Geochemistry of Sveconorwegian augen gneisses from SW Norway at the amphibolite–granulite facies transition

BERNARD BINGEN

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The augen gneisses of Rogaland–Vest-Agder were emplaced as amphibole–biotite granodiorites rich in K-feldspar phenocrysts. They were probably pre- or syntectonically emplaced and were metamorphosed under lower amphibolite to granulite facies conditions after their emplacement. Three metamorphic zones defined by two isograds (Cpx–in and Opx–in) can be established in the augen gneisses using ferromagnesian minerals: zone 1 = Bt ± Am zone; zone 2 = Bt ± Am ± Cpx zone and zone 3, close to the Rogaland anorthosite complex, in granulite facies = Bt ± Am ± Cpx ± Opx zone. Pyroxene forming reactions occur in two stages in the augen gneisses (first producing Cpx and then Opx); amphibole appears to be an important reactant in the pyroxene-forming reactions while biotite is not. Sphene and allanite, present in zone 1, disappear as Cpx appears (zone 2). Trace amounts of monazite also appear at this isograd. The augen gneisses are granodioritic to granitic in composition. They are of K-rich calc–alkaline affinity and they are enriched in incompatible elements (Ba, Rb, K, Sr). They contain various kinds of enclaves, including some of calc–alkaline lamprophyric composition. The augen gneisses of the three metamorphic zones define a single geochemical trend, implying that they represent a single magmatic episode. The augen gneisses of granulite facies (zone 3) are not depleted in Rb, K nor, presumably, in other LIL elements, relative to their amphibolite facies equivalents (zones 1 and 2). The presence of K-rich minerals (K-feldspar and biotite) in the augen gneisses seems to inhibit the LILE depletion process.

B. Bingen, Lab. associés de géologie, pétrologie et géochronologie, Université Libre de Bruxelles, 50 Av. F. Roosevelt, 1050 Bruxelles, Belgium. (Research Assistant at the Belgian National Fund for Scientific Research.)

Granulite-facies metamorphism has been recognized both at the SW (close to the Rogaland anorthosite complex; Michot 1960) and SE (Bamble area near Arendal; Barth 1969; Touret 1971a, b) extremities of the Sveconorwegian (= Grenvillian) province of S. Norway. In the Rogaland–Vest-Agder area (Fig. 1), the amphibolite–granulite facies transition has been mapped by Tobi (1965) and Hermans et al. (1975) on the basis of the appearance of orthopyroxene in migmatitic banded gneisses. Within the granulite facies domain, several isograds (most importantly osumilite-in and pigeonite-in) were defined by Maijer et al. (1981) and Tobi et al. (1985) indicating increasing metamorphic grade towards the Rogaland anorthosite complex.

Three distinct metamorphic events were recognized by Maijer et al. (1981): M1, of early Sveconorwegian age (≃1200 Ma); M2, considered as the major Sveconorwegian event (at 1050–1000 Ma: Pasteels & Michot 1975; Pasteels et al. 1979; Wielen et al. 1981; Demaiffe & Michot 1985); M3, which re-equilibrated the M2 associations (≃950 Ma).

The temperature of the M2 phase is estimated to be 800–900°C (Jansen et al. 1985) on the basis of pyroxenes, oxides and Grt–Opx thermometry (symbols for minerals: see appendix). Pressure estimates are controversial: Jansen et al. (1985) suggest a low P metamorphism (3–4 Kbar), linked to the assumed high-level emplacement of the anorthosites, while Wilmart & Duchesne (1987) provide evidence supporting the emplacement of the late-stage charnockites associated with the anorthosite complex at pressures of 6–8 Kbar (Ol-Opx-Qtz equilibrium, density of CO_2-rich fluid inclusions).

The gneisses in the Rogaland–Vest-Agder region have been subdivided into three major units (Tobi 1965; Falkum 1966, 1985; Hermans et al. 1975): banded gneisses (often migmatitic and locally of metasedimentary origin), granitic gneisses and augen gneisses.

Several deformation phases have been

described in the region (Falkum 1966, 1985; Falkum & Petersen 1980). The first deformation is only observed in the banded gneisses which represent the oldest formation. The Sveconorwegian deformation (associated with M2 metamorphism) proceeded in a number of stages between 1100 and 980 Ma (F2 to F4 phases of Falkum 1985). The late-tectonic 'Homme' granite is dated at 1000 Ma (Falkum & Pedersen 1979), while the first post-tectonic granite is dated at 980 Ma (Wilson et al. 1977).

In this paper, the petrographical evolution of the augen gneisses is examined at the amphibolite–granulite facies transition. Their geochemical affinity is defined. It is shown that granulite facies augen gneisses are not LILE depleted relative to their amphibolite facies equivalents. The geological evolution of the augen gneisses is considered.

The augen gneisses: field description and petrography

The augen gneisses crop out as elongated bodies concordant with regional structures. Several units have been recognized (Fig. 1; Falkum 1982). From east to west, these units are Mandal–Holum–Svindal, Håland, Leland, Lyngdal, Feda–Sirdal–Tonstad–Sira, Bjørnstadvatnet and Liland. The augen gneisses are granodioritic to granitic gneisses, characterized by the presence of large (up to 15 cm) K-feldspar megacrysts.

Field observations in the augen gneisses of Feda–Sira and Liland bring minor modifications to the maps of Falkum (1972, 1982) and Hermans et al. (1975) (Fig. 2).

More than 250 thin sections of augen gneisses collected in the different units were examined, including 80 from the collection of the State University of Utrecht. The mineral associations of the Leland unit are described in detail by Petersen (1977). Petrographic observations in the Håland and Mandal–Holum–Svindal units were done by Wilson et al. (1977) and Falkum (pers. comm.). Using this information, three metamorphic zones separated by two isograds were delineated in the augen gneisses on the basis of the ferromagnesian mineral associations in samples of granodioritic composition (Fig. 1). The easternmost zone (zone 1) is characterized by the association Bt + Am. The transition between zones 1 and 2 is marked by the Cpx-in isograd; the characteristic mineral association of zone 2 is thus Bt + Am + Cpx, although Bt + Am still occurs. The westernmost zone (zone 3) is characterized by the development of orthopyroxene; it belongs to the granulite facies. In granodioritic samples, the associations Bt ± Am ± Cpx + Opx, Bt + Am + Cpx and more rarely Bt + Am occur west of the Opx-in isograd. Biotite is the only ferromagnesian mineral in the most quartzofeldspathic samples in all metamorphic zones.

The position of the Opx-in isograd in the augen gneisses is in good agreement with the one mapped in banded gneisses by Hermans et al. (1975) (Fig. 1).

The Feda augen gneiss (zone 2), which is well exposed and has been the object of detailed observation and sampling (Fig. 2), will be described in particular. The augen gneisses from zones 1 and 3 will be described only in as much as they differ from those of zone 2. The Feda augen gneiss outcrops in the core of an antiform with a N–S axial plane and a southerly plunge (Fig. 2). The rock is grey to greyish-blue. Granodioritic and granitic facies are present. A systematic mapping of the different facies is impossible due to their random spacial distribution and the gradual transitions between them. The augen gneiss contains K-feldspar megacrysts from 3 to 15 cm in diameter; the megacrysts are more abundant in the granodioritic facies than in the granitic facies.

The Feda augen gneiss shows a zoned structure. In its central part, the body is little deformed and displays a porphyritic structure with large euhedral non-oriented K-feldspar megacrysts. A foliation appears towards the borders and it is particularly well developed close to the contact. The foliation plane is defined by the general alignment of biotite flakes and by elongated aggregates of the other ferromagnesian minerals. Towards the borders, the megacrysts become reduced in size and show pressure shadows of granular K-feldspar. The penetrative deformation is not homogeneously distributed throughout outcrops but is concentrated in planar zones, ca. 1–5 m thick, in which the augen gneiss appears darker and the megacrysts are more intensely granulated or even completely disaggregated.

The boundary between the augen gneiss and the granitic gneisses is transitional over 10 to 50 m; it is marked by the gradual disappearance of the megacrysts. At the contact with the banded gneisses, mafic mineral-enriched bands appear in the augen gneiss and K-feldspar megacrysts

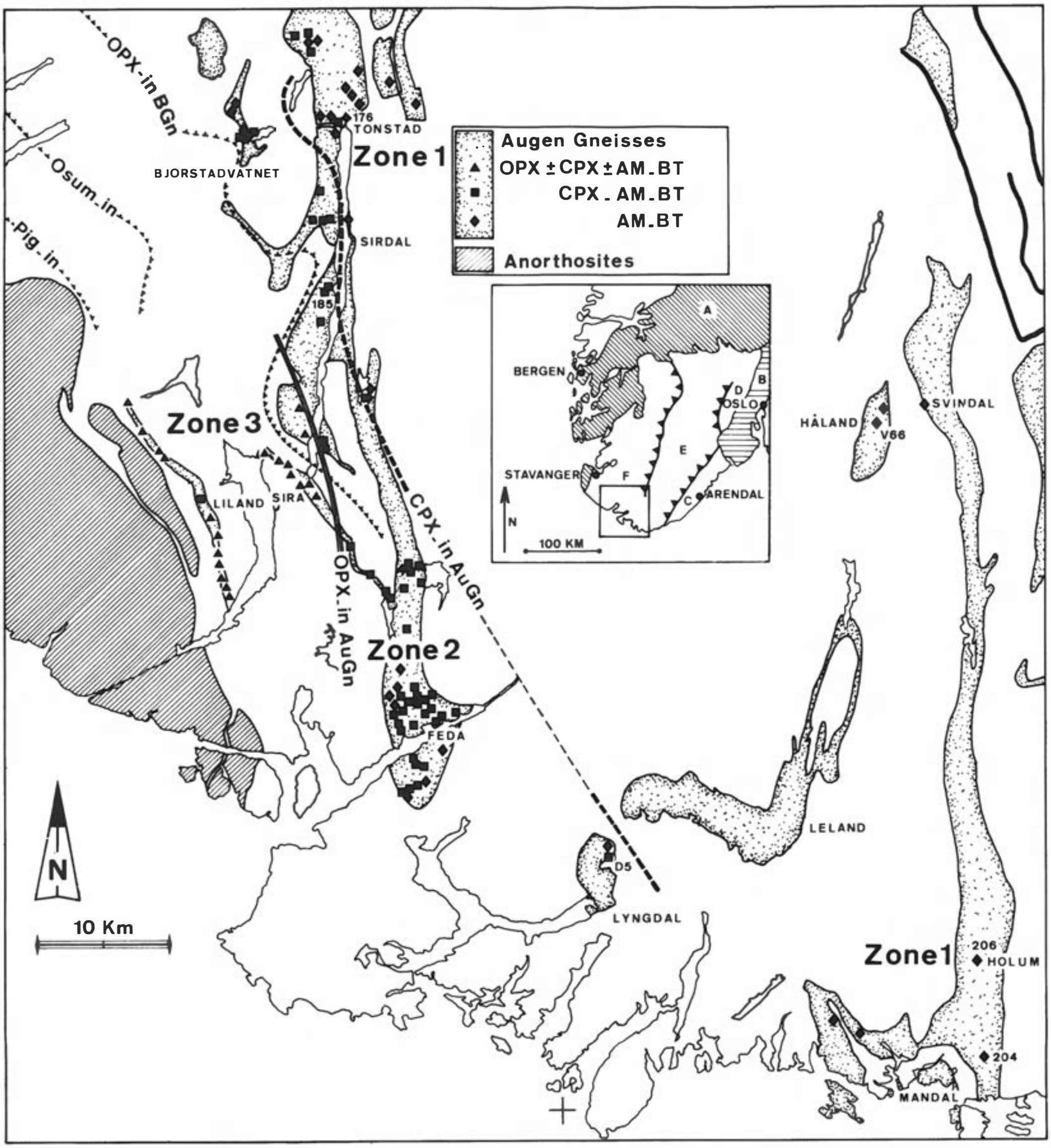

Fig. 1. Sketch map showing the different augen gneiss units recognized in the field (Falkum 1982) as well as the approximate limits of the three metamorphic zones in the augen gneisses. Zone 1: Bt ± Am zone; zone 2: Bt ± Am ± Cpx zone; zone 3: Bt ± Am ± Cpx ± Opx zone in the granulite facies. Pig-in and Osum-in: Pigonite-in and Osumilite-in isograds (Maijer et al. 1981 and Tobi et al. 1985); Opx-in BGn: Opx-in isograd in banded gneisses (Hermans et al. 1975); Opx-in AuGn and Cpx-in AuGn: Opx-in and Cpx-in isograds in augen gneisses. Each symbol corresponds to 1, 2 or 3 samples. Biotite-bearing samples have not been plotted. Numbers refer to samples of Table 1. Inset map: (A) Caledonian orogenic area; (B) Oslo graben; (C) Bamble sector; (D) Kongsberg sector; (E) Telemark sector; (F) Rogaland–Vest-Agder sector.

gradually disappear from felsic horizons. The foliation in the augen gneiss is concordant with that in the surrounding granitic and banded gneisses.

Xenoliths of granitic and banded gneisses occur in the augen gneiss. These are lenticular, vary from a few metres to 50 m in thickness and are elongated in the plane of the foliation in the augen gneiss. Lenses (0.5 to 5 m thick) enriched in ferromagnesian minerals are also present. A few mafic enclaves rich in K-feldspar and biotite but

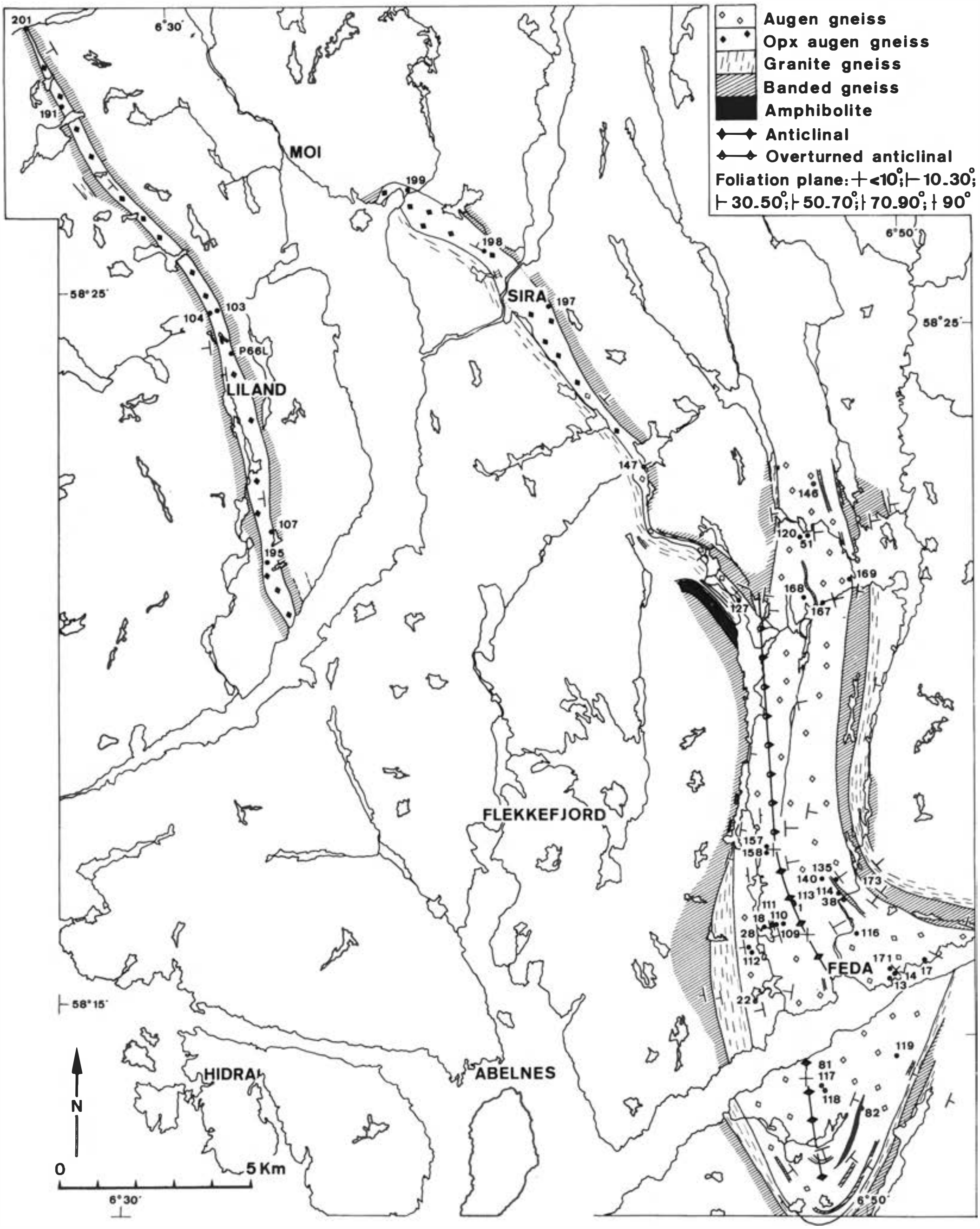

Fig. 2. Geological map of the augen gneisses of Feda, Sira and Liland. This map diverges from those of Hermans et al. (1975) and Falkum (1982) at the northern tip of Liland augen gneiss and the western edge of Feda augen gneiss. Blank areas have not been mapped. Numbers refer to samples of Table 1.

with only minor quantities of quartz have been found; they locally contain K-feldspar megacrysts (these enclaves of lamprophyric composition are described in the next section). In the central undeformed part of the augen gneiss they display an ameoboid (lobate) shape.

The groundmass of the Feda augen gneiss has a granoblastic texture. Millimeter-sized quartz, plagioclase (An 20–30), K-feldspar (orthoclase) and biotite are ubiquitous, together with minor quantities of ilmenite (with abundant hematite exsolution lamellae) and magnetite. The clinopyroxene (salite) often contains inclusions of amphibole or surrounds it as a thin rim. Apatite, zircon (generally zoned) and pyrite are accessory minerals. Minor amounts of secondary epidote, calcite and chlorite are present in most samples. The K-feldspar megacrysts (orthoclase) contain numerous inclusions, mainly of plagioclase, quartz, biotite, amphibole and, in minor quantity, ilmenite, magnetite, apatite, zircon and sphene. Plagioclase inclusions are often orientated parallel to the crystallographic planes of the host K-feldspar. Inclusions are sometimes arranged in concentric zones and some of them are euhedral.

The augen gneisses of zone 3 (granulite facies) are more deformed than those of the Feda area. Some granulation appears at the contact between the minerals and K-feldspar megacrysts are smaller. The Opx is hypersthene and the K-feldspar is orthoclase.

The augen gneisses of zone 1 contain numerous lenses (1 to 50 m thick) of banded gneisses and mafic gneisses, often strongly deformed. Discordant aplitic and granitic veins are abundant. The K-feldspar of the groundmass is microcline giving a pink aspect to the rock and phenocrysts are either microcline or orthoclase. Accessory sphene and allanite are widely distributed.

Heavy minerals were separated in 10 samples (3 in zone 1, 4 in zone 2, and 3 in zone 3). A microprobe examination shows that monazite is present in trace amounts (less than 1% of the zircon fraction) in all the samples of zones 2 and 3, while it is absent in allanite-bearing samples of zone 1. Thorite has been detected in most samples and fluorine in one sample.

The characteristic mineral associations of the augen gneisses in the three metamorphic zones are summarized in Fig. 3.

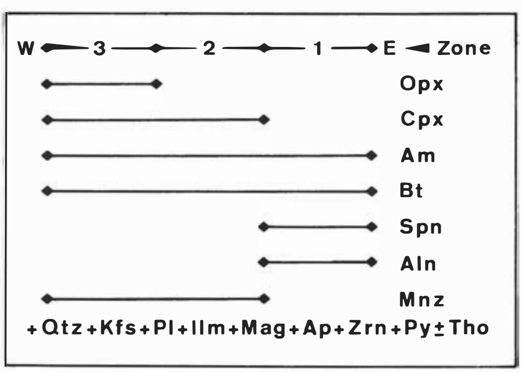

Fig. 3. Mineral associations in the three metamorphic zones of the augen gneisses: zone 1 (east), zone 2, zone 3 (west) (Fig. 1). Kfs, Qtz, Pl, Bt, Ilm, Mag, Ap, Zrn and Py are present in all samples while Opx, Cpx, Am, Spn, Aln and Mnz are present only in some samples of appropriate composition in the corresponding zone. Tho (thorite) is present in trace amount in some samples.

Bulk rock geochemistry

Major and some trace elements were analysed by X-ray fluorescence spectrometry in selected augen gneisses from the three metamorphic zones (10 samples in zone 3, 31 samples in zone 2 and 4 samples in zone 1). The mineralogy of the analysed samples and the analyses are given in Tables 1, 2 and 3. Because of the size and distribution of the megacrysts, large samples of up to 35 Kg were used.

The augen gneisses are granodioritic to granitic in composition (Fig. 4a): they have SiO_2 contents ranging from 60 to 73 wt%. In the A.F.M. ($A = Na_2O + K_2O$, $F = FeO_{tot}$, $M = MgO$ in wt%) and in the Peacock (1931) ($Log(CaO/Na_2O + K_2O)$ versus SiO_2) diagrams, the augen gneisses display a typical calc-alkaline trend (Figs. 4b and 5a). Average FeO_{tot}/MgO ratio of the Feda augen gneiss is 2.2 ($Fe/Fe + Mg = 0.64$).

The A.B. diagram of Debon & Lefort (1983), ($A = Al - (K + Na + 2Ca)$, $B = Mg + Fe + Ti$ in gram–atoms) tests the aluminous character of plutonic suites. In this diagram, the augen gneisses are located in the metaluminous domain: A is negative in amphibole + biotite ± pyroxene granodioritic samples and becomes slightly positive in biotite-bearing granitic samples. The augen gneisses plot on (or just below) the typical calc-alkaline trend (Fig. 6).

K_2O (wt%) ranges from 3.2 to 5.5% for the most acid samples; according to the Peccerillo & Taylor (1976) classification of calc-alkaline volcanic rocks, the augen gneisses belong to the high-K calc-alkaline series (Fig. 5b).

The augen gneisses are enriched in incompatible elements: Ba = 1400 ppm, Rb = 110 ppm, K_2O = 3.5%, Sr = 1100 ppm at the SiO_2-poor end of the trend (SiO_2 = 60%; Tables 2 and 3). Enrichment factor of Nb (15 ppm) is of lesser amplitude than that of the other incompatible

Table 1. Mineral contents of the augen gneisses and their lamprophyric enclaves.

Sample		X	Y	Pl	Qtz	Opx	Cpx	Am	Bt	Spn	Aln	Mnz	Tho
Z1	176	3 67.6	65 05.8	+	+	−	−	−	+	+	+		
	204a	4 15.2	64 35.0	+	+	−	−	+	+	+	+	−	−
	206	4 13.2	64 40.6	+	+	−	−	+	+	+	+	−	−
	V66	4 07.3	64 82.1	+	+	−	−	+	+	+	+		
Z2	13a	3 73.3	64 60.1	+	+	−	+	+	+	−	−	+	−
	18h	3 70.3	64 61.6	+	+	−	−	+	+	−	−		
	18k	3 69.8	64 61.5	+	+	−	−	+	+	−	−		
	18n	3 69.7	64 61.4	+	+	−	−	−	+	s	−		
	22	3 69.7	64 59.6	+	+	−	+	+	+	−	−		
	28	3 69.5	64 60.9	+	+	−	−	+	+	s	−		
	38a	3 72.2	64 62.2	+	+	−	+	+	+	s	−		
	51	3 71.2	64 71.8	+	+	−	+	+	+	−	−		
	109b	3 70.5	64 61.6	+	+	−	−	+	+	−	−		
	110	3 70.3	64 61.6	+	+	−	+	+	+	−	−		
	111	3 70.2	64 61.6	+	+	−	+	−	+	−	−		
	112	3 69.5	64 60.9	+	+	−	+	+	+	−	−		
	113a	3 70.8	64 62.1	+	+	−	+	+	+	−	−		
	113c	3 70.8	64 62.1	+	+	−	+	+	+	−	−	+	+
	114	3 72.1	64 62.2	+	+	−	+	+	+	−	−	+	+
	116	3 72.4	64 61.3	+	+	−	+	+	+	−	−		
	118	3 71.6	64 57.2	+	+	−	+	+	+	−	−		
	119	3 73.4	64 58.1	+	+	−	−	+	+	−	−		
	120a	3 71.0	64 71.7	+	+	−	−	+	+	−	−		
	127a	3 69.4	64 70.1	+	+	−	+	+	+	−	−		
	135	3 71.8	64 62.8	+	+	−	−	−	+	−	−		
	140a	3 71.5	64 62.8	+	+	−	+	+	+	−	−	+	−
	146	3 71.3	64 73.0	+	+	−	+	+	+	−	−		
	147	3 66.8	64 73.5	+	+	−	+	+	+	−	−		
	158	3 70.1	64 63.5	+	+	−	−	+	+	−	−		
	168	3 71.1	64 70.1	+	+	−	+	+	+	−	−		
	169	3 72.2	64 70.6	+	+	−	+	+	+	−	−		
	171	3 73.4	64 60.4	+	+	−	+	+	+	−	−		
	173	3 72.6	64 62.4	+	+	−	+	+	+	−	−		
	185	3 65.5	64 93.2	+	+	−	+	+	+	s	−		
	D5	3 86.0	64 50.7	+	+	−	+	+	+	s	−		
Z3	103	3 55.6	64 77.6	+	+	−	+	+	−	−	−		
	104	3 55.4	64 77.5	+	+	−	−	−	+	−	−	+	+
	107	3 57.0	64 71.8	+	+	+	+	+	+	−	−	+	+
	191	3 51.6	64 83.0	+	+	−	−	−	+	−	−		
	195a	3 56.9	64 71.1	+	+	−	+	+	+	−	−		
	197	3 64.3	64 77.7	+	+	−	−	+	+	−	−		
	198	3 62.6	64 79.1	+	+	+	+	+	+	−	−	+	+
	199	3 60.6	64 80.7	+	+	+	+	+	+	−	−		
	201	3 50.6	64 84.9	+	+	+	+	+	−	−	−		
	P661	3 56.1	64 76.5										
En	81a	3 71.4	64 57.3	+	−	−	+	+	+	−	−		
	117b	3 71.4	64 57.3	+	+	−	+	+	+	−	−		
	157	3 70.1	64 63.6	+	−	−	+	+	+	−	+		
	167	3 71.4	64 70.0	−	+	−	+	+	+	−	−		

Z1, Z2, Z3: zones 1, 2 and 3; En: enclaves of lamprophyric composition. X, Y: coordinates of the 1/50000 ordnance map. +: present; −: absent; s: secondary; blank: heavy minerals not separated. Kfs, Ilm, Mag, Ap, Zrn are present in all samples.

elements. These are typical features of the K-rich calc-alkaline series (Gill 1981).

In binary and ternary geochemical diagrams (Figs. 4, 5, 6 and others not shown), the augen gneisses, whatever their geographic location and metamorphism, define a single trend. Mapping of the different units under the same label is therefore confirmed (Falkum 1982). The Fennefoss augen gneiss (Evje area, Telemark) is of similar affinity (Pedersen 1980).

The K-rich basic enclaves are of special interest. The average SiO_2 content of the four analysed

Table 2. Major elements of the augen gneisses.

Sample		SiO_2	TiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Total
Z1	176	69.76	0.39	15.62	1.26	1.54	0.00	1.06	2.09	3.77	4.15	0.26	100.05
	204a	64.70	0.77	15.54	1.88	2.08	0.00	1.83	2.93	3.17	4.74	0.40	98.37
	206	62.97	0.96	15.97	1.85	2.91	0.00	2.77	3.40	3.31	4.63	0.43	99.56
	V66	67.15	0.37	14.95	1.78	1.22	0.00	1.08	2.30	3.57	5.28	0.21	98.13
Z2	13a	66.82	0.59	14.76	2.22	1.49	0.00	1.72	3.23	3.21	4.07	0.25	98.66
	18h	65.68	0.75	16.05	2.41	1.64	0.00	1.26	3.63	3.78	3.99	0.28	99.77
	18k	66.30	0.66	15.20	2.28	1.58	0.03	1.48	2.91	3.56	4.62	0.29	99.20
	18n	73.32	0.25	13.98	1.16	0.60	0.00	0.43	1.58	3.35	4.79	0.11	99.87
	22	67.94	0.55	16.32	2.04	1.41	0.00	1.23	2.63	3.45	4.81	0.29	100.98
	28	66.56	0.66	15.24	2.05	1.27	0.00	1.22	2.41	3.86	5.00	0.23	98.78
	38a	65.53	0.66	15.21	2.26	1.81	0.00	1.89	3.40	3.48	4.22	0.35	99.07
	51	61.24	0.95	15.96	3.28	2.36	0.08	2.49	4.40	3.51	3.45	0.48	98.46
	109b	65.06	0.68	15.70	2.30	1.78	0.00	1.87	3.25	3.77	3.82	0.35	98.81
	110	62.66	0.81	16.71	2.73	2.19	0.00	2.12	3.65	3.69	4.15	0.39	99.39
	111	68.81	0.49	15.16	1.76	1.14	0.00	1.03	2.28	3.09	4.39	0.23	98.65
	112	64.33	0.77	16.80	2.40	1.81	0.00	1.60	3.20	3.41	4.27	0.31	99.19
	113a	70.61	0.34	14.01	1.56	1.14	0.00	1.26	2.27	2.91	3.91	0.24	98.39
	113c	65.85	0.71	15.12	2.41	1.88	0.00	1.90	3.52	3.10	3.56	0.34	98.62
	114	66.29	0.68	15.59	2.41	1.76	0.00	1.81	3.35	3.21	3.85	0.30	99.51
	116	62.18	0.88	16.11	2.88	2.33	0.00	2.45	4.01	3.31	3.68	0.39	98.52
	118	65.24	0.71	15.57	2.74	1.82	0.00	2.04	3.26	3.39	4.18	0.41	99.61
	119	64.78	0.73	15.55	2.73	1.95	0.00	2.16	3.62	3.45	3.26	0.37	98.80
	120a	60.49	1.07	16.31	3.43	2.95	0.01	2.95	4.65	3.34	3.53	0.47	99.47
	127a	68.75	0.49	14.98	2.04	1.42	0.00	1.52	2.88	3.48	3.83	0.29	99.85
	135	73.35	0.17	14.50	1.20	0.65	0.00	0.48	1.07	2.87	5.46	0.16	100.01
	140a	57.65	1.28	17.03	3.11	3.81	0.00	3.53	5.90	3.49	3.29	0.52	99.92
	146	64.73	0.82	16.29	2.49	1.97	0.00	1.90	3.41	3.34	4.42	0.37	100.06
	147	62.90	1.00	16.11	2.93	2.33	0.00	2.56	3.97	3.55	4.04	0.47	100.18
	158	65.10	0.72	16.20	2.22	1.69	0.00	1.56	3.04	3.95	4.47	0.36	99.59
	168	62.37	0.96	16.19	2.88	2.45	0.06	2.34	4.51	3.21	4.09	0.35	99.76
	169	66.06	0.81	16.31	3.63	1.57	0.00	1.48	2.35	3.29	4.04	0.28	100.16
	171	67.27	0.61	15.46	1.90	1.61	0.00	1.90	3.31	3.44	3.74	0.31	99.82
	173	64.05	0.98	16.17	2.49	1.99	0.00	2.21	3.76	3.57	3.92	0.42	99.87
	185	62.95	0.95	15.99	2.87	2.30	0.00	2.50	3.92	3.54	4.11	0.62	100.08
	D5	60.98	0.99	15.89	2.64	2.81	0.00	3.02	3.98	3.17	4.59	0.55	98.99
Z3	103	69.39	0.67	15.22	2.84	1.32	0.00	0.98	2.97	3.96	3.32	0.29	101.17
	104	69.76	0.53	14.33	1.61	1.12	0.00	1.32	1.93	3.47	5.03	0.28	99.56
	107	66.88	0.63	15.69	2.30	1.30	0.00	1.62	2.80	3.44	4.56	0.34	99.83
	191	67.78	0.39	15.90	1.90	1.21	0.00	1.06	2.11	3.71	4.74	0.34	99.32
	195a	65.99	0.72	15.67	2.36	1.53	0.00	1.68	2.77	3.10	5.01	0.39	99.52
	197	63.05	1.02	15.81	3.02	2.02	0.00	2.45	3.60	3.37	4.87	0.59	100.26
	198	64.94	0.81	15.90	2.71	1.86	0.00	2.10	3.48	3.50	4.19	0.47	100.27
	199	65.32	0.64	15.76	3.29	0.89	0.00	1.93	3.20	3.64	4.36	0.42	99.72
	201	68.33	0.53	14.68	1.44	1.57	0.00	1.35	2.51	3.49	4.44	0.36	98.87
	F661	68.59	0.52	14.29	0.69	2.78	0.06	0.87	2.30	3.35	4.80	0.22	98.75
En	81a	49.99	2.08	13.17	6.08	4.11	0.18	6.37	6.57	1.24	7.08	2.17	99.69
	117b	49.68	2.07	13.41	5.26	4.17	0.17	6.36	7.45	1.51	6.62	1.96	99.43
	157	50.23	1.90	12.02	4.22	5.02	0.14	7.65	9.85	1.59	4.99	1.98	100.49
	167	52.61	2.10	13.47	3.44	4.23	0.06	6.48	5.49	1.33	7.31	1.80	99.31

Major elements in wt% by XRF; FeO by titration; SrO and BaO included in the total. Representative samples: 120a, 114, 135.

enclaves is approximately 50 wt%; two of them are quartz normative while the other two are olivine normative. They are also of calc-alkaline affinity with 6.7 wt% MgO and a FeO_{tot}/MgO ratio of 1.3. Their mean K_2O content is 6.5 wt%. According to the classification of K-rich magmatic rocks (Rock 1984; Bergman 1987), these basic enclaves are chemically comparable to calc-alkaline lamprophyres.

Table 3. Trace elements of the augen gneisses.

Sample		Ni	Rb	Sr	Y	Zr	Nb	Ba	Pb	Weight
Z1	176	14	184	455	14	243	7	902	26	5.3
	204a	31	133	1014	25	307	10	1890	25	7.2
	206	48	137	1102	25	332	9	2047	25	9.5
	V66	12	111	513	59	284	10	1387	24	3.0
Z2	13a	21	126	988	17	240	5	1634	24	3.2
	18h	23	131	985	21	309	8	1641	23	1.1
	18k	18	135	897	17	298	6	1655	25	1.5
	18n	7	137	808	7	201	2	1825	28	0.7
	22	15	125	878	17	282	6	1842	25	2.4
	28	14	125	816	17	297	9	1647	26	1.5
	38a	25	128	874	19	252	7	1399	23	5.0
	51	30	101	945	27	308	9	1287	20	2.5
	109b	25	132	856	19	262	8	1169	23	32.1
	110	26	133	991	21	323	10	1565	25	33.8
	111	13	123	865	12	243	5	1522	25	13.1
	112	20	110	926	19	315	7	1635	25	19.3
	113a	16	116	603	14	191	3	637	23	10.9
	113c	26	101	859	19	269	7	1164	21	32.8
	114	24	116	919	17	256	7	1321	24	30.0
	116	33	109	1026	23	297	9	1640	21	27.4
	118	25	126	868	26	311	10	1346	22	14.8
	119	30	98	787	21	295	9	972	20	23.2
	120a	40	110	1008	32	364	15	1355	20	24.4
	127a	20	107	827	16	246	5	631	23	5.3
	135	9	146	346	10	151	1	557	30	10.2
	140a	47	80	1212	27	358	11	1516	18	6.7
	146	27	130	1001	20	306	9	1822	27	3.0
	147	36	137	1033	36	340	15	1817	25	4.4
	158	20	126	840	19	325	10	1577	26	4.6
	168	29	94	1240	29	319	10	1839	25	8.9
	169	19	131	1008	16	322	8	2018	26	6.8
	171	23	112	949	17	266	8	1400	22	10.2
	173	26	109	985	20	316	6	1778	23	7.5
	185	34	121	1076	25	359	12	1841	27	6.5
	D5	53	131	1105	39	351	12	2113	26	5.3
Z3	103	14	79	702	34	278	6	1134	21	9.2
	104	13	150	507	9	210	2	1090	25	2.8
	107	21	129	801	20	247	8	1570	28	4.0
	191	13	142	486	13	217	3	1123	25	13.4
	195a	26	147	851	38	273	12	1775	29	7.4
	197	39	100	1431	25	361	8	2604	32	7.2
	198	30	122	981	22	297	10	1710	26	13.0
	199	25	117	851	32	269	11	1539	24	14.3
	201	22	132	512	28	255	10	986	27	3.7
	P661	25	123	844	19	243	8	1629		
En	81a	103	264	1713	39	479	15	3980	31	<1
	117b	108	242	2389	36	389	15	4343	33	<1
	157	193	109	3735	43	52	14	4094	72	<1
	167	150	135	3314	36	154	16	5360	54	<1

Trace elements in ppm by XRF; weight: weight of sample in Kg.

LILE depletion

Selective depletion in LILE (Large Ion Lithophile Elements: K, Rb, Th, U . . .) has been well documented in many granulite terranes. K/Rb ratios greater than 500 are typically observed in depleted granulites (Heier & Thorensen 1971; Sighinolfi & Gorgoni 1978; Field et al. 1980; Rollinson & Windley 1980; Weaver & Tarney 1981). Several mechanisms leading to LILE depletion have been suggested (Lambert & Heier 1968; Sighinolfi & Gorgoni 1978; Wells 1979; Pride & Muecke 1980; Weaver & Tarney 1981; Janardhan et al. 1982; Lamb et al. 1986; Clemens

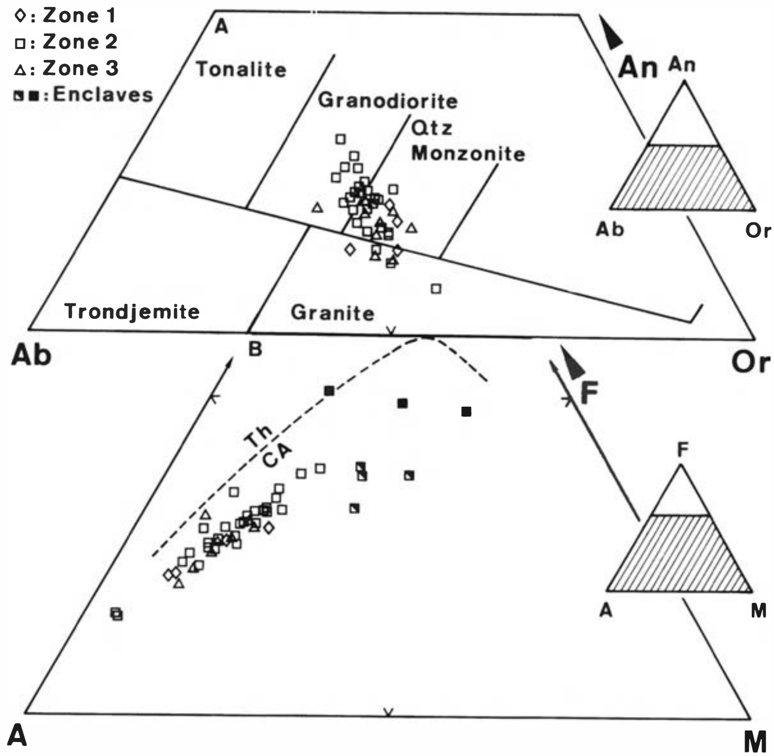

Fig. 4. Major element compositions of the augen gneisses of the three metamorphic zones and their enclaves (half-filled squares: enclaves of lamprophyric composition; filled squares: other enclaves. A. Normative Ab–An–Or diagram with field limits from O'Connor (1965). B. A.F.M. diagram (A = $Na_2O + K_2O$, F = FeO_{tot}, M = MgO). The augen gneisses display a calc-alkaline trend. Limit between tholeiitic (Th) and calc-alkaline (CA) series from Arth & Barker (1976).

& Vielzeuf 1987). LILE depletion is not always observed, however, as has been documented by Rollinson & Windley (1980), Barbey & Cuney (1982) and Iyer et al. (1984).

In the augen gneisses, the transition between amphibolite and granulite facies appears to be isochemical: there is no depletion in K_2O or Rb (Fig. 5) in the granulite facies rocks relative to their amphibolite facies equivalents. Moreover, the K/Rb ratio is quite constant throughout the whole series: 290 ± 170 (2σ) in zone 1; 290 ± 55 in zone 2 and 310 ± 80 in zone 3 (Fig. 7). The average value for all the samples is slightly higher (300 ± 74) than the mean crustal value defined by Shaw (1968) for magmatic rocks (K/Rb = 230).

Rollinson & Windley (1980) and Rudnick et al. (1985) point out the specific role of K-feldspar and biotite in the depletion process. If present, these minerals retain important amounts of K and Rb. As a result, K-rich granulites are generally not depleted and do not display very high K/Rb ratios. In the augen gneisses, biotite and K-feldspar are present in all samples. As shown in the next section, biotite is probably not involved in the pyroxene-forming reactions and it remains stable into the granulite facies.

In the augen gneisses which are K-enriched rocks, biotite and K-feldspar thus probably inhibited LILE depletion during granulite facies metamorphism (zone 3 relative to zones 1 and 2) in agreement with the observation of Rudnick et al. (1985).

Discussion: origin and evolution of the augen gneisses

Granodioritic precursors

There are three arguments showing that the augen gneisses are orthogneisses:

(1) In the central part of the Feda unit, the rock is almost undeformed; it has a typical porphyritic texture with idiomorphic K-feldspar phenocrysts.

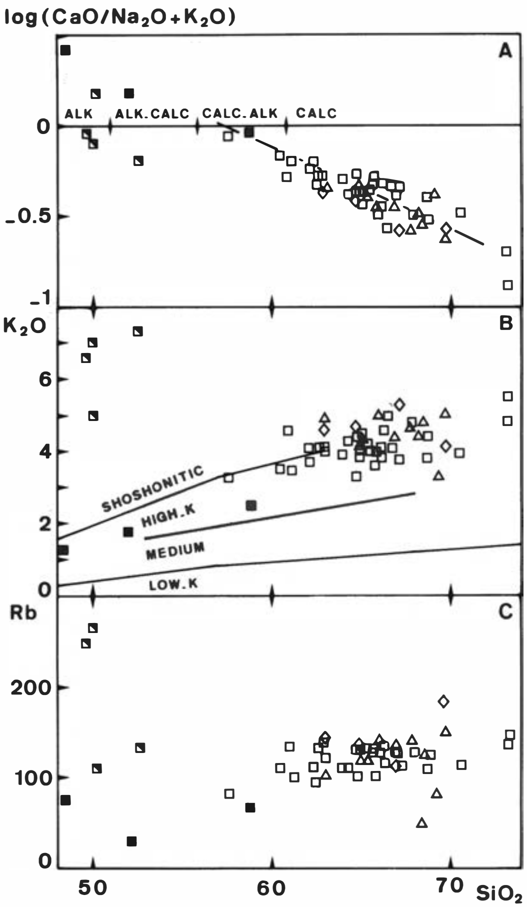

Fig. 5. SiO_2 variation diagrams. Symbols as in Fig. 4. □ A. Peacock (1931) diagram. The augen gneisses display a calc-alkaline trend. Alk: alkaline; Alk-Calc: alkali–calcic; Calc-Alk: calc-alkaline; Calc: calcic. □ B. K_2O–SiO_2 diagram. The augen gneisses belong to a K-rich calc-alkaline series following the classification of Peccerillo & Taylor (1976). □ C. Rb–SiO_2 diagram. The augen gneisses from the different zones define a single trend.

(2) K-feldspar megacrysts show oriented inclusions (mainly of plagioclase) which is commonly explained by a synneusis phenomenon occurring in a magmatic environment (Vance 1969; Dusel-Bacon & Aleinikoff 1985; Vernon 1986). Inclusions sometimes occur in concentric rims. Some of them are idiomorphic and most probably crystallized during a magmatic stage. K-feldspar megacrysts are thus phenocrysts.

The presence of amphibole and biotite inclusions shows that the augen gneisses initially crystallized as amphibole and biotite granodiorites.

(3) Geochemically, the different augen gneiss units define a magmatic high-K calc-alkaline trend implying that they represent a single magmatic episode of regional extent. They are associated with enclaves of calc-alkaline lamprophyric composition which represent magmatic enclaves (Vernon 1984); this is a classical association in calc-alkaline series (Rock 1984).

Thus the augen gneisses were emplaced as amphibole and biotite phenocryst-bearing granodiorites (magmatic precursors).

Deformation and metamorphism

The granodioritic precursors were metamorphosed and deformed into augen gneisses. The augen gneisses are concordant with regional structures. They were deformed in most places but left nearly intact in the central part of large, deformation resistant units. The boundary between the augen gneisses and the adjacent units is transitional.

Some features can also be interpreted as evidence of a syntectonic magmatic emplacement (Bouchez & Guineberteau 1984; Hibbard 1987): the elongated form of the units (up to 50 km long: Fig. 1; Falkum 1982) is typical of syntectonic granites; the irregular distribution of the deformation and its partial concentration in narrow zones occurs in partially solidified intrusions.

While the time relations between the magmatic emplacement and the deformation of the augen gneisses cannot be interpreted unequivocally (deformation during magmatic emplacement or later), the petrographic study clearly shows that the metamorphic event in lower amphibolite and granulite facies is prograde. It is superimposed on the magmatic precursor:

(1) in metamorphic zones 2 and 3 the pyroxenes clearly crystallized after the amphibole; they surround it as thin reaction rims or replace it so that they contain relic inclusions of amphibole;

(2) K-feldspar megacrysts never contain inclusions of pyroxene; pyroxenes are thus of metamorphic origin; their amphibole and biotite inclusions (sometimes idiomorphic) are relics of the magmatic stage;

(3) in zone 2, some K-feldspar megacrysts contain idiomorphic inclusions of sphene. This mineral is present in the groundmass of the augen gneisses in zone 1 but has not been observed in zones 2 and 3. This suggests that it was present during the magmatic stage in all occurrences but

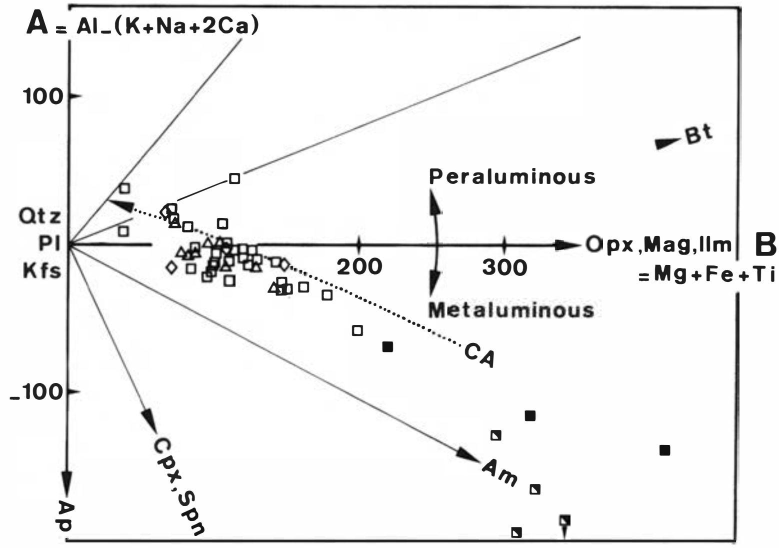

Fig. 6. A.B. diagram of Debon & Lefort (1983) (A = Al − (K + Na + 2Ca), B = Mg + Fe + Ti in gram-atoms 10^3). Symbols as in Fig. 4. The augen gneisses plot in the metaluminous domain along (or just below) the typical calc–alkaline trend. The positions (or the direction of the positions) of the minerals present in the augen gneisses are shown.

was destroyed during subsequent metamorphism of the groundmass in zones 2 and 3, only being preserved as inclusions in megacrysts.

The amphibolite–granulite metamorphic transition in the augen gneisses is characterized by the development of Cpx (zone 2) prior to Opx (zone 3). Sphene and allanite disappear between zones 1 and 2 where Cpx appears.

Pyroxene-forming reactions cannot be balanced simply; they are multivariant. Amphibole is a major reactant of these reactions: (1) it is often contained in pyroxenes and (2) pyroxenes appear only in granodioritic samples ($SiO_2 < 68\%$) where amphibole is present.

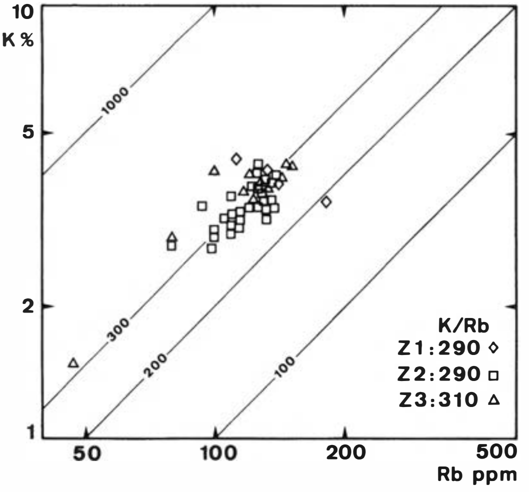

Fig. 7. K–Rb diagram. The average K/Rb values in the three metamorphic zones are given.

On the contrary, biotite is probably not an important reactant: (1) it is rarely observed included in pyroxenes; (2) in granitic samples ($SiO_2 > 68\%$), biotite is the only ferromagnesian mineral in the three metamorphic zones and pyroxenes do not appear in zones 2 and 3; (3) there is no important decrease in the modal abundance of biotite in granulite facies samples.

One stage amphibole breakdown reactions have classically been invoked to explain the transition between amphibolite and granulite facies metamorphic zones (De Waard 1965; Sen & Ray 1971; Wells 1979). On the contrary, in the experimental work of Spear (1981) on quartz-absent and quartz-bearing amphibole–plagioclase rocks, pyroxene-forming reactions proceed in two stages. With increasing temperature of metamorphism and at oxygen fugacities close to those of the FMQ buffer, Spear (1981) observed successively: (1) the disappearance of sphene, (2) the appearance of Cpx, (3) the appearance of Opx, and finally (4) the disappearance of amphibole. The stability field of sphene is enlarged under more oxidizing conditions; its temperature of disappearance is close to the clinopyroxene appearance temperature between the FMQ and HM buffers. Although, the starting material of this experimental work is not compositionally close to the augen gneisses, the two stage appearance of pyroxenes and the position of the disappearance of sphene match what is observed in the augen gneisses.

Conclusions

The augen gneisses of Rogaland–Vest-Agder were emplaced as K-feldspar phenocryst bearing amphibole and biotite granodiorites. They underwent amphibolite to granulite facies metamorphism after their emplacement. Two isograds (Cpx-in and Opx-in) define three metamorphic zones in the augen gneisses at the amphibolite–granulite facies transition, indicating a two-stage pyroxene-forming reaction. Amphibole is a major reactant in the pyroxene-forming process.

The augen gneisses define a K-rich calc-alkaline trend with marked enrichment in incompatible elements. They represent a magmatic event of regional extent. The metamorphism appears to be isochemical. The augen gneisses of the granulite facies are not depleted in Rb and K relative to their amphibolite facies equivalents. The presence of K-feldspar and biotite in the augen gneisses of the three metamorphic zones seems to inhibit LILE depletion.

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References

Arth, J. G. & Barker, F. 1976: Rare-earth partitioning between hornblende and dacitic liquid and implication for the genesis of trondhjemitic–tonalitic magmas. *Geology 4,* 534–536.

Barbey, P. & Cuney, M. 1982: K, Rb, Sr, Ba, U and Th geochemistry of the Lapland granulites (Fennoscandia). LILE fractionation controlling factors. *Contributions to Mineralogy and Petrology 81,* 304–316.

Barth, T. F. W. 1969: Granulite facies rocks of the Precambrian of South Norway, particularly around Arendal. *Sciences de la Terre 14,* 361–368.

Bergman, S. C. 1987: Lamproites and other potassium-rich igneous rocks: a review of their occurrence, mineralogy and geochemistry. *In* Fitton, J. & Upton, B. (eds.): *Alkaline Igneous Rocks. Geological Society Special Publication 30,* 103–190.

Bouchez, J.-L. & Guineberteau, B. 1984: Ecoulement dans les granitoïdes: de l'état visqueux à l'état solide. *In: Uranium et Granitoïdes.* CREGU, Nancy, 19 pp.

Clemens, J. D. & Vielzeuf, D. 1987: Constraints on melting and magma production in the crust. *Earth and Planetary Science Letters 86,* 287–306.

Debon, F. & Lefort, P. 1983: A chemical-mineralogical classification of common plutonic rocks and associations. *Transactions of the Royal Society of Edinburgh 73,* 135–149.

Demaiffe, D. & Michot, J. 1985: Isotope geochronology of the Proterozoic crustal segment of southern Norway: a review. *In* Tobi, A. C. & Touret, J. (eds.): *The Deep Proterozoic Crust in the North Atlantic Provinces. NATO Advanced Study Institute Series C158,* 411–434. Reidel.

De Waard, D. 1965: A proposed subdivision of the granulite facies. *American Journal of Science 263,* 455–461.

Dusel-Bacon, C. & Aleinikoff, J. N. 1985: Petrology and tectonic significance of augen gneiss from a belt of Mississipian granitoids in the Yukon–Tanana terrane, East–central Alaska. *Geological Society of America Bulletin 96,* 411–425.

Falkum, T. 1966: Structural and petrological investigations of the Precambrian metamorphic and igneous charnockite and migmatite complex in the Flekkefjord area, S. Norway. *Norges geologiske undersøkelse 242,* 19–25.

Falkum, T. 1972: Geological map of the Flekkefjord area, Vest-Agder, Southern Norway. 1/100000.

Falkum, T. 1982: Geologisk kart over Norge, berggrunnskart Mandal 1:250,000. *Norges geologiske undersøkelse.*

Falkum, T. 1985: Geotectonic evolution of southern Scandinavia in light of a late-Proterozoic plate collision. *In* Tobi, A. C. & Touret J. (eds.): *The Deep Proterozoic Crust in the North Atlantic Provinces. NATO Advanced Study Institute Series C158,* 309–322. Reidel.

Falkum, T. & Pedersen, S. 1979: Rb–Sr age determination on the Precambrian Homme granite and consequences for dating the last regional folding in the Flekkefjord region, S.W. Norway. *Norsk Geologisk Tidsskrift 59,* 59–65.

Falkum, T. & Petersen, J. 1980: The Sveconorwegian orogenic belt, a case of Late Proterozoic plate-collision. *Geologisch Rundschau 69,* 622–647.

Field, D., Drury, S. A. & Cooper, D. C. 1980: Rare-earth and LIL element fractionation in high-grade charnockitic gneisses, South Norway. *Lithos 13,* 281–289.

Gill, J. 1981: *Orogenic Andesites and Plate Tectonics.* Springer-Verlag. 390 pp.

Heier, K. & Thoresen, K. 1971: Geochemistry of high grade metamorphic rocks, Lofoten–Vesteraalen, North Norway. *Geochimica et Cosmochimica Acta 35,* 89–99.

Hermans, G. A., Tobi, A. C., Poorter, R. P. & Maijer, C. 1975: The high-grade metamorphic Precambrian of the Sirdal–Ørsdal area, Rogaland/Vest-Agder, Southwest Norway. *Norges geologiske undersøkelse 318,* 51–74.

Hibbard, M. J. 1987: Deformation of incompletely crystallized magma systems: granitic gneisses and their tectonic implications. *Journal of Geology 95,* 543–561.

Iyer, S. S., Choudhuri, A., Vasconcellos, M. B. A. & Cordani, U. G. 1984: Radioactive element distribution in the Archean granulite terrane of Jequié – Bahia, Brazil. *Contributions to Mineralogy and Petrology 85,* 95–101.

Janardhan, A. S., Newton, R. C. & Hansen, E. C. 1982: The transformation of amphibolite facies gneiss to charnockite in southern Karnataka and northern Tamil Nadu, India. *Contributions to Mineralogy and Petrology 79,* 130–149.

Jansen, B., Blok, R., Bos, A. & Scheelings, M. 1985: Geothermometry and geobarometry in Rogaland and preliminary results from the Bamble area, South Norway. *In* Tobi, A. C. & Touret, J. (eds.): *The Deep Proterozoic Crust in the North Atlantic Provinces. NATO Advanced Study Institute Series C158,* 499–517. Reidel.

Kretz, R. 1983: Symbols for rock-forming minerals. *American Mineralogist 68,* 277–279.

Lamb, R. C., Smalley, P. C. & Field, D. 1986: P–T conditions for the Arendal granulites, southern Norway: implications for the roles of P, T and CO2 in deep crustal LILE-depletion. *Journal of Metamorphic Geology 4,* 143–160.

Lambert, I. B. & Heier, K. S. 1968: Geochemical investigations of deep-seated rocks in the Australian shield. *Lithos 1,* 30–53.

Maijer, C., Andriessen, P., Hebeda, E., Jansen, J. & Verschuren, R. 1981: Osumilite, an approximately 970 Ma old high-temperature index mineral of the granulite-facies metamorphism in Rogaland, S.W. Norway. *Geologie en Mijnbouw 60,* 267–272.

Michot, P. 1960: La géologie de la catazone: le problème des anorthosites, la palingenèse basique et la tectonique catazonale dans le Rogaland méridional, (Norvège). *International Geological Congress*, Oslo 1960, guide to excursion A 9, 60 pp.

O'Connor, J. T. 1965: A classification for quartz-rich igneous rocks based on feldspar ratios. *U.S. Geological Survey Professional Paper 525b,* 79–84.

Pasteels, P., Demaiffe, D. & Michot J. 1979: U–Pb and Rb–Sr geochronology of the eastern part of the South Rogaland igneous complex, southern Norway. *Lithos 12,* 199–208.

Pasteels, P. & Michot, J. 1975: Geochronologic investigation of the metamorphic terrain of southwestern Norway. *Norsk Geologisk Tidsskrift 55,* 111–134.

Peacock, M. A. 1931: Classification of igneous rock series. *Journal of Geology 39,* 54–67.

Peccerillo, A. & Taylor, S. R. 1976: Geochemistry of eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey. *Contributions to Mineralogy and Petrology 58,* 63–81.

Pedersen, S. 1980: Rb/Sr age determination on late Proterozoic granitoids from the Evje area, South Norway. *Bulletin of the Geological Society of Denmark 29,* 129–143.

Petersen, J. S. 1977: The migmatite complex near Lyngdal (S. Norway), and related granulite metamorphism. *Norsk Geologisk Tidsskrift 57,* 65–84.

Pride, C. & Muecke, G. K. 1980: Rare earth element geochemistry of the scourian complex N.W. Scotland: evidence for the granite–granulite link. *Contributions to Mineralogy and Petrology 73,* 403–412.

Rock, N. M. S. 1984: Nature and origin of calc–alkaline lamprophyres: minettes, vogesites, kersantites and spessartites. *Transactions of the Royal Society of Edinburgh 74,* 193–227.

Rollinson, H. R. & Windley, B. F. 1980: Selective elemental depletion during metamorphism of Archean granulites, Scourie, NW Scotland. *Contributions to Mineralogy and Petrology 72,* 257–263.

Rudnick, R. L., McLennan, S. M. & Taylor, S. R. 1985: Large ion lithophile elements in rocks from high-pressure granulite facies terrains. *Geochimica et Cosmochimica Acta 49,* 1645–1655.

Sen, S. K. & Ray, S. 1971: Breakdown reactions for natural hornblendes in granulite facies. *Neues Jahrbuch für Mineralogie Abhandlungen 114,* 301–319.

Shaw, D. M. 1968: A review of K–Rb fractionation trends by covariance analysis. *Geochimica et Cosmochimica Acta 32,* 573–601.

Sheraton, J. W. 1984: Chemical changes associated with high-grade metamorphism of mafic rocks in the East Antarctic shield. *Chemical Geology 47,* 135–157.

Sighinolfi, G. P. & Gorgoni, C. 1978: Chemical evolution of high-grade metamorphic rocks – Anatexis and remotion of material from granulite terrains. *Chemical Geology 22,* 157–176.

Spear, F. S. 1981: An experimental study of hornblende stability and compositional variability in amphibolite. *American Journal of Science 281,* 697–734.

Tobi, A. C. 1965: Fieldwork in the charnockitic Precambrian of Rogaland (SW Norway). *Geologie en Mijnbouw 44,* 208–217.

Tobi, A. C., Hermans, G., Maijer, C. & Jansen, B. 1985: Metamorphic zoning in the high-grade Proterozoic of Rogaland–Vest Agder, S.W. Norway. *In* Tobi, A. C. & Touret, J. (eds.): *The Deep Proterozoic Crust in the North Atlantic Provinces. NATO Advanced Study Institute Series C158,* 477–499. Reidel.

Touret, J. 1971a: Le faciès granulite en Norvège méridionale. Les associations minéralogiques. *Lithos 4,* 239–249.

Touret, J. 1971b: Le faciès granulite en Norvège méridionale. Les inclusions fluides. *Lithos 4,* 423–436.

Vance, J. A. 1969: On synneusis. *Contributions to Mineralogy and Petrology 24,* 7–29.

Vernon, R. H. 1984: Microgranitoid enclaves in granites – globules of hybrid magma quenched in a plutonic environment. *Nature 309,* 438–439.

Vernon, R. H. 1986: K-feldspar megacrysts in granites–phenocrysts, not porphyroblasts. *Earth Science Reviews 23,* 1–63.

Weaver, B. L. & Tarney, J. 1981: Lewisian gneiss geochemistry and Archaean crustal development models. *Earth and Planetary Science Letters 55,* 171–180.

Wells, P. R. 1979: Chemical and thermal evolution of Archean sialic crust, Southern West Greenland. *Journal of Petrology 20,* 187–226.

Wielen, J., Andriessen, P., Boelrijk, N., Hebeda, E., Priem, H., Verdurmen, E. & Verschure, R. 1981: Isotope geochronology in the high-grade metamorphic precambrian of Southwestern Norway: new data and reinterpretations. *Norges geologiske undersøkelse 359,* 1–30.

Wilmart, E. & Duchesne, J. C. 1987: Geothermobarometry of igneous and metamorphic rocks around the Ana-Sira massif: implications for the depth of emplacement of the South Norwegian anorthosites. *Norsk Geologisk Tidsskrift 67,* 185–196.

Wilson, R., Pedersen, S., Berthelsen, C. R. & Jakobsen, B. M. 1977: New light on the Precambrian Holum granite, South Norway. *Norsk Geologisk Tidsskrift 57,* 348–360.

Appendix

Symbols for minerals (Kretz 1983): Aln: allanite; Am: amphibole; Ap: apatite; Bt: biotite; Cpx: clinopyroxene; Grt: garnet; Ilm: ilmenite; Kfs: K-feldspar; Mag: magnetite; Mnz: monazite; Ol: olivine; Opx: orthopyroxene; Pl: plagioclase; Py: pyrite; Qtz: quartz; Spn: sphene; Tho: thorite; Zrn: zircon.