Strontium isotope study of two supposed satellite massifs of the Egersund Anorthosite Complex: the Sjelset Igneous Complex and the Undheim Leuconorite

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The Sjelset Igneous Complex is an undeformed inhomogeneous granitic body with two main rock types: biotite granite and Fe-rich pyroxene ± fayalite charnockite. The nearby Undheim Leuconorite shows only minor deformation and recrystallization and preserves a cumulate texture. Both the Sjelset Igneous Complex and the Undheim Leuconorite occur in the westernmost part of the autochthonous Proterozoic basement and probably continue below the Caledonian Nappe system. The two bodies have been dated by the Rb–Sr whole rock and mineral isochron method. Variable partial resetting of the isotopic systems of rocks and minerals took place during slow Proterozoic cooling and/or Caledonian overthrusting. Field, mineralogical, chemical and isotopic data show that the Sjelset granite (985 Ma) and Sjelset charnockite (900–930 Ma) represent two separate intrusions. Similarities with the upper (Quartz) Monozonitic Phase of the Bjerkreim–Sokndal Lopolith suggest that the Sjelset charnockites result from anorthositic magmatism. The Sjelset biotite granite is probably of crustal origin. Correlation of the Undheim Leuconorite (1028 Ma) with the lower anorthositic-noritic units of the Bjerkreim–Sokndal Lopolith and with the Hidra Leuconorite is uncertain. A NNW continuation of the hypersthene-in isograd in the northern part of the Rogaland isograd pattern is probably related to the NNW continuation of anorthostic magmatism.

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The Proterozoic basement of Rogaland, SW Norway, can be divided into two main units (Fig. 1):

1. The Egersund Anorthosite Complex comprising several massif-type anorthosites and the folded Bjerkreim–Sokndal Lopolith (e.g. Duchesne & Michot 1987; Duchesne et al. 1985).
2. A high-grade polymetamorphic envelope, in which peak metamorphism under granulite facies conditions reached high to very high temperatures, up to about 1000°C, at a relatively low pressure of about 4 kb (Jansen et al. 1985). However, this 4 kb pressure at peak metamorphic conditions is contested by Wilmart & Duchesne (1987). Several isograds (e.g. hypersthene-in, osumilite-in and pigeonite-in) roughly follow the outlines of the Egersund Anorthosite Complex in which temperatures in excess of 1000°C must have prevailed at the time of emplacement. A genetic relationship between this phase of very high-grade metamorphism and the emplacement of the very high temperature Egersund Anorthositic Complex is generally accepted (e.g. Tobi et al. 1985; Jansen et al. 1985; Maijer & Padget 1987). The explanation of the northern extension of the hypersthene-in isograd, however, is controversial. It may be related either to a NNW continuation of anorthositic magmatism, which is obscured by the overthrusted Caledonian nappe system, or to an older phase of metamorphism (see discussion in Maijer & Padget, 1987, pp. 71–72).

Furthermore, several smaller igneous bodies of various ages have been emplaced in the high-grade gneisses of the polymetamorphic envelope (Fig. 1). These include the Sjelset Igneous Complex and the Undheim Leuconorite (previouslv designated as Pyroxene Anorthosite, Maijer et al. 1987), the Botnavatn Igneous Complex (Rietmeijer 1979), the Gloppurdi Igneous Complex (Rietmeijer 1979), the zoned Kleivan Granite (Petersen & Pedersen 1978; Petersen 1980), the Lyngdal Granite and the Farsund Charnockite (Falkum et al. 1972, 1979), the Homme Granite (Falkum 1976; Falkum & Pedersen 1979), the Holum Granite (Wilson et al. 1977) and the Hidra Leuconorite (Demaiffe 1977; Demaiffe & Hertogen 1981). Several of these intrusions are believed to be associated with the anorthositic magmatism (Duchesne et al. 1985).

The Sjelset Igneous Complex

The Sjelset Igneous Complex (Fig. 2) is an undeformed, inhomogeneous body of granitic rocks, previously

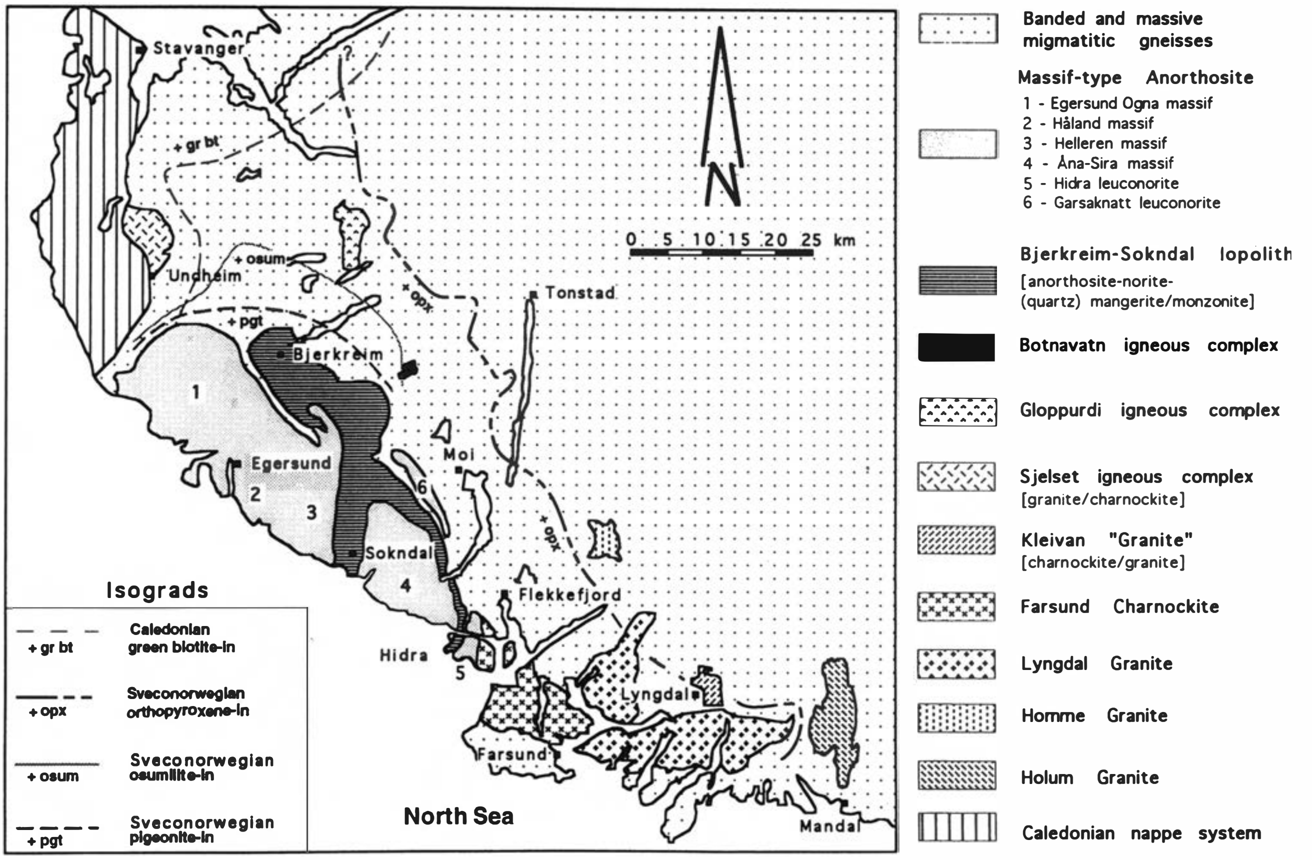


Fig. 1. Geological sketch map of the area between Stavanger and Mandal (southwestern Norway).

mapped as 'Adamellite de Sjelset' (Michot 1960), 'Adamellite charnockitique', or 'Adamellite diapirique de Sjelset' (Michot & Pasteels 1972), or 'porphyritic granite' (Jorde 1980; Birkeland 1981).

The exposed area of the Sjelset Igneous Complex measures 6 × 9 km, forming the westernmost part of the autochthonous South Norwegian Proterozoic basement. Aeromagnetic maps suggest that the complex has a westward continuation underneath a cover of poorly exposed Caledonian nappes. The complex is situated about 20 km SSE of Stavanger and about 10 km NNW of the NW limit of the Egersund–Ogna Anorthosite.

Two main types of granitic rock can be distinguished in the Sjelset Igneous Complex (Fig. 2):

I Leucocratic, coarse-grained, porphyritic biotite granite, which occurs mainly in the northern and eastern parts of the complex.

II Mesocratic, coarse-grained, Fe-rich pyroxene ± fayalite charnockite*, occurring mainly in the southern, western and central parts of the complex. The predominant pyroxene is inverted pigeonite, consisting of an orthopyroxene host with abundant augite exsolution lamellae parallel to (001) and (100) (Kloprogge et al. 1989).

On the basis of decreasing Mg # = MgO/(MgO + MnO + FeO_{tot}), the type II granitic rock, charnockite, can be divided in three subtypes (Table 1):

II_a inverted pigeonite + augite charnockite
II_b inverted pigeonite + augite + fayalite charnockite
II_c augite + fayalite charnockite

Furthermore, the charnockite contains brown or greenish brown hornblende, ilmenite, magnetite and relatively abundant, large apatite and zircon. The hornblende forms overgrowths on pyroxenes and fayalite and is clearly a late magmatic phase. The charnockite commonly shows an indistinct cumulate texture, with coarse-grained cumulus microperthite, unzoned plagioclase and quartz grains with finer grained intercumulus Fe–Mg minerals and opaques.

The difference in colour index and mineralogy between the Sjelset granite and the Sjelset charnockite is clearly reflected in their chemical compositions (Table 1). The charnockites have lower SiO_2, K_2O, Rb and Th contents and higher TiO_2, FeO, CaO, P_2O_5, Zr, Ba, Sr than the biotite granite. The normative anorthite content of the plagioclase and colour index of the charnockite are higher than in the biotite granite (Table 1). The biotite granite cannot be regarded as a fractionation product of the charnockites because of its higher Mg # (Table 1).

* Charnockites are defined as granitic rocks containing orthopyroxene instead of biotite (Tobi 1971). Here, the name charnockite is also used for granitic rocks containing inverted pigeonite and/or fayalite + augite as primary Fe–Mg minerals.

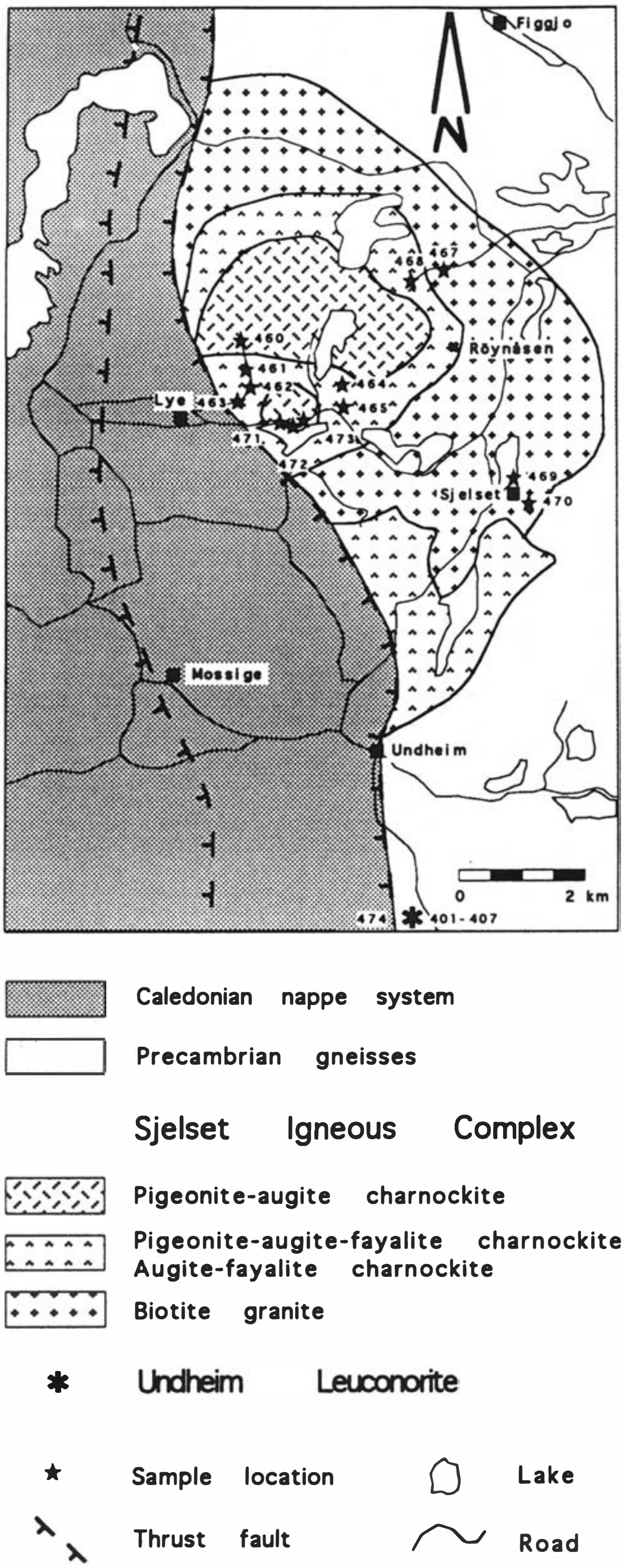


Fig. 2. Geological sketch map of the Sjelset Igneous Complex (Rogaland, south-western Norway).

Moreover, field evidence shows that the charnockite is younger than the granite, since:

(a) The eastern contact of the biotite granite with the country rocks south of Sjelset is cut off by charnockite (Fig. 2).

(b) The occurrence of xenoliths of porphyritic biotite granite enclosed in pyroxene charnockite near Röynåsen (UTM $^{3}146$-$^{65}160$).

The Sjelset charnockite is LILE depleted (i.e., lower contents of Rb, Th, higher K/Rb ratios, Table 1) relative to the more 'normal' upper crustal Sjelset biotite granite. There is no correlation between the cumulus quartz-feldspar and intercumulus Mg/Fe fractionation trends of the charnockite, stressing its cumulate character.

The rocks of the Sjelset Igneous Complex have suffered variable alteration and retrogradation during slow cooling at the close of the Sveconorwegian orogeny (Rietmeijer 1984) and Caledonian overthrusting and low-grade metamorphism (Sauter et al. 1983).

The Sjelset granite contains two generations of biotite: (i) primary brown sagenitic biotite that is commonly bleached along cracks, rims and around concentrations of sagenite, and (ii) secondary, fine-grained, green biotite. The green biotite replaces feldspars or chloritized primary brown biotite and opaques (see also Verschure et al. 1980).

Other alterations involve (Table 2): the production of sericite and saussurite from plagioclase (cores); fibrous amphibole, opaque and carbonate from pyroxene, especially orthopyroxene; cummingtonitic amphibole, serpentine and opaque from fayalite. Moreover, tiny cracks, especially in quartz and K-feldspar, are filled with carbonate and/or saussurite. Occasionally, veinlets around altered fayalite contain ilvaite. Chlorite and stilpnomelane can be found in some of the biotite granites replacing biotite and feldspars.

The Sjelset Igneous Complex has been emplaced in a banded sequence of charnockitic migmatites, garnet-bearing metapelitic gneisses, pyroxene amphibolites and two-pyroxene gneisses. All these rocks show the imprint of granulite facies metamorphism. Country rock xenoliths with a granulite facies mineralogy can be found at several places in all rock types of the complex, but they are most numerous in the biotite granite of the eastern part.

There is a large-scale concordance between the contacts of the Sjelset Igneous Complex and the banding and foliation of the country rocks in the north, east and south. However, discordant contacts are observed on a small scale.

The Undheim Leuconorite

The Undheim Leuconorite comprises a small (about 100 m × 100 m), isolated exposure on the summit of a low hill near Nyland, 3 km south of Undheim (Fig. 2) (UTM $^{3}136$-$^{65}067$). Spatial relationships with the Sjelset rocks and the country rocks are unknown owing to lack of exposures.

The Undheim Leuconorite exhibits an exceptionally well-developed, intergranular structure. Plagioclase

Table 1. Chemical characteristics of both types of Sjelset granitic rocks and the Undheim Leuconorite (oxides in wt%; trace elements in ppm).

	Sjelset granitic rock Type I			Sjelset granitic rock Type II					
	Biotite granite			Pyroxene ± fayalite Charnockite			Undheim Leuconorite		
	Range	Average	[n]	Range	Average	[n]	Range	Average	[n]
SiO_2	70–74	72.18	[5]	59–65	63.48	[23]	48–52	50	[2]
TiO_2	0.2–0.4	0.29	[5]	0.80–1.46	1.01	[23]	3.42	3.42	[2]
Al_2O_3	13.24–14.22	13.91	[5]	12.80–14.79	13.96	[23]	18.80–19.30	19.05	[2]
FeO [tot]	1.6–4.1	2.42	[5]	6.2–10.5	8.39	[23]	8.8–9.8	9.3	[2]
MnO	0.03–0.04	0.034	[5]	0.07–0.18	0.13	[23]	0.12–0.21	0.16	[2]
MgO	0.18–0.47	0.34	[5]	0.36–0.97	0.56	[23]	3.84–4.11	3.96	[2]
CaO	1.0–1.2	1.14	[5]	2.81–5.35	3.79	[23]	7.4–7.5	7.45	[2]
K_2O	5.5–6.0	5.75	[5]	3.14–5.39	4.31	[23]	1.05–1.19	1.12	[2]
Na_2O	2.93–3.44	3.18	[5]	2.32–3.13	2.78	[23]	3.68–4.23	3.95	[2]
P_2O_5	0.03–0.17	0.086	[5]	0.31–0.66	0.43	[23]	0.21–0.37	0.29	[2]
Rb	185–386	284	[5]	67–114	93	[23]	–	15	[1]
Sr	124–216	166	[5]	290–406	340	[23]	–	871	[1]
Ba	465–1027	688	[5]	1264–1752	1466	[23]	–	331	[1]
Zr	142–679	307	[5]	698–1910	1014	[23]	–	95	[1]
Th	23–69	46	[5]	1–6	3.3	[23]	–	6	[1]
An % plag [norm]	14–18	15.7	[5]	28–38	33.9	[23]	45–49	47	[2]
Colour index [volume]	2.5–6	3.9	[5]	10–17	12.5	[23]	20–23	21.5	[2]
K/Rb	128–251	177	[5]	328–472	387	[23]	–	598	[1]
Mg # [mol %]				IIa 11–16	12.6	[11]			
	17–33	23.4	[5]	II_b 8–10	9.0	[5]	41–44.4	42.6	[2]
$\left[= \frac{100\,MgO}{MgO + MnO + FeO_{tot}}\right]$				II_c 7–11	8.4	[7]			

forms cumulus crystals up to 2 cm in length showing minor deformation and recrystallization. An indistinct igneous lamination, mainly the result of parallelism of plagioclase crystals, dips about 20°W. Plagioclase occasionally forms star-shaped clusters in the plane of the lamination.

The Undheim Leuconorite contains up to 16 volume percent pyroxene (mainly orthopyroxene, commonly with clinopyroxene exsolution lamellae parallel to (100)), up to 6 volume percent opaques (mainly ilmenite) and minor fresh, brown biotite. The rock is cut by a number of up to 10 cm thick leucocharnockitic veins. The Undheim Leuconorite is situated in an area with distinct negative anomalies on gravity and magnetic maps, as are the other anorthosites.

Samples, experimental procedures and constants

Seven 1 kg samples of the leucocharnockitic veins cutting the Undheim Leuconorite (Rog 401–407) were collected, as well as thirteen 5 to 10 kg samples (Rog 460–473) from all types of Sjelset rocks, where possible from fresh, blasted exposures. One 2 kg sample of the Undheim Leuconorite (Rog 474) has been added for comparison and possible correlation. Textural and mineralogical details of the samples are given in Table 2.

Minerals have been separated from two Sjelset samples, biotite granite Rog 470 and fayalite–augite charnockite Rog 464 and the Undheim Leuconorite sample Rog 474. Separation was achieved using a Faul dry shaking table, heavy liquid separation by means of an overflow centrifuge (IJlst 1973a, 1973b), a modified Frantz magnetic separator (Verschure & IJlst 1969) and hand-picking.

Rb/Sr ratios and Rb and Sr contents of whole rocks were measured on pressed-powder pellets (major elements on beads) by X-ray fluorescence spectrometry, using a Philips PW 1450/AHP automatic spectrometer. Mass-absorption corrections for both sample and external standard are based upon the Compton scattering of the Mo-K_α primary beam (Verdurmen 1977). Rb/Sr ratios and Rb and Sr contents of all minerals were measured in duplicate by isotope dilution. The Sr isotope composition of whole rocks was measured directly on unspiked Sr. The whole rock Sr isotope analyses of the Undheim leucocharnockitic vein rocks were made on a computer-controlled Varian-Mat CH5 mass-spectrometer with digital output. All the other isotope analyses were performed on a Finnigan-Mat 261. The analytical accuracies for the whole rock samples measured with the Varian-Mat CH5 are considered to be within 1% for XRF Rb/Sr and 0.05% for $^{87}Sr/^{86}Sr$. The analytical accuracies for the whole rock and mineral samples measured with the Finnigan-Mat 261 are considered to be within 0.5% for XRF Rb/Sr, 0.5% for isotope dilution of Rb and Sr and 0.002% for $^{87}Sr/^{86}Sr$. The values of the ratios are quoted with an additional decimal to lessen the cumulative effects of rounding errors in subsequent calculations. The accuracies of the Rb/Sr ratios as measured by XRF are better than those of the individual Rb and

Table 2. Textural and mineralogical characteristics of the analysed samples of the Sjelset granite and charnockite and of the Undheim Leuconorite and the Undheim charnockitic veins.

Sample No.	UTM coordinates	Rock type	Texture	Colour index	Qtz	Kfsp	Pl	An%	Bt	Amph	Cpx	Pgt	Opx	Ol	Ap	Zrn	Opaque	Aln	Secondary minerals	Alteration
Sjelset																				
Rog 460	$^{3}113-^{65}160$	type IIa (charnockite)	c	14	xx	xxx	xxx	35	a	φ	φ	[x]			aa	aa	φ		Carbonate	+
Rog 461	$^{3}114-^{65}152$	type IIc (charnockite)	c; cum	12	xx	xxx	xx	36	a	φ	φ		a	φ	aa	aa	φ		Carbonate	±
Rog 462	$^{3}116-^{65}154$	type IIc (charnockite)	c; cum	12	xx	xxx	xxx	33	a	φ	φ			x	aa	aa	φ		Carbonate	±
Rog 463	$^{3}115-^{65}150$	type IIc (charnockite)	c; cum	11	xx	xxx	xxx	32		φ	φ			[φ]	aa	aa	φ			+
Rog 464	$^{3}131-^{65}152$	type IIc (charnockite)	c; cum	12	xx	xxx	xxx	32	a	φ	φ			φ	aa	aa	φ		Carbonate	–
Rog 465	$^{3}131-^{65}148$	type IIc (charnockite)	c; cum	11	xx	xxx	xxx	34		φ	φ			φ	aa	aa	φ		Ilvaite	±
Rog 467	$^{3}147-^{65}171$	type I (granite)	c	4	xxx	xxx	xxx	15	φ						a	a	a		gn Bt, Stp	±
Rog 468	$^{3}139-^{65}168$	type IIb (charnockite)	c; cum	12	xx	xxx	xxx	32		a	x	a		x	aa	aa	φ		Carbonate	+
Rog 469	$^{3}156-^{65}137$	type I (granite)	c	3	xxx	xxx	xxx	14	[φ]						a	a	a		Chl	–
Rog 470	$^{3}157-^{65}135$	type I (granite)	c	3	xx	xxx	xx	26	φ						a	a	a		gn Bt	–
Rog 471	$^{3}124-^{65}148$	type IIa (charnockite)	c; cum	11	xx	xxx	xxx	28		φ		φ			aa	aa	φ			±
Rog 472	$^{3}124-^{65}148$	type IIa (charnockite)	c; cum	17	xx	xxx	xxx	31	a	x		x			φ	aa	φ			–
Rog 473	$^{3}125-^{65}148$	type IIa (charnockite)	c	15	xx	xxx	xxx	35		x		[x]			φ	aa	φ		Carbonate	+
Undheim																				
Rog 474	$^{3}136-^{65}067$	leuconorite	c; cum	20			xxx	45	φ				x		a		x			
Rog 401	$^{3}136-^{65}067$	charnockitic vein	f	7	xx	xxx	xx		a				φ		a	a	φ	aa	Chl, Ep, Carb, gn Bt	±
Rog 402	$^{3}136-^{65}067$	charnockitic vein	f–m	3	xxx	xx	xx	25			a	a	φ		a	a	φ	a		–
Rog 403	$^{3}136-^{65}067$	charnockitic vein	f–m	7	xx	xxx	xx	25					φ		a	a	φ	aa		–
Rog 404	$^{3}136-^{65}067$	charnockitic vein	t; porph	3	xx	xxx	xx						[φ]		a	a	φ	a		±
Rog 405	$^{3}136-^{65}067$	charnockitic vein	f–m	5	xx	xx	xx		a		φ	φ	[φ]		a	a	φ	a	Ser, Chl, Ep	+
Rog 406	$^{3}136-^{65}067$	charnockitic vein	f	5	xx	xxx	xx	25			φ	φ	φ		a	a	φ	a		–
Rog 407	$^{3}136-^{65}067$	charnockitic vein	f–m	3	xxx	xxx	xx						[φ]		a	a	φ		Chl, Ep	±

f = fine-grained; m = medium-grained; c = coarse-grained
porph = porphyritic; cum = cumulate structure; [ ] = altered
+ = strong alteration; ± = moderate alteration; – = minor alteration
x = 5–15%; xx = 15–25%; xxx = >25%
φ = 1–5%; a = accessory; aa = relatively abundant accessory

Sr values. Best-fit lines through the Rb–Sr data-points were calculated by means of a least-squares regression analysis according to York (1966, 1967). The errors quoted for the isochron ages and intercepts are 95% confidence limits, inclusive a correction for the MSWD. The age calculations are based upon the IUGS decay constant of $\lambda^{87}Rb = 1.42 \times 10^{-11}\ a^{-1}$.

Results

The results of whole rock Rb and Sr isotope analysis of 13 Sjelset granite and charnockite samples, 1 Undheim Leuconorite sample and 7 samples of Undheim charnockitic veins are presented in Table 3. The data of Rb and Sr isotope analyses of various mineral concentrates are presented in Table 4. Calculated ages with their $Sr_{(i)}$ and MSWD values are listed in Table 5 and visualized in Figs. 3 and 4.

Discussion

In the past the Sjelset Igneous Complex was mapped as a single intrusive granitic body. However, field, mineralogical and chemical data show that the two types of Sjelset rocks, granite and charnockite represent two separate intrusions of different origin (Maijer et al. in prep.). Rb and Sr isotopes analyses and resulting age calculations (Table 5) are in agreement with their being two separate intrusions. In this respect the 1020 ± 66 Ma errorchron age (Visser 1987) of the combined Sjelset rock types makes no sense, although it agrees well with the 7-point isochron age (1028 ± 77 Ma) of the charnockitic veins of the Undheim Leuconorite. These ages are therefore not an indication for a genetic relationship between the Sjelset Igneous Complex and the Undheim Leuconorite.

The Sjelset biotite granite

The lack of evidence for high temperature granulite facies metamorphism in the biotite granite and its undeformed character prove that it postdates the Sveconorwegian peak metamorphism in SW Norway related to anorthositic magmatism, 1050–1000 Ma ago (Wielens et al. 1981; Priem & Verschure 1982; Demaiffe & Michot 1985; Maijer & Padget 1987).

However, Duchesne et al. (1993) regarded this age of Sveconorwegian peak metamorphism as predating magmatic activity. Their precise U–Pb ages of zircon and baddeleyite from the Egersund–Ogna and Åna–Sira Anorthosite Massifs are interpreted by them as emplacement ages. In strong contrast with earlier ideas of long-lasting activities they consider that emplacement of these anorthosites took place within a short time interval between 920 and 930 Ma. The baddeleyites and zircons were extracted from large orthopyroxenes with crystallization conditions estimated around 10–12 Kb and 1100–1200°C (Duchesne & Maquil 1987). Yet the peak of metamorphism in southwestern Norway at about 1000–1050 Ma is so clearly related to be the emplacement of the Egersund Anorthosite Complex (e.g. Tobi et al. 1985; Jansen et al. 1985; Maijer & Padget 1987) that an age controversy is created. We believe that Duchesne et al.'s (1993) zircon and baddeleyite ages of 920–930 Ma do

Table 3. Rb–Sr whole rock data of the Sjelset Igneous Complex, the Undheim Leuconorite and the Undheim charnockitic veins.

Sample No.	Rock type	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Sjelset					
Rog 460	charnockite [type IIa]	69	418	0.4767	0.712571
Rog 461	charnockite [type IIc]	94	325	0.8231	0.716815
Rog 462	charnockite [type IIc]	102	310	0.9571	0.718384
Rog 463	charnockite [type IIc]	98	296	0.9552	0.718692
Rog 464	charnockite [type IIc]	101	307	0.9573	0.718755
Rog 465	charnockite [type IIc]	95	335	0.8261	0.717088
Rog 467	granite [type I]	386	124	9.147	0.838602
Rog 468	charnockite [type IIb]	92	339	0.7903	0.717204
Rog 469	granite [type I]	264	159	4.828	0.777911
Rog 470	granite [type I]	298	142	6.156	0.797169
Rog 471	charnockite [type IIa]	101	313	0.9338	0.717919
Rog 472	charnockite [type IIa]	93	299	0.8964	0.717365
Rog 473	charnockite [type IIa]	94	332	0.8203	0.715893
Undheim					
Rog 474	leuconorite	15	871	0.0491	0.704500
Rog 401	charnockitic vein	145	250	1.680	0.72911
Rog 402	charnockitic vein	140.5	238.5	1.709	0.72966
Rog 403	charnockitic vein	99	267	1.073	0.72113
Rog 404	charnockitic vein	114.5	169	1.968	0.73500
Rog 405	charnockitic vein	63	394	0.4610	0.71182
Rog 406	charnockitic vein	91	264.5	0.9938	0.72057
Rog 407	charnockitic vein	61	450	0.3942	0.71089

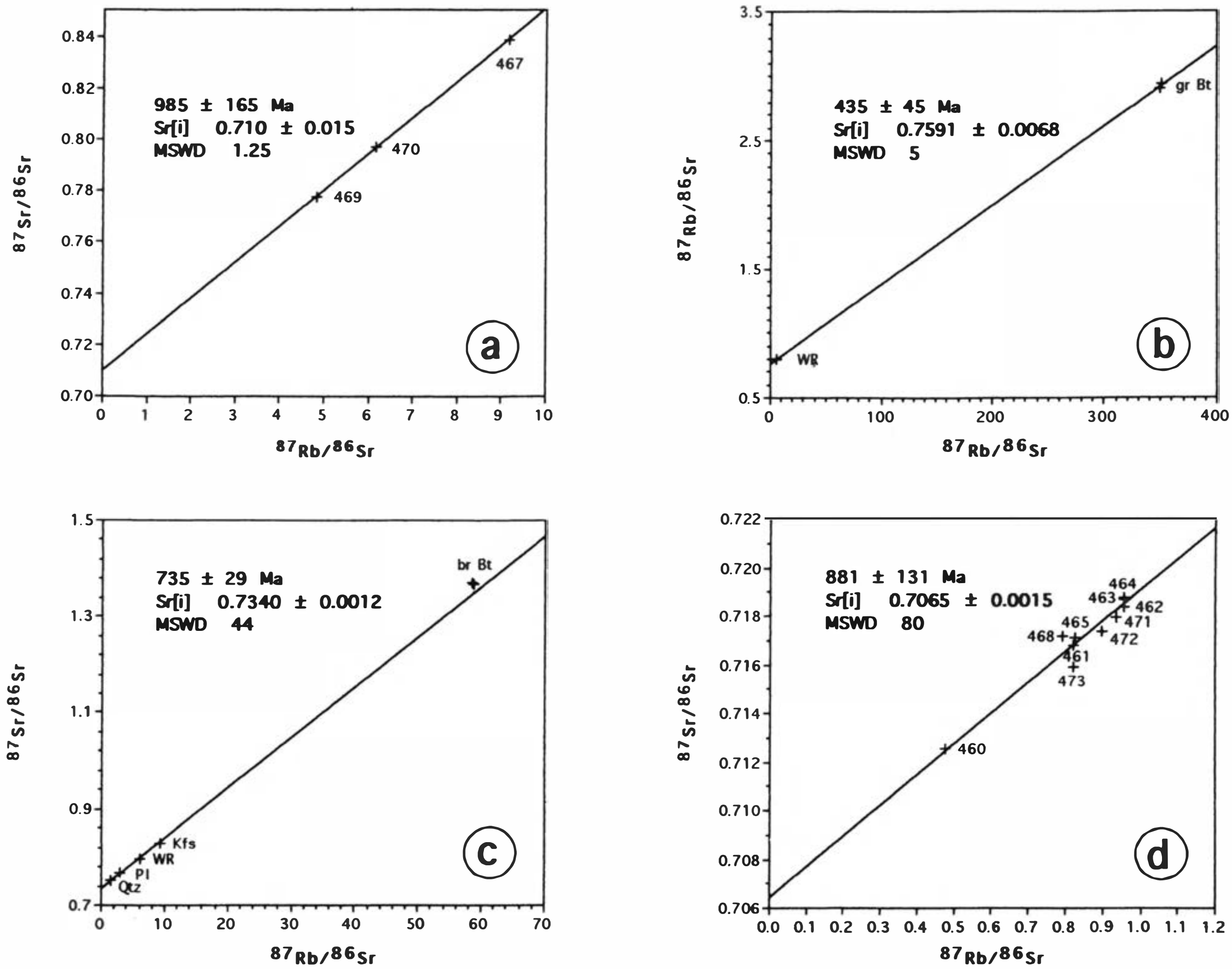
Table 4. Rb–Sr mineral data of the Sjelset Igneous Complex and the Undheim Leuconorite. All minerals were analysed in duplicate.

Sample No.	Rock type	Material	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Rog 464	Sjelset charnockite [type IIc]	whole-rock	101	307	0.9573	0.718755
		pyroxene	2.694	18.47	0.4221	0.711860
		pyroxene	2.706	18.27	0.4287	0.710754
		plagioclase	1.644	32.06	0.1484	0.708520
		plagioclase	1.652	32.09	0.1490	0.708497
		quartz	1.645	187.3	0.0254	0.706897
		quartz	1.633	187.5	0.0252	0.706882
		K-feldspar	287.4	486.8	1.711	0.728620
		K-feldspar	287.4	487.1	1.711	0.728611
Rog 470	Sjelset granite [type I]	whole-rock	298	142	6.156	0.797169
		quartz	12.47	23.82	1.521	0.749934
		quartz	12.46	23.89	1.515	0.749985
		K-feldspar	515.6	160.5	9.392	0.827992
		K-feldspar	513.6	160.5	9.369	0.827919
		plagioclase	36.61	35.18	3.028	0.766321
		plagioclase	36.63	35.21	3.027	0.766228
		green biotite	1196	12.02	350.8	2.94845
		green biotite	1206	12.11	350.3	2.91038
		brown biotite	1185	62.54	58.38	1.37203
		brown biotite	1198	62.76	58.81	1.36856
Rog 470	Undheim leuconorite	whole-rock	15	871	0.0491	0.704505
		plagioclase	5.02	1205	0.0121	0.704036
		plagioclase	5.055	1209	0.0121	0.704055
		biotite	348.0	28.90	36.38	1.16215
		biotite	350.5	28.90	36.65	1.16294
		orthopyroxene	1.734	53.38	0.0940	0.705259
		orthopyroxene	1.781	53.80	0.0958	0.705648
		ilmenite	0.8794	10.82	0.2352	0.707162
		ilmenite	0.8273	10.55	0.2269	0.707030

Table 5. Results of the Rb–Sr investigation on whole rock and mineral samples of the Sjelset Igneous Complex and the Undheim Leuconorite.

Whole rocks	n	Calculated age	$Sr_{[i]}$	MSWD	Figure
Sjelset Igneous Complex					
Type I + II					
[combined granite and charnockite]	13	1020 ± 66 Ma	0.70494 ± 0.00087	99	
Type I					
[biotite granite]	3	985 ± 165 Ma	0.7101 ± 0.015	1.25	3a
Type II					
[charnockite]	10	881 ± 131 Ma	0.7065 ± 0.0015	80	3d
Type IIa					
[pigeonite charnockite]	4	789 ± 269 Ma	0.7071 ± 0.0026	67	
Type IIb + IIc					
[combined fayalite ± pigeonite]	6	805 ± 463 Ma	0.7077 ± 0.0046	40	
Undheim Leuconorite					
leucocharnockitic veins*	7	1028 ± 77 Ma	0.7052 ± 0.0014	3	4e
Minerals					
Sjelset Igneous Complex					
Biotite granite Rog 470					
[WR + Qtz + Kfs + Pl + br Bt]	9	735 ± 29 Ma	0.7340 ± 0.0012	44	3c
[WR + gr Bt]	3	435 ± 45 Ma	0.7591 ± 0.0068	5	3b
Augite Fayalite-charnockite Rog 464					
[WR + Qtz + Pl + Kfs + Pyr]	8	896 ± 13 Ma	0.70657 ± 0.00005	5	3e
(1 Pyroxene datum omitted)					
Undheim Leuconorite					
Leuconorite Rog 474					
[WR + Pl + Pyr + IIm + Bt]	9	909 ± 79 Ma	0.70402 ± 0.00019	146	4a
[WR + Pl + Pyr + IIm]	6	980 ± 48 Ma	0.70387 ± 0.00008	9	4c
(1 Pyroxene datum omitted)					
[WR + IIm]	3	996 ± 102 Ma	0.70381 ± 0.00024	0.2	4d
[WR + Bt]	3	879 ± 39 Ma	0.70389 ± 0.00019	0.6	4b

*Measurement performed with the MAT CH5 mass spectrometer.



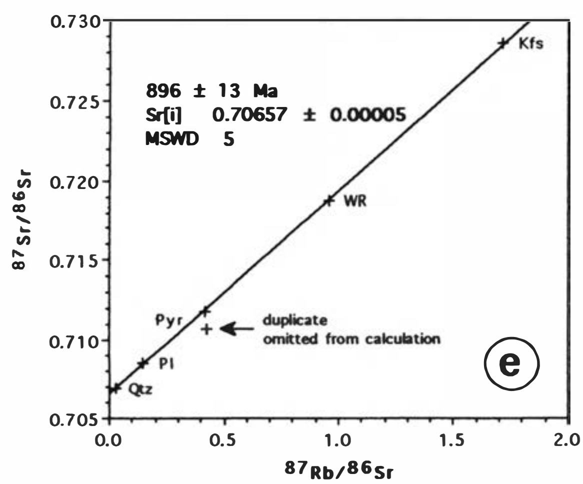


Fig. 3. Sjelset Igneous Complex: a. Isochron plot of three biotite granite samples from the Sjelset Igneous Complex. b. Internal isochron plot of green biotite (duplicate) and whole rock from biotite granite Rog 470. c. Internal isochron plot of brown biotite (duplicate), quartz (duplicate), plagioclase (duplicate), K-feldspar (duplicate) and whole rock from biotite granite Rog 470. d. Isochron plot of 10 charnockites from the Sjelset Igneous Complex. e. Internal isochron plot of pyroxene, quartz (duplicate), plagioclase (duplicate), K-feldspar (duplicate) and whole rock from augite–fayalite charnockite Rog 464. One pyroxene omitted.

not represent the time of their magmatic crystallization but of their isotopic closure at lower temperature. However, nothing is known at present of the U–Pb closure temperature of zircon and baddeleyite, especially for conditions involving extremely high magmatic temperatures and very slow cooling.

The excellent alignment [MSWD = 1.25] in the isochron diagram of the three samples of biotite granite (Fig. 3a) suggests an intrusion age of 985 Ma with a large uncertainty of ±165 Ma.

The occurrence of two generations of biotite in the biotite granite clearly indicates that some recrystallization must have taken place. Apparently this did not disturb the isotopic whole rock system on the scale of the samples. The $Sr_{(i)}$, 0.710 ± 0.015 of the biotite granite is indicative of a crustal origin.

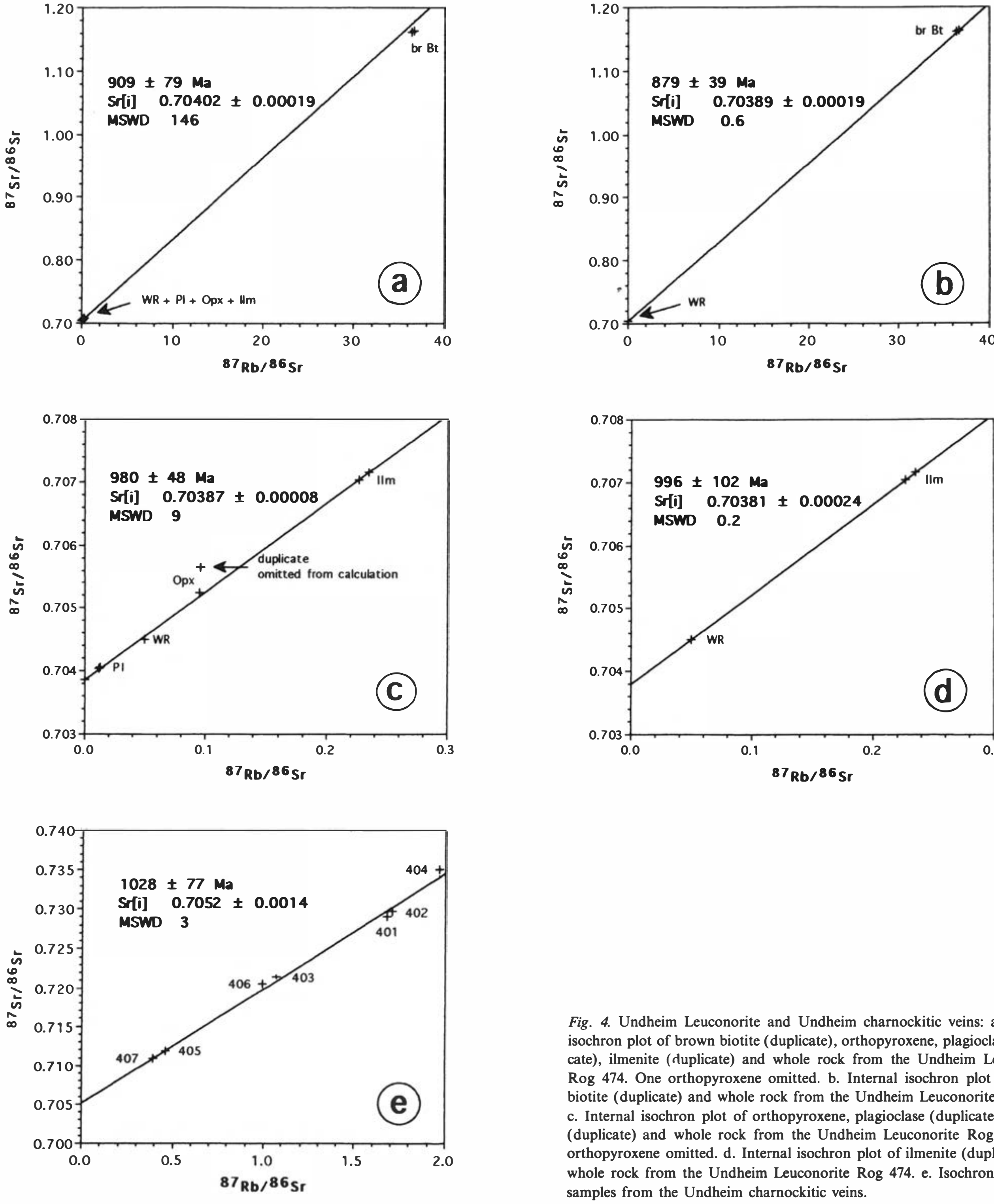


Fig. 4. Undheim Leuconorite and Undheim charnockitic veins: a. Internal isochron plot of brown biotite (duplicate), orthopyroxene, plagioclase (duplicate), ilmenite (duplicate) and whole rock from the Undheim Leuconorite Rog 474. One orthopyroxene omitted. b. Internal isochron plot of brown biotite (duplicate) and whole rock from the Undheim Leuconorite Rog 474. c. Internal isochron plot of orthopyroxene, plagioclase (duplicate), ilmenite (duplicate) and whole rock from the Undheim Leuconorite Rog 474. One orthopyroxene omitted. d. Internal isochron plot of ilmenite (duplicate) and whole rock from the Undheim Leuconorite Rog 474. e. Isochron plot of 7 samples from the Undheim charnockitic veins.

The Sjelset Igneous Complex (Fig. 1) is situated within the Caledonian green biotite-in isograd (Verschure et al. 1980; Sauter et al. 1983). Indeed, the green biotite–whole rock age from granite sample Rog 470 435 ± 45 Ma (Fig. 3b) shows that green biotite formed during the Caledonian orogeny as a consequence of Caledonian overthrusting and metamorphism. This was already indicated for a similar generation of green biotite in augen gneisses further north (Verschure et al. 1980).

The primary brown biotite from the same biotite granite sample Rog 470 largely determines the mineral errorchron (excluding green biotite) age of 735 ± 29 Ma (Fig. 3c). This age is younger than the calculated whole rock age of the biotite granite and points to partial resetting, i.e. redistribution of Sr isotopes. This partial resetting holds for brown biotite in the first place but to a lesser extent also for quartz and feldspars, as is evident from the unusually high contents of Sr (see Table 4).

These can probably be attributed to the tiny veinlets of carbonate in quartz grains and of saussurite and stilpnomelane in K-feldspar. This partial resetting probably took place during the Caledonian orogeny, since the mineral errorchron age of Rog 470 is younger than the regional Svenconorwegian biotite Rb–Sr and K–Ar cooling ages of about 870 Ma outside the green biotite-in isograd (Verschure et al. 1980; Wielens 1981; Priem & Verschure 1982). Partial resetting is also evidenced by the strongly increased $Sr_{(i)}$ value of 0.7340 ± 0.0012 of the Rog 470 mineral errorchron (excluding green biotite, Fig. 3c) compared to the $Sr_{(i)}$ value of 0.710 ± 0.015 for the biotite granite (Fig. 3a). The partial Caledonian resetting of brown biotite is petrographically manifested by extensive sagenitic exolution and decolorization zones along margins and cracks of the brown biotite crystals (see Fig. 2 in Verschure et al. 1980).

The Sjelset pyroxene ±fayalite charnockite

The calculated whole rock age of the charnockite is 881 ± 131 Ma (Fig. 3d). Comparison of this age with that of the Sjelset biotite granite, 985 ± 165 Ma, is meaningless because of the large uncertainties. However, a younger intrusion age of the charnockite is indicated by field observations.

Some whole rock resetting and therefore a too low whole-rock age for the Sjelset charnockites is strongly suggested by:

(i) the still younger whole-rock ages that can be calculated for the Type II_a (789 Ma) and Type $II_b + II_c$ rocks (805 Ma) separately (Table 5);
(ii) their higher $Sr_{(i)}$ values (Type $II_a = 0.7071 \pm 0.0026$, Type $II_b + II_c = 0.7077 \pm 0.0046$) (Table 5);
(iii) the slightly higher age of the primary mineral errorchron of sample Rog 464 (896 ± 13 Ma, Fig. 3e, Table 5).

The relatively low $Sr_{(i)}$ value (0.7065 ± 0.0015) of the Sjelset charnockites precludes a direct mantle derivation. This $Sr_{(i)}$ value is comparable to $Sr_{(i)}$ values of several acidic rocks in SW Norway, e.g. the zoned Kleivan 'Granite' (0.7053 ± 0.0002, Petersen & Pedersen 1978) and of the top (Quartz) Monzonitic Phase of the Bjerkreim–Sokndal lopolith (0.7075 ± 0.0028, Wielens 1981). These $Sr_{(i)}$ values in combination with striking similarities in mineralogy and chemistry may indicate a genetic link with the Egersund magmatism. The (Quartz) Monozonitic phase of the Bjerkreim–Sokndal lopolith is considered to be related to anorthosites through differentiation (Demaiffe et al. 1979; Duchesne et al. 1987), but isotope constraints require variable contamination by supracrustal material. Such an origin may equally hold for the Sjelset charnockite.

In view of its small MSWD value (5) and error limits, the primary mineral errorchron age of 896 ± 13 Ma of Rog 464 (Fig. 3e) has a much smaller uncertainty than the charnockite whole-rock age of 881 ± 131 Ma (Fig. 3d). However, minor resetting of the Rog 464 minerals seems probable, especially in view of the even more unusual high contents of Sr in quartz and feldspars (Table 4). Again these may be attributed to tiny veinlets of carbonate and saussurite, which are even more abundant in the charnockites than in the biotite granites. But the resulting clockwise pivoting of the mineral data around the whole-rock data point cannot be large in face of the relatively low $Sr_{(i)}$ of 0.70657 ± 0.00005 (Fig. 3e). Comparison of the ages and $Sr_{(i)}$ values of the charnockites and the Rog 464 minerals shows that the intrusion age of these rocks must be slightly above 896 Ma, but cannot be more than 930 Ma because of the restrictions imposed by assumed realistic $Sr_{(i)}$ values.

The scatter of whole-rock data points of the Sjelset charnockites in a 1/Sr versus $^{87}Sr/^{86}Sr$ diagram – also when recalculated for any assumed intrusion age – prevents speculation on mixing. However, the excellent alignment in the isochron plot of the three samples of biotite granite (Fig. 3a) could be explained as: (i) the intrusion age of 985 Ma when no mixing has taken place, or (ii) a somewhat younger intrusion age in combination with some mixing with material with lower $Sr_{(i)}$ values.

The linear plot of 1/Sr versus $^{87}Sr/^{86}Sr$ values recalculated to an age of 930 Ma ago (about the maximum age of the Sjelset charnockites and – the Sjelset granite being older – near the minimum age of the Sjelset granite) for all the analysed Sjelset samples indicates that the Sjelset granite samples might be regarded as mixtures of granitic material with variable amounts of Sjelset charnockite. On the other hand, the lack of correlation between the Sjelset granite and Sjelset charnockite samples in a SiO_2 versus Mg # plot makes this assumption of mixing very improbable.

The Undheim Leuconorite and the Undheim charnockitic veins

The Undheim charnockitic veins are probably the result of back-veining, i.e. infiltration of melts originating from the partial melting of country rocks by the heat of the intruding Undheim Leuconorite. The whole-rock isochron age of the charnockitic veins, 1028 ± 77 Ma (Fig. 4e) therefore provides a minimum age for the emplacement of the Undheim Leuconorite. The leucocharnockitic vein samples cannot be regarded as a mixing product of partly molten country rocks with leuconoritic material, as becomes evident from plots of 1/Sr values versus $^{87}Sr/^{86}Sr$ values recalculated to: (i) their assumed intrusion age 1028 Ma, or (ii) an age of 980 Ma imposed by the mineral errorchron of Undheim Leuconorite Rog 474 (Fig. 4c).

The 909 ± 79 Ma whole rock + plagioclase + orthopyroxene + ilmenite + brown biotite age of the leuconorite Rog 474 (Fig. 4a) does not indicate the emplacement age of the Undheim Leuconorite. This age is especially lowered by the isotopic characteristics of brown biotite. The whole rock + brown biotite age of 879 ± 39 Ma (Fig. 4b) agrees well with the regional brown biotite cooling age of about 870 Ma (e.g. Verschure et al. 1980).

The whole rock + plagioclase + orthopyroxene + ilmenite age of 980 ± 48 Ma (Fig. 4c) and especially of the whole rock + ilmenite age of 996 ± 102 Ma (Fig. 4d) conform better with the supposed emplacement time of the Undheim Leuconorite of 1028 Ma ± 77, but still indicate some resetting through minor loss of ^{87}Sr from biotite, ilmenite and pyroxene and gain of ^{87}Sr by plagioclase.

Conclusions

1. The striking mineralogical, chemical similarities and corresponding $Sr_{(i)}$ values of the Sjelset charnockites and the upper (Quartz) Monzonitic Phase (Rietmeijer 1979) – indicated as (Quartz) Mangerite Phase by Michot (1960) and Duchesne (1987) – of the Bjerkreim–Sokndal Lopolith, suggest a comparable origin. The age determinations are compatible with the rock suites being consanguineous:

   - 900–930 Ma for the Sjelset charnockite, see above.
   - 910–930 Ma (zircon U–Pb, Pasteels et al. 1979) and the 928 ± 50 Ma (Rb–Sr whole rock, Wielens et al. 1981) for the (Quartz) Mangerite Phase of the Bjerkreim–Sokndal Lopolith.

   With regard to the consanguinity with the Egersund anorthositic magmatism a mantle origin for the Sjelset charnockites is probable, although crustal contamination has to be invoked in face of the $Sr_{(i)}$ of 0.7065 ± 0.0015.
2. The rocks of the Undheim Leuconorite resemble the rocks of the lower anorthositic–noritic units of the Bjerkreim–Sokndal layered intrusion in various aspects, e.g. plagioclase cumulate texture, planar lamination (Duchesne 1987). However, the small occurrence of the Undheim Leuconorite prohibits a clear correlation with the large 6 km thick lower layered series of the Bjerkreim–Sokndal Lopolith. Moreover, their intrusion ages, though both indirectly determined and therefore less certain, seem different:

   - The whole rock Rb–Sr age of 1028–77 Ma for the charnockitic veins of the Undheim Leuconorite.
   - The U–Pb age of the Bjerkreim–Sokndal Lopolith of ≈955 Ma of Pasteels et al. (1979) determined on monazite from country rocks 5 m from the contact with the Bjerkreim–Sokndal layered intrusion, or the Sm–Nd plagioclase isochron age of 944 Ma (Barling et al. 1993).

   In some aspects the Undheim Leuconorite resembles the leuconoritic rocks of the undeformed Hidra Massif (Demaiffe 1977; Demaiffe & Hertogen 1988). The latter are equally younger (U–Pb zircon 950 ± 5 Ma and 930 ± 10 Ma; whole-rock Rb–Sr charnockitic dikes 892 ± 25 Ma, Pasteels et al. 1979) than the Undheim rocks.

   A mantle origin for the Undheim Leuconorite seems evident in view of the $Sr_{(i)}$ value 0.70387 ± 0.00008 of the mineral errorchron of the Undheim Leuconorite Rog 474 (Fig. 4c).
3. Contrary to the Sjelset charnockite the Sjelset biotite granite has no equivalents in the Bjerkreim–Sokndal Lopolith. In view of their 'normal' mineralogy and chemistry, e.g. lower Fe–Mg ratios and higher $Sr_{(i)}$ values of 0.7101 ± 0.0145, a crustal origin for the Sjelset biotite granite seems most probable.
4. The Undheim Leuconorite and the Sjelset charnockites are probably related to the anorthositic magmatism in SW Norway. If so, they are evidence of a continuation of the anorthositic magmatism to the NNW, roughly parallel to the hypersthene-in isograd on the lower temperature side of the Rogaland isograd zonation (Fig. 1). Therefore, the hypersthene-in isograd in the northern part of the Rogaland granulite facies area is probably related to the isograd pattern (e.g. the osumulite-in and pigeonite-in isograds) that roughly follows the outlines of the Egersund Anorthositic Complex at higher grade conditions. The hypersthene-in isograd therefore not only follows the present outlines of the Egersund Anorthosite Complex, but also a belt of partially concealed anorthositic and anorthosite-related complexes in NNW direction.
5. Common minerals, which are seldom used for dating purposes, like quartz and ilmenite, have proved of value in this study. Especially ilmenite seems less sensitive to resetting during slow cooling and/or reheating than feldspars and biotite.
6. The U–Pb zircon and baddeleyite ages of 920–930 Ma for the Anorthositic Egersund Complex (Duchesne et al. 1993) probably do not represent crystallization ages but cooling ages of these minerals.

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