Petrography and geochemistry of peralkaline, ultrapotassic syenite dykes of Middle Permian age, Sunnfjord, West Norway

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Two peralkaline, ultrapotassic syenite dykes from Sunnfjord, West Norway yield Middle Permian K-Ar ages. The hydrothermally-altered dykes are composed of microcline, Si-rich and Al-poor phlogopite, an Al-deficient brown mica partly altered to saponite, eckermannite, celadonite, apatite, calcite, baryte and the rare minerals dalyite and labuntsovite. The dykes are strongly enriched in K_2O, Rb, Sr, Zr, Nb and LREE, and the ratios K_2O/Na_2O and K_2O/Al_2O_3 are exceptionally high. They are geochemically similar to peralkaline lavas from Leucite Hills and may be related to comparable dykes in the Orkneys.

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This account deals with the mineralogy and textural relationships of two hydrothermally-altered, peralkaline, potassic syenite dykes from Dalsfjorden, West Norway (Fig. 1), which yield Middle Permian K-Ar ages. The dykes represent a new occurrence of high-K magmatic rocks and the first occurrence of such rocks in Norway. The genesis and regional significance of the dykes are briefly discussed.

Analytical methods

Whole-rock K/Ar analyses were performed on samples crushed to about 1 mm chips in order to homogenise the material prior to argon analyses. Part of this material was then reduced to about 200 mesh for potassium analysis. Determination of potassium was done by flame photometry using an EEL 450 instrument with a lithium internal standard. Argon isotopic analyses were performed by isotope dilution on a MS 10 spectrometer, the gas extraction system being coupled directly to the instrument.

The electron microprobe analyses were carried out on an ARL SEMQ, using an accelerating voltage of 15 KV, and beam-currents of between 7 and 10 nA. A mixture of minerals, synthetic oxides and pure metals were employed as standards. Net peak intensities, corrected for dead-time effects and beam-current drift as monitored from the objective aperture, were reduced by MAGIC IV (Colby 1968).

The major oxides and trace elements were analysed by X-ray fluorescence spectroscopy (XRF). International standards and Flanagan's (1973) recommended values were used for calibration. The major oxides were analysed on glass beads prepared by the method of Padfield & Gray (1971), and the trace elements on powder pellets. Ferrous iron was determined titrimetrically.

Geological relationships and age

The general geological relationships in the Dalsfjord region are shown in Fig. 1. The ultrapotassic dykes described in this account are known from only one locality, i.e. at Heilefjellet within the charnockitic-mangeritic rocks of the Dalsfjorden Nappe. They were recorded as sandstone dykes by N. H. Kolderup in 1921, and the samples he collected are the subject of the present investigation. According to Kolderup's field notes the dykes are about 10 cm wide, nearly vertical and trend approximately E-W. Major faults in the area also trend E-W (Skjerlie 1974). Despite an intense search the dykes have not
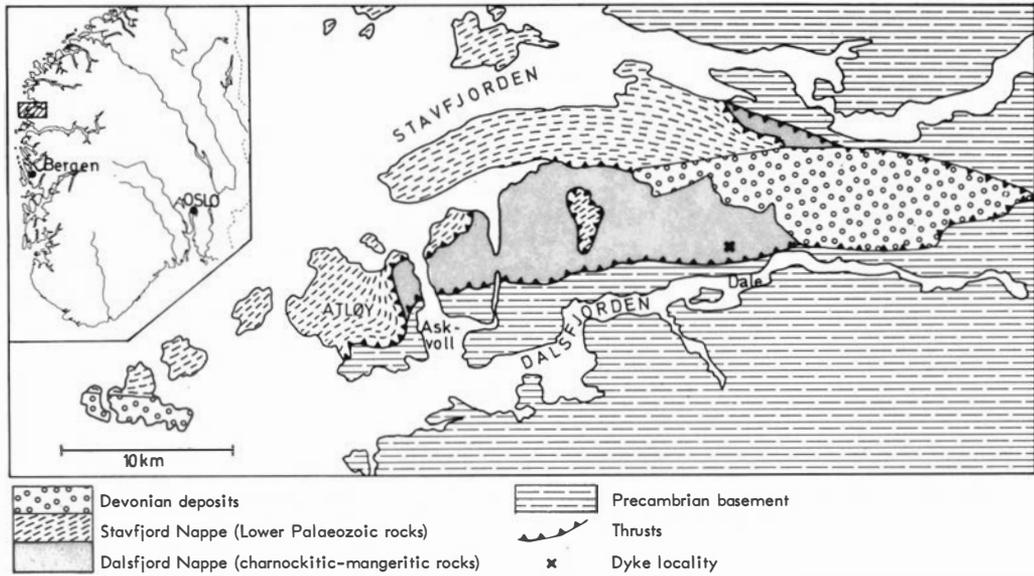
Fig. 1. Simplied geological map of the Sunnfjord area (after Skjerlie 1974), showing location of the dykes.

been relocated, but there is no reason to doubt that Kolderup's samples were from the Heilefjellet area.

Samples from both dykes have been dated by the K-Ar method, yielding concordant Middle Permian ages (Table 1). The concordancy is strong evidence that the K-Ar isotopic system has not been subsequently disturbed, and that the age obtained has geological significance. Post-magmatic Al-Si ordering of the feldspar (Halliday & Mitchell 1975) and hydrothermal alteration of the dykes may, however, have reduced the age significantly. The feldspar in these dykes is highly ordered and unless recrystallization and alteration occurred immediately after emplacement the dates must be regarded as a minimum age for their intrusion. The interpretation of the K-Ar age regarded as most plausible

is that they reflect a hydrothermal event which resulted in the thorough alteration of the dykes.

Petrography and mineral chemistry

Hand specimens of the Sunnfjord dykes superficially resemble micaceous sandstones. In thin section, however, the dykes are holocrystalline and consist of euhedral to subhedral K-feldspar microphenocrysts (75–80%) and phlogopite (15–20%) together with minor amounts of eckermannite (1–2%), celadonite (1–2%), apatite (< 1%), labuntsovite (~ 1% in IP71), small amounts of dalyite and calcite (in IP71), and traces of baryte. On a mineralogical basis the dykes can be classified as hydrothermally-altered phlogopite-bearing syenites.

The paragenesis of the dykes is regarded as largely secondary and the result of low-temperature alteration of an igneous assemblage containing K-feldspar (sanidine?) and phlogopite as well as apatite and other accessory minerals.

K-feldspar (microcline). – Most of the individual feldspar grains are four or six-sided euhedral to subhedral crystals 0.1–0.2 mm in diameter (Fig. 2a). More complex aggregates of six-sided form are defined by intergrown clusters of grains. Each crystal consists of a mosaic of K-feldspars

Table 1. Whole rock potassium-argon analyses of the dyke from Sunnfjord.

Sample	K_2O	v/m mm^3gm^{-1}	% Atmos	Age
IP70	12.04 ± 0.27	$(1.067 \pm 0.009)10^{-1}$	6.8	256 ± 6
		$(1.069 \pm 0.009)10^{-1}$	6.8	256 ± 6
IP71	11.51 ± 0.02	$(1.039 \pm 0.009)10^{-1}$	8.3	260 ± 2
		$(1.044 \pm 0.009)10^{-1}$	8.5	261 ± 6

Table 2. Electron microprobe analyses of K-feldspar

	Average (n = 16)	Range
SiO_2	64.45	62.78–66.75
TiO_2	0.06	0.00– 0.25
Al_2O_3	17.71	17.13–18.53
FeO^t	0.52	0.05– 1.06
MnO	0.02	0.00– 0.04
MgO	0.18	0.02– 0.58
CaO	0.03	0.00– 0.21
Na_2O	0.05	0.00– 0.09
K_2O	15.92	15.23–16.93
Total	98.94	

Formula based on 24 oxygens

Si	9.026
Ti	0.007
Al	2.934
Fe	0.061
Mn	0.002
Mg	0.039
Ca	0.005
Na	0.013
K	2.845
Or	99.4
Ab	0.4
An	0.2

Fig. 2a. Euhedral to subeuhedral microphenocrysts of microcline. – *b.* Grains of microcline showing cores of completely recrystallised, low-birefringent microcline (dark colour). – *c.* Microcline crystal with a concentric arrangement of inclusions.

which show variations in optical properties, indicating that the original microphenocrysts have suffered complete recrystallization. A common feature is that the cores have lower birefringence than the rims (Fig. 2b). Inclusions of apatite, Al-deficient brown mica, Ti-rich mineral(s) (labuntsovite?) and a green alteration mineral (celadonite?) occur in most crystals, and in some cases they are arranged in a concentric fashion (Fig. 2c).

The chemical composition of the K-feldspar is shown in Table 2. A characteristic feature is the very low Na_2O content, in no case exceeding 0.09 wt%. Within individual crystals there are no significant compositional variations.

XRD studies show that feldspar in both dykes is microcline, exhibiting a high degree of Al, Si ordering. The obliquity obtained using (131) and (1$\bar{3}$1) reflections (Goldsmith & Laves 1954) indicates triclinicities of 0.803 (IP 70) and 0.795 (IP 71). The ratio of the reciprocal axes c^*/b^* measured using the (040) and (002) reflections are 1.996 (IP 70) and 1.998 (IP 71), giving degrees of Al, Si ordering of 78% and 68% respectively (Jones 1966). The degree of Al, Si ordering is dependent upon a number of variables such as temperature, time and peralkalinity of the
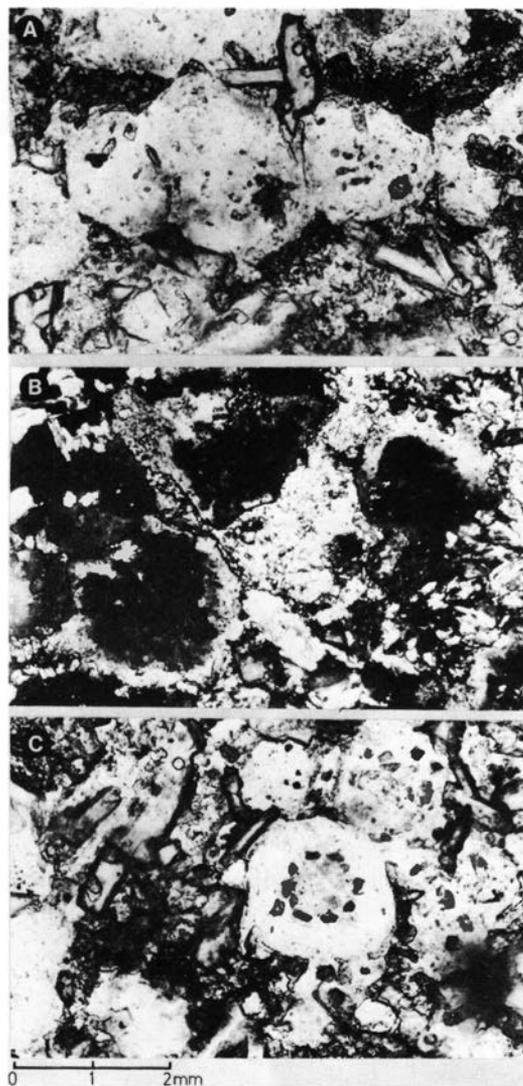
magma (Martin 1972). These dykes are unlikely to have cooled very slowly from magmatic temperatures, and therefore it is probable that the peralkaline composition of the dyke rocks and the hydrothermal alteration were important factors controlling the degree of order attained. It is interesting to note that Martin (1972) has proposed that in perpotassic rocks with Or/Ab>0.95 high sanidine inverts to maximum microcline via

Table 3. Electron microprobe analyses of mica and associated saponite (?)

Phlogopite			Al-deficient brown mica	Altered Al-deficient mica (saponite?)	
				Brown fibrous	Dark brown, amorphous-like
	n = 18	Range	n = 3	n = 3	n = 5
SiO_2	44.66	42.70–47.52	48.10	40.87	40.28
TiO_2	4.34	3.87– 5.24	4.14	8.22	9.14
Al_2O_3	4.54	3.61– 5.67	0.95	0.43	0.48
FeO^t	5.69	4.41– 7.63	10.80	18.88	18.30
MnO	0.04	0.00– 0.17	0.03	0.27	0.31
MgO	23.68	21.94–24.94	15.19	10.84	10.37
CaO	0.03	0.00– 0.11	0.09	2.84	3.08
BaO	0.47	0.43– 0.50	0.39	–	–
Na_2O	0.14	0.06– 0.24	0.26	2.02	1.51
K_2O	10.53	10.18–11.02	10.26	1.04	0.66
Total	94.12		90.21	85.41	84.13
Formula based on 22 oxygens					
Si	6.515		7.208	6.776	6.750
Ti	0.477		0.457	1.024	1.153
Al	0.781		0.168	0.066	0.094
Fe	0.695		1.354	2.619	2.566
Mn	0.005		0.003	0.038	0.044
Mg	5.149		3.400	2.684	2.483
Ca	0.004		0.014	0.505	0.540
Ba	0.027		0.033	–	–
Na	0.040		0.073	0.650	0.492
K	1.960		1.964	0.220	0.141
Mg/Fe	7.6		2.5	1.1	1.0

Table 4. Interplanar distance d_{060} as a function of Si, Al and Mg.

	Si	Al^{iv}	Al^{vi}	Mg	d_{060}
This work	6.513	0.765	0.000	5.143	1.5468
Experimental	6.000	2.000	0.000	6.000	1.5349
Experimental	5.500	2.500	1.500	4.000	1.5258
Experimental	8.000	0.000	0.000	5.000	1.518

Table 4. Experimental work (Robert 1976).
   The d_{060} value of this work is the mean value of six determinations.

an ordered orthoclase at 5 Kbar at about 550°C. This relatively high inversion temperature is in contrast with the lower values of 200–400°C suggested by other authors.

Phlogopite occurs as subhedral crystals about 0.2–0.4 mm long. It has a weak pleochroism β = yellowish brown to α = light yellow. The phlogopite invariably wraps around labuntsovite and calcite crystals and often around K-feldspar microphenocrysts, and thus curved phlogopite grains are common (Fig. 6). The phlogopite may contain inclusions of small, euhedral apatite grains. The chemical composition of the phlogopite is shown in Table 3. Characteristically it contains high SiO_2 and low Al_2O_3, and is rather different from phlogopites reported from other high-K, K-feldspar- and/or leucite-bearing rocks (Fig. 3a). The sum of Si and Al does not fill the tetrahedral positions. Farmer & Boettcher (1981) have suggested that the tetrahedral site preference in phlogopite is $Si>Al>Ti>Fe^{3+}$ According to Arima & Edgar (1981) the Ti content of phlogopites generally increases with de-

Fig. 4. Aggregate of fibrous eckermannite (E) overgrowing microcline (M) and phlogopite (P).
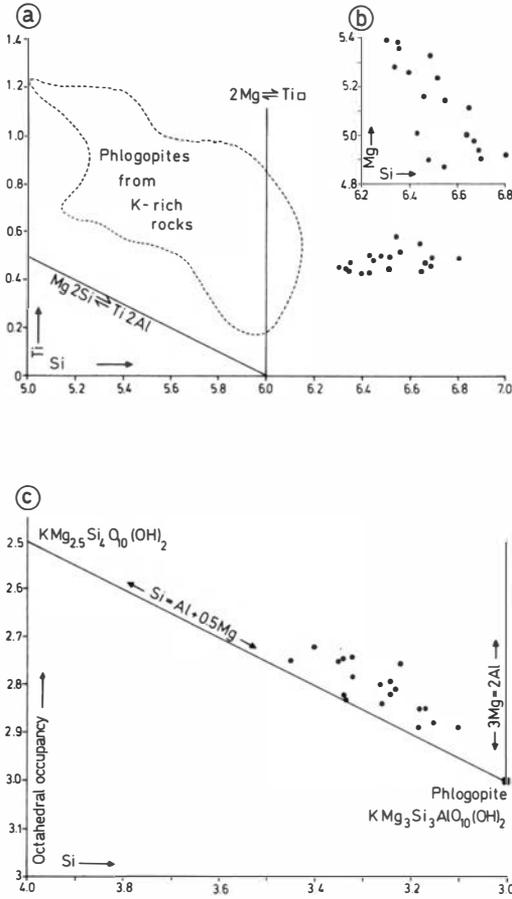

Fig. 3a. Ti – (Si + Al^{vi}) relationships of phlogopites from the Sunnfjord dykes, compared with phlogopites from other high-K rocks from central New South Wales, Leucite Hills, Murcia, West Kimberley, Lake Nyungu, Guessberg, Holsteinborg, Smokey Butte, Alban Hills, Buell Park, Narssausq and Tugtutoq, Shonkin Sag, Laacher See and Vico (after Arima & Edgar 1981). – *b.* Si-Mg relationships. – *c.* Plot of Si versus octahedral occupancy. The data groups parallel to, but slightly above the substitution line Al + 0.5 Mg = Si (after Seifert & Schreyer 1971). From this diagram the phlogopite from the Sunnfjord dykes may be considered as mixed crystals of the three components phlogopite, $KMg_{2.5}(Si_4O_{10})$ (OH)$_2$ and muscovite.

and 1000 bar produced a mica with the composition $K_2(Mg_{5+u})^{vi}(Si_{8-u}Mg_u)^{vi}O_{20}(OH)_4$ where $0.55 < u < 0.7$ (Robert 1976).

Robert (1976) showed that the interplanar distance d_{060} increased progressively with increasing Si-dMg and decreasing Al. The measured d_{060} value for the phlogopite reported here is considerably higher than the highest reported by Robert (1976) (Table 4), and this may suggest that the Al-deficiency has a pronounced effect on the interlayer distance.

Al-deficient, brown mica occurs as small inclusions in K-feldspar, labuntsovite and phlogopite. Its chemical composition is shown in Table 3. Characteristically it is nearly free of Al, and has much higher Fe and lower Mg than the associated phlogopite. In many places it is partially or completely replaced by a fibrous dark brown to nearly black, cryptocrystalline material. This material is significantly lower in SiO_2, MgO, K_2O, and higher in TiO_2, FeO, Na_2O and CaO than the associated brown mica (Table 3), and resembles saponite (a trioctahedral member of the smectite group), whose ideal formula is $(Ca, Na)_{0.66}$ $(Mg)_{6.00}(Si,Al)_{8.00}O_{20}(OH)_4$ (Andrews 1980).

Eckermannite occurs as fibrous aggregates up to 0.2 mm long, overgrowing the K-feldspar, phlogopite and labuntsovite (Fig. 4). It is pleochroic from dark blue/bluish green to pale blue/anomalous light brown. The extinction angle is difficult to measure precisely, but appears to be around 20° (α:z). The average of five electron microprobe analyses is shown in Table 5. In the structural formula of this amphibole the sum of all cations (excluding Ca + Na + K) has been recal-
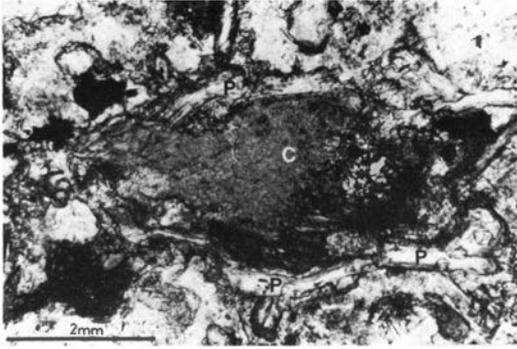
creasing Si + Al^{vi}, whereas in the present case the opposite is observed. There is no relationship between total Fe and Si. However, an antipathetic relationship exists between Si and Mg (Fig. 3b). This may suggest the substitution Mg^{vi}2Al $\rightleftharpoons$ Si$^{vi}\square^{vi}$, as suggested by Seifert & Schreyer (1971) for Si-rich, Al-poor phlogopites (Fig. 3c). It is interesting to note that experimental work in the $K_2O\text{-}MgO\text{-}Al_2O_3\text{-}SiO\text{-}H_2O$ system at 800°

Fig. 5. Aggregate of scaly celadonite (C) overgrowing phlogo-pite (P).

culated to 13, and Fe^{3+} was calculated to give 23(0). According to the classification scheme of Leake (1978), the amphibole is eckermannite. Goncharov et al. (1974) demonstrated experimentally that a magnesian amphibole of the eckermannite-arfvedsonite series could be produced by the hydrothermal treatment of a natural phlo-

gopite with a silica-saturated aqueous solution of Na_2O_3 at 330°C and 720 atm. The appearance of a sodium-rich mineral at a relatively late stage in the evolution of the dyke is problematic. It is suggested that the sodium may have been introduced from an external source during hydrothermal alteration of the dykes.

Celadonite occurs as aggregates of minute green scales a few microns in diameter overgrowing K-feldspar, phlogopite, labuntsovite, calcite and eckermannite (Fig. 5). In places it can be seen to have developed along eckermannite grain boundaries. Its average chemical composition is shown in Table 5. Each oxide is well within the range of that reported for celadonite (e.g. Andrews 1980), though K is very high. Table 5 shows that the structural formula based on 22 oxygens fits well with that of celadonite – $K_2Fe^{3+}Mg_2(Si_8O_{20})$ $(OH)_4$ (Pe-Piper, in press) though $Mg + Fe$ is high compared to the ideal formula. The composition of the material transitional between eckermannite and celadonite is

Table 5. Electron microprobe analyses of eckermannite and associated celadonite

Eckermannite			Celadonite	
	n = 5	Range	n = 5	Range
SiO_2	53.61	53.00–54.42	53.65	53.02–54.36
TiO_2	1.68	0.96– 2.23	0.83	0.51– 1.22
Al_2O_3	0.07	0.01– 0.11	0.42	0.20– 0.70
FeO^t	15.14	14.50–15.88	12.61	11.36–13.44
MnO	0.07	0.04–0.11	0.04	0.00– 0.07
MgO	13.10	12.95–13.31	14.15	12.85–15.61
CaO	0.07	0.03– 0.10	0.04	0.02– 0.08
Na_2O	7.35	6.41– 7.97	0.10	0.01– 0.20
K_2O	5.12	4.87– 5.44	10.65	10.23–11.25
Total	96.21		92.49	

Formula based on:

	23 oxygens		22 oxygens	
Si	8.078		7.985	
Ti	0.190		0.093	
Al	0.012		0.073	
Fe	1.908		1.567	
Mn	0.009		0.005	
Mg	2.943		3.137	
Ca	0.011		0.006	
Na	2.145		0.023	
K	0.985		2.022	

Calculated:

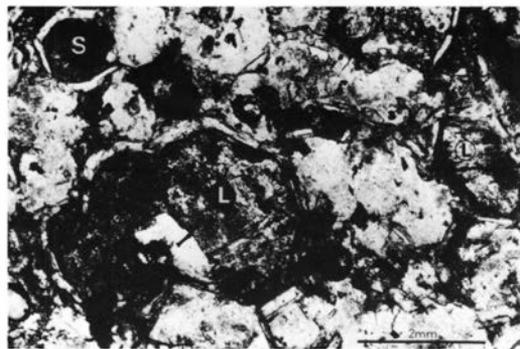| | | |
|---|---|
| Fe^{2+} | 1.38 |
| Fe^{3+} | 0.50 |
| $Mg/(Mg+Fe^{2+})$ | 0.68 |
| $Fe^{3+}/(Fe^{3+}Al^{vi})$ | 0.98 |

Fig. 6. Labuntsovite crystals (L) enveloped by phlogopite. The dark six-sided crystal in the upper left corner is a saponitized brown mica (S).
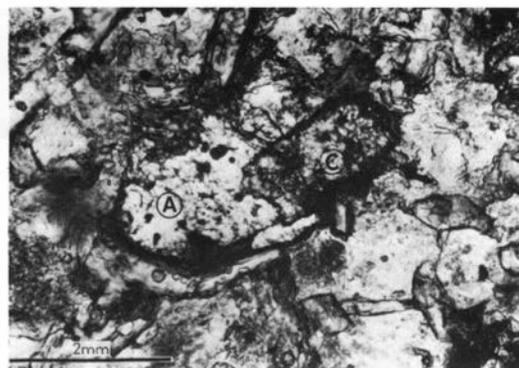

Fig. 7. Calcite (C) and apatite (A) enveloped by phlogopite.

well demonstrated by the intermediate values of the K_2O and Na_2O contents. SiO_2, however, is lower than that of both eckermannite and celadonite. A transition from phlogopite into celadonite is occasionally recorded, but no analyses of this are available. It thus seems that both eckermannite and phlogopite can be the host to the late-stage, low-temperature alteration product celadonite. Andrews (1980) suggests that the formation of celadonite in basalts probably occurred below 100°C, and oxygen isotopes suggest formation temperatures as low as 26°C (Seyfried et al. 1978, Kastner & Gieskes 1976).

Labuntsovite forms euhedral, four to six-sided crystals up to 0.5 mm long which are most frequently enveloped by phlogopite crystals (Fig. 6). In an apparently unaltered state it is colourless with high birefringence. However, in most cases the crystals are more or less densely dusted by a dark brown material, and in some cases this phase is dominant. Table 6 shows the average chemical composition of apparently unaltered labuntsovite. The chemistry of the dark brown, altered equivalent is similar, but is more variable with respect to all oxides.

Labuntsovite was originally described in association with albite and natrolite in drusy cavities of alkaline pegmatites on the Kola peninsula (Semenov & Burova 1955). The most recently reported structural formula for this orthorhombic mineral is $(K, Ba, Na, Ca)_8 (Ti, Nb)_9 (O, OH)_{10} (Si_4O_{12})nH_2O$ (Golovastikov 1974). It is a late, low-temperature, hydrothermal mineral, and has been reported to grow authigenically below 200°C (Milton et al. 1960). Between 200–400°C, H_2O is gradually released (Vlasov et al. 1966).

Apatite occurs either as tiny euhedral grains in K-feldspar and phlogopite or as larger, completely

Table 6. Electron microprobe analyses of various minerals in sample IP71

	Dalyite (n = 10)	Labuntsovite (n = 10)	Apatite (n = 4)	Carbonate (n = 2)
SiO_2	63.07	41.22	0.24	–
Al_2O_3	0.06	0.10	0.02	–
TiO_2	1.23	26.48	–	–
ZrO_2	19.37	0.22	–	–
CaO	0.02	3.12	49.21	58.56
MgO	0.10	0.73	0.04	0.26
MnO	0.02	0.24	0.05	1.43
FeO^t	0.28	2.41	0.19	0.23
K_2O	15.60	4.27	–	–
Na_2O	0.04	1.21	0.39	–
BaO	0.11	10.61	0.86	0.10
P_2O_5	0.04	n.d.	34.43	–
Total	99.94	90.61	85.43	60.58

Table 7. Major and trace element geochemistry of the dykes from Sunnfjord compared with other K-rich rocks

	Sunnfjord dykes		Mamilites		Wyomingite	Orendite	Leucitite	Trachyte
	IP 70	IP 71	1	2	3	4	5	6
SiO_2	56.97	56.14	52.79	54.48	55.43	55.14	50.9	58.00
Al_2O_3	11.17	10.68	11.37	9.87	9.73	10.35	9.86	11.06
TiO_2	2.95	3.19	5.00	5.57	2.64	2.58	3.42	1.02
Fe_2O_3	2.69	3.45	5.41	4.89	2.12	3.27	2.46	2.64
FeO	0.85	0.71	1.83	1.70	1.48	0.62	3.78	2.22
MgO	5.07	4.99	4.84	5.35	6.11	6.41	7.95	6.73
CaO	2.50	2.15	2.21	1.89	2.69	3.45	4.63	6.79
Na_2O	1.11	1.42	0.45	0.88	0.94	1.21	1.65	2.08
K_2O	12.05	11.61	11.40	11.06	12.66	11.77	11.61	6.72
MnO	0.20	0.21	0.07	0.09	0.08	0.06	0.09	0.14
P_2O_5	0.94	0.87	1.03	0.40	1.52	1.40	1.48	0.52
L.o.i.	2.87	3.25	2.53	2.25	3.14	2.24	1.77	1.08
Total	99.37	98.67	98.93	98.43	98.54	98.50	99.60	99.00
V	174	192					106	
Cr	108	96			137	274	306	342
Co	19	22						
Ni	92	90					233	314
Zn	70	71					72	
Rb	154	150				310	315	200
Sr	1576	1211		1353	2283	2198	1808	800
Y	14	16					18	
Zr	894	1020		518	2073	1999	1004	300
Nb	63	68					90	
La	84	96				116	210	109
Ce	136	151				244	337	202
Nd	78	97				99		95
K/Rb	650	642				315	306	279
Rb/Sr	0.098	0.124				0.141	0.174	0.250
K_2O/Na_2O	10.9	8.2	25.3	12.6	13.5	9.7	7.0	3.2
SiO_2/K_2O	4.7	4.8	4.6	4.9	4.4	4.7	4.4	8.6
K_2O/Al_2O_3	1.08	1.09	1.00	1.12	1.30	1.14	1.18	0.61

Table 7. *Mamilites (1 &2):* 1. Sample 19245 from Mamilu Hill, Fitzroy Basin, West Australia (Prider 1960). 2. Sample 246 A from Hills Cone, West Kimberley Area, West Australia (Wade & Prider 1940).
   Wyomingite (3): Sample LH 7 from Leucite Hills (Carmichael 1967).

Orendite (4): Sample LH 12 from Leucite Hills (Carmichael 1967).
Leucitite (5): Mean of 11 analyses of leucitites from Gaussberg, Antarctica (Sheraton & Cundari 1980).
Sanidine trachyte (6): Sample 666 from Buell Park, Arizona (Kay & Gast 1973).

recrystallized grains associated with labuntsovite and carbonate (Fig. 7). Table 6 gives the chemical composition of the latter apatites. Characteristically the totals are low, but energy-dispersive spectra show pronounced Sr peaks as well as detectable REE peaks. XRD studies show the characteristic lines for carbonate-apatite.

Dalyite is a rare K-Zr silicate ($K_2ZrSi_6O_{15}$) that previously has only been reported from Ascension Island (Van Tassel 1952) and the Azores (Cann 1967) where it occurs in peralkaline granite and peralkaline quartz syenite respectively.

The Sunnfjord occurrence will be dealt with separately (Robins et al., 1983. It is colourless with moderately strong birefringence and an average chemical composition as shown in Table 6. The dalyite is commonly surrounded by phlogopite and often contains subhedral to euhedral inclusions of K-feldspar.

Dalyite has been synthesized hydrothermally at 340°C and 600 bars (Caruba et al. 1970). At higher temperatures the formation of dalyite may be accompanied by the growth of wadeite ($K_2ZrSi_3O_8$, Prider 1939) dependent on the rate at which the temperature is increased (Thibault
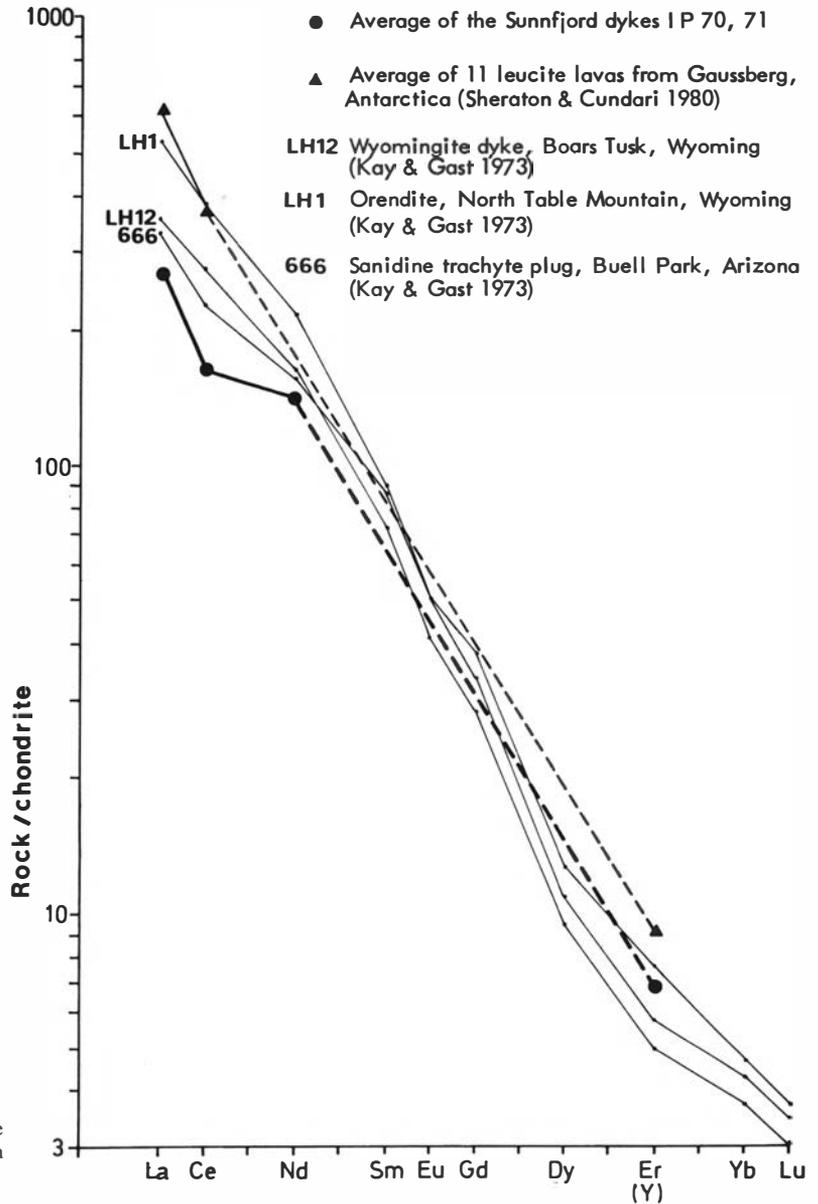
Fig. 8. REE pattern for the Sunnfjord dykes, compared with other high-K rocks.

et al. 1972).

Calcite occurs as subhedral crystals. When found in association with labuntsovite and apatite, which is commonly the case, it is always overgrown by these two minerals, and if not, it is enveloped by the Al-deficient brown mica or phlogopite (Fig. 7). Microprobe analyses show that the carbonate is nearly a pure calcite with a small rhodochrosite component ($MnCO_3$) (Table 6).

Baryte. – One grain of baryte ($BaSO_4$) has been detected in sample IP 71.

Geochemistry

The major- and trace-element compositions of the two dykes from Sunnfjord are shown in Table 7. They have high concentrations of TiO_2, K_2O, P_2O_5, V, Cr, Ni, Rb, Sr, Zr, Nb and LREE, whereas Al_2O_3, Na_2O and Y are low. The aver-
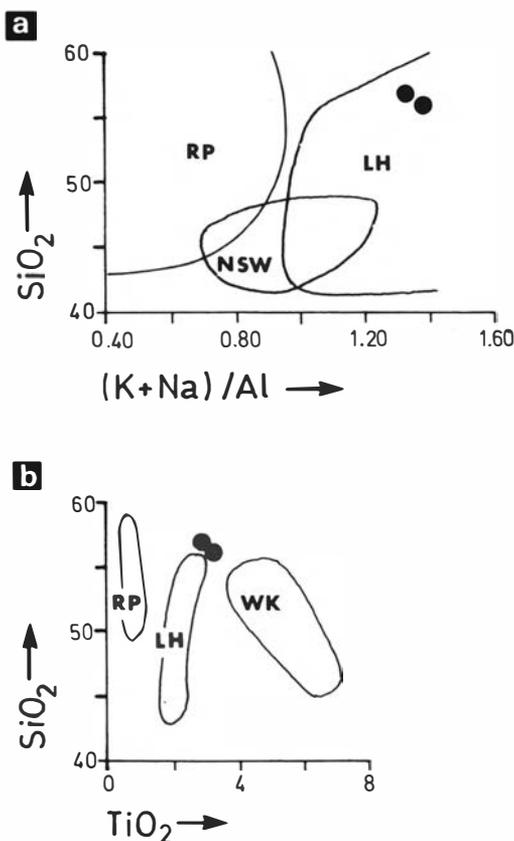
Fig. 9. (a) $SiO_2 - (K + Na)/Al$, and (b) SiO_2-TiO_2 plots of the two Sunnfjord dykes, compared with high-K rocks from Roman Province (RP), Leucite Hills (LH), New-South Wales (NSW) and West Kimberley (WK) (after Barton 1979).

age 'REE' pattern (La, Ce, Nd and Y) shows a steep slope (Fig. 8), and compares rather well with REE patterns of wyomingite, orendite, sanidine trachyte (Kay & Gast 1973), and with that of leucitites from Antarctica (Sheraton & Cundari 1980). Some of the most striking geochemical features are the unusually high K_2O/Na_2O, K_2O/Al_2O_3 and low SiO_2/K_2O ratios. These ratios, and indeed all the other major oxides, are remarkably similar to those of the rare rock types mamilite, wyomingite, orendite and to some extent leucitite. The mineralogical composition of the Sunnfjord dykes is, however, quite different from these rock types whose principal components are leucite, magnophorite, ± diopside, ± phlogopite.

Fig. 9 shows the $SiO_2 - (K + Na)/Al$ and $SiO_2 - TiO_2$ relationships compared with other well-known potassium-rich alkaline rocks. On this basis the Sunnfjord dykes are best compared with

the Leucite Hills-type peralkaline lavas.

Although both dykes have clearly undergone low-temperature alteration, sample IP 71 has been more strongly altered than sample IP 70. This is reflected in its higher Fe_2O_3/FeO ratio (4.86 versus 3.16 for IP 70), H_2O content (Table 7) and also the more extensive alteration of mica.

Petrogenetic considerations

The highly-ordered microcline and the occurrence of such low-temperature phases as celadonite, labuntsovite and a smectite suggest that the Sunnfjord dykes have been subjected to a thorough hydrothermal alteration. The presence of dalyite and the Al-poor phlogopite, however, show that their peralkaline, potassium-rich composition is a primary feature. Textural relationships indicate that K-feldspar was one of the first magmatic phases to crystallize – it forms microphenocrysts preserving a crystal form suggestive of sanidine. The feldspar appears to have been postdated by phlogopite. Inclusions of apatite, labuntsovite and dalyite in feldspar and phlogopite may be interpreted either as early phases in the magmatic paragenesis or, in the case of labuntsovite and dalyite, as alteration products of high-temperature phases (including murmanite and wadeite?). Eckermannite, celadonite, saponite and probably also the Al-deficient brown mica are regarded as alteration products which overgrew the primary phases during hydrothermal activity. Eckermannite and saponite are the only minerals present in the dykes which contain significant amounts of Na_2O, suggesting the introduction of sodium during the course of the alteration.

In view of the unknown role of the alteration process in the detailed major- and trace-element chemistry of the Sunnfjord dykes and the fact that samples from only two dykes were available to the authors it would be premature to attempt to reach any definite conclusion regarding the petrogenesis of the syenites described in this account. Despite these reservations, some comments on the unusually high K_2O, Rb, Sr, Nb, and LREE contents, the steep chondrite-normalised REE pattern and the high K_2O/Na_2O and K_2O/Al_2O_3 ratios are considered pertinent.

Based on REE distribution, Kay & Gast (1973) proposed that K-rich magmas could be produced by small degrees of partial melting of hydrous garnet peridotite. Regarding the REE pattern

alone, such an interpretation may well be applied to the Sunnfjord dykes. However, in order to explain the high K_2O/Na_2O and K_2O/Al_2O_3 ratios, it would seem necessary that the mantle source from which they were derived contained phlogopite, and furthermore that phlogopite comprised a high proportion of the phases entering the melt.

The extremely high K_2O/Na_2O ratios of the K-feldspar (averaging 340), suggests that the melt must have been nearly free of sodium. This implies either that sodium never was present in the primary magma, or more probably, that it had been removed by some fractionation process prior to K-feldspar crystallization.

High-pressure eclogite fractionation is a process that has been suggested by many authors for the generation of high-K peralkaline rocks (Holmes 1932, Wade & Prider 1940, O'Hara & Yoder 1967, Appleton 1972, Upton & Thomas 1973). This would be compatible with the steep REE pattern since garnet would prefentially remove HREE from the melt (Nicholls & Harris 1980) and most probably also Y which behaves rather similarly to the HREE. Crystallization of jadeitic pyroxene would also efficiently remove sodium from the liquid, thus increasing the K_2O/Na_2O ratio.

Another unusual feature of the Sunnfjord dykes is the very high K/Rb ratio of around 650 (Table 7). This is about 2 to 3 times higher than in chemically similar rocks (Table 7). Sheraton & Cundary (1980) have shown, however, that the K/Rb ratios of leucitites and related K-rich, leucite-bearing rocks increase with fractionation, and suggest leucite fractionation as the causal phenomenon. There is no evidence that leucite ever crystallized from the dyke magmas, and unless fractionation of K-feldspar has the same effect, for which there is no experimental support (Long 1978), other explanations have to be sought.

Regional significance

Extensive phases of magmatic activity associated with rifting in NW Europe are well documented by the Carboniferous lavas of the Midland Valley, Scotland (Francis 1965) and the Permian alkaline volcanic/plutonic rocks of the Oslo Graben (Ramberg 1972, Sundvoll 1978, Neumann 1980). These were coeval with the initiation of rifting in the North Sea, creating the 'West Nor-

way Trough' (Whiteman et al. 1975), which is regarded as the forerunner of the Viking and Central Graben with their widespread Middle Jurassic basaltic volcanism (Woodhall & Know 1979). Further to the southeast, in the Egersund sub-Basin, potassium-rich trachyte dykes of Lower Jurassic (Pliensbachian) age were emplaced (Furnes et al. 1982).

The peralkaline, K-rich syenite dykes from Sunnfjord are possibly related to an early magmatic phase associated with rifting in the North Sea and may be correlated with the oldest (Lower-Middle Permian) alkaline basaltic dykes in Sunnhordland, west Norway (Færseth et al. 1976). However, all the Sunnhordland dykes have a N-S trend, parallel to the main trend of the North Sea rifts, while those from Sunnfjord strike E–W. This is an unusual trend, and it is interesting to note that the upper Middle Permian (245 ± 12 Ma) dyke swarms in the Orkneys (Flett Brown 1975) are highly alkaline and potassic and have a distinct E–W to ENE–WSE trend (Mykura 1976).

Summary

The peralkaline, ultrapotassic syenite dykes from Sunnfjord, West Norway, yield concordant Middle Permian K-Ar ages. They represent the first documented occurrence of high-K magmatic rocks in Norway. Mineralogically they consist of nearly pure K-feldspar (microcline probably inverted from sanidine) ($Or_{99.38}Ab_{0.41}An_{0.21}$), Si-rich, Al-poor phlogopite (Mg/Fe ratio 7.7), Al-deficient mica (Mg/Fe ratio of 2.5) and its alteration product saponite, eckermannite ($Mg/Mg + Fe^{2+}$ 0.68; $Fe^{3+}/Fe^{3+}+Al^{vi}$ 0.98), labuntsovite, calcite, carbonate-apatite, dalyite, celadonite and traces of baryte. Geochemically they are characterized by very high K_2O (average 11.83 wt%), and other 'incompatible' elements such as Rb, Sr, Zr, Nb and LREE, and also high contents of Ni and Cr, whereas Y is very low. The K_2O/Na_2O, K_2O/Al_2O_3, SiO_2/K_2O and K/Rb ratios are 9.55, 1.09 and 4.75, respectively. It is tentatively proposed that these features may indicate partial melting of a phlogopite-bearing mantle, and that the magma generated subsequently underwent high-pressure eclogite fractionation with depletion in Na and Al.

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