Worden *et al.*, 1989, 1990) has confirmed earlier suspicions (Brace *et al.*, 1972; Sprunt and Brace, 1974; Montgomery and Brace, 1975) that the turbidity is related to the presence of numerous micropores. It has also been shown by oxygen exchange experiments (Walker, 1990) that micropores within alkali feldspars are interconnected, thus forming a fine-scale channel network for fluid flow.

If the micropores were formed via fluid interaction, providing a network for further fluid flow, it might be expected that the microporosity of red-luminescing areas of feldspar would be greater than in those which luminesced blue. In order to investigate this, backscattered SEM images of red- and blue-luminescent areas in one sample (BM13) were obtained using a Cambridge Stereo-Scan scanning electron microscope, to determine whether those areas which luminesce red could be correlated with areas of greater microporosity. The results of this comparison are presented in Fig. 3.

In addition to small-scale comparison of microporosities within a single sample, the microporosity of the sample as a whole may vary sympathetically with the f.l.i. of the rock. However, there are practical difficulties with such a study, since microporosity determinations are normally carried out on freshly cleaved surfaces (as described in Worden *et al.*, 1990), whereas accurate determinations of f.l.i. are only possible on polished faces. So that an attempt could be made to compare the microporosity and f.l.i. of samples across the traverse, microporosity determinations (1500 points) were carried out on cleaved fragments of samples from the traverse. The point counting data are presented in Table 1.

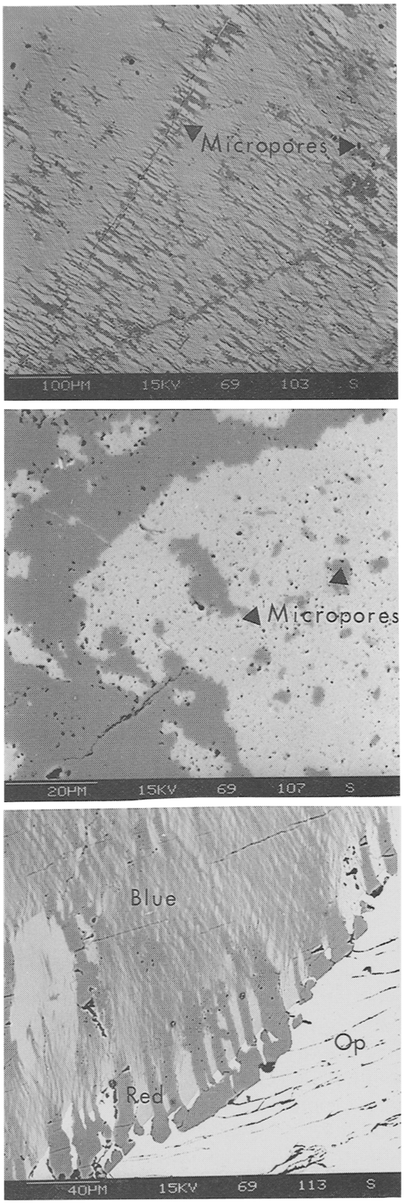

FIG. 3. Backscattered SEM photomicrographs of areas of blue-luminescing (Top) and red-luminescing (Middle) feldspar. Micropores have been marked in both photographs. The bottom photograph demonstrates an area of feldspar adjacent to an opaque grain (Op) with blue-luminescent braid-perthite separated from the opaque grain by a band of red-luminescing patch perthite. The blue-luminescing perthite has a much lower microporosity than its red-luminescing equivalent.

Table 1 : Microporosities, feldspar luminescence indices and $\delta^{18}O$ values for Blå Måne Sø perthosite.

Sample No.	Microporosity/%	f.l.i./%	$\delta^{18}O$/‰
BM1	3.9	95.9	n.d.
BM2	3.2	81.2	4.9
BM3	4.1	66.5	4.2
BM4	2.9	56.7	1.9
BM5	3.2	48.1	n.d.
BM6	3.5	62.9	6.8
BM7	3.3	62.0	8.1
BM8	3.5	68.8	5.6
BM9	3.1	n.d.	7.3
PEGMATITE			
BM10	1.8	68.7	3.4
BM11	2.7	74.2	2.9
BM12	4.0	n.d.	6.8
BM13	1.9	51.3	n.d.
BM14	3.3	58.7	n.d.
BM15	2.9	63.2	6.2
BM16	3.2	60.9	5.0
BM17	4.1	73.7	7.3
BM18	3.9	79.0	n.d.
PEGMATITE			
BM19	2.9	92.0	6.3
BM20	0.9	60.0	5.3
EDGE			
BM21	2.6	50	4.9

n.d. = not determined

Oxygen isotopic data

Many studies of alkali metasomatism have hinted at the possibility that the fluids causing the alteration are derived, at least in part, from the volatile component of the alkali magmas, separated after cooling and solidification of the silicate phase (e.g. Parsons, 1980). However, other studies (e.g. Taylor and Forester, 1979, from the Skaergård intrusion) have stressed the role of meteoric fluids in penetrating and altering igneous plutons.

Few isotopic data exist for the Gardar province. Sheppard (1986) analysed whole-rock and separates from some intrusions in the Gardar province for $\delta^{18}O$, and found them to generally lie within values of other syenites, in the field of juvenile origin. Konnerup-Madsen *et al.* (1988) examined $\delta^{13}C$ and δD values of methane-bearing fluid inclusions from the Ilímausaq intrusion, and also concluded tentatively that the fluids were magmatically derived.

For the present study, isotopic analyses have been carried out only on feldspar separates, to negate the effects of modal variation between samples. Values obtained generally agree with those of Sheppard, although the range of values found in the present study is greater (1.9 to 8.1‰) (Fig. 4 and Table 1). It is concluded therefore that the isotopic composition of both fluid and rock were close to equilibrium. Although the bulk of the data lie within the range of juvenile waters, the lowest values of $\delta^{18}O$ lie marginally outside (e.g. BM4) (A. E. Fallick, pers. comm., 1989). This may indicate either the presence of a small low-$\delta^{18}O$ (meteoric) component in the fluids, or alternatively, these low-$\delta^{18}O$ values may derive

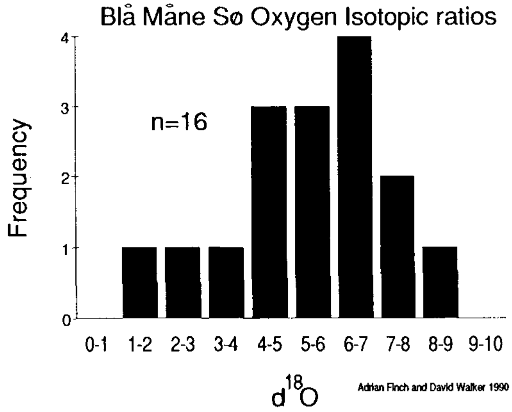

FIG. 4. Histogram of $\delta^{18}O$ isotopic values for alkali feldspars separates from the traverse.

from poor precision in the data. We have been unable to explain the spatial distribution of these low-$\delta^{18}O$ samples across the traverse.

Discussion

The examination of small areas of blue- and red-luminescent feldspar show that the red-luminescing areas are associated with greater microporosities than in blue-luminescent areas (Fig. 3). In addition, data for each of the points along the traverse have been compared in an attempt to determine whether the microporosity and f.l.i. could be correlated statistically on the hand-specimen scale. Values were compared as non-parametric variables using Kendall's Tau test and significant correlations identified (see Conover, 1980). The test demonstrated a correlation (Tau) value of 0.198, which corresponds to a low (less than 90%) significance.

Despite the clear correlation between f.l.i. and microporosity on the small scale (Fig. 3), the statistical approach to comparing the two parameters on the hand-specimen scale failed to show convincing correlation. This suggests either that there is a complex relationship between the volume of fluid flow and the degree of reddening of feldspar luminescence, or, perhaps more likely, as microporosity and f.l.i. determinations within hand-specimens were not carried out on the same rock fragments, variations in both microporosity and f.l.i. within hand-specimens are obscuring the correlation implied by small scale observations.

CL-textural studies suggest strongly that much of the fluid alteration is associated with grain boundaries in the syenite. However, in many cases, metasomatic reddening is observed to penetrate to the centres of crystals without the assistance of obvious cracks or microfractures. Walker (1990) has shown that the micropore network present in alkali feldspars is permeable to fluid movement at pressures and temperatures appropriate for Gardar rocks (1 kbar, 500 °C), and hence the presence of interconnected micropores inside the Blå Måne Sø feldspars suggests that, in addition, metasomatic fluids may flow *through the body of the alkali feldspars themselves*. Despite the high feldspar luminescence indices of these rocks, the maximum microporosities of the Blå Måne Sø feldspars constitute 4.1% of the volume of the feldspars. Feldspars from other intrusions with lower f.l.i. values can show higher microporosities of up to about 5% (Worden *et al.*, 1989, 1990), and hence the level of microporosity development between centres is probably not a simple function of metasomatism. Although from the observations discussed above, the microporosity could have been brought about by the action of a magmatically-derived fluid, Worden *et al.* (1990) have suggested that the microporosity may result, at least in part, from expulsion of water exsolved from the alkali feldspars themselves. Later metasomatic fluid may therefore merely be exploiting and enhancing a pre-existing micropore network, dependent on alkali feldspar exsolution of water (Walker, 1990). Water derived in this manner from alkali feldspars alone, however, cannot explain the volumes and compositions of metasomatic fluids from the Gardar (Finch, 1990). It may well be that this exsolved water, although probably minor with respect to the total volume of fluid, may be significant in determining whether alkali metasomatic fluids can penetrate the body of the feldspars and hence the degree of metasomatism that can occur. This in turn determines the final composition of the rock.

The lack of correlation between f.l.i. and oxygen-isotopic data (Table 1) indicates that the rock and fluid isotopic compositions were closely equivalent. This implies that the bulk of the fluid is juvenile in origin, deriving from the alkaline magmas themselves, in accordance with previous suggestions (Parsons, 1980). The range of oxygen-isotopic ratios in the samples, and the occasional low-$\delta^{18}O$ value, indicate that although the vast majority of the fluid was juvenile, and only a small meteoric component could have been present in the fluid.

Conclusions

It is concluded that the rocks of the Blå Måne Sø perthosite were subject to large-scale interaction with a magmatically derived fluid. An empirical index of this interaction (feldspar luminescence index, f.l.i.) is defined as the percentage of red luminescing alkali feldspar divided by the sum of altered (red luminescing) and magmatic (blue luminescing) feldspar present. The Blå Måne Sø rocks have indices ranging from 48 to 96%. The action of a fluid on the alkali feldspars in the stock led to the development of increased intracrystalline microporosities of up to 4.1%. The microporosity may have resulted from direct interaction between the metasomatic fluid and the alkali feldspars. An alternative explanation is that it formed by interaction with water exsolved from the alkali feldspars themselves, with later fluids merely exploiting and enhancing a pre-existing micropore network. The fluid was derived largely from the magma itself, with a small but significant part possibly exsolved from the feldspars themselves.

Whatever the origins of the micropore network, fluids flowed along grain boundaries and, via the micropore network, through the body of the alkali feldspars themselves. The presence of the micropore network assisted pervasive fluid motion and alteration of the unit. Metasomatism had little overall effect on the $\delta^{18}O$ values of the feldspars.

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