

Evolution of feldspars at the amphibolite-granulite-facies transition in augen gneisses (SW Norway): geochemistry and Sr isotopes

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Abstract. The Sveconorwegian Augen Orthogneisses of Rogaland – Vest-Agder (SW Norway) were emplaced as amphibole- and biotite-bearing granodiorites at 1040 Ma (concordant Rb/Sr and zircon U/Pb ages). They underwent prograde metamorphism which increased from lower amphibolite-facies in the eastern zone to granulite-facies in the western zone, close to the Rogaland anorthosite complex. K-feldspar megacrysts initially crystallised as phenocrysts and were chemically equilibrated during metamorphism, as shown by the flat Ba concentration profiles and the increase of the anorthite content from An_{1.1} in the amphibolite-facies to An_{2.6} in the granulite-facies. This increase of the An content suggests an increase in metamorphic temperature. The REE content of the megacrysts is related to the associated accessory minerals which depend upon the metamorphic grade: sphene + allanite + apatite + zircon and rarely thorite in amphibolite-facies, and apatite + zircon + monazite ± thorite in lower amphibolite- and granulite-facies. Amphibole and biotite inclusions in megacrysts were also equilibrated during metamorphism. Groundmass K-feldspar and plagioclase experienced late-metamorphic changes during uplift. An internal Rb/Sr mineral isochron (plagioclase, apatite, K-feldspar) defines an age of 870 Ma, which represents the closure of the Rb/Sr isotopic system in minerals of the augen gneisses. This age also represents a K-feldspar cooling age in regionally distributed augen gneiss samples. The K-feldspar cooling age appears to be similar to or slightly older than the biotite cooling age.

Norway (Fig. 1), Smithson (1965, p. 66) concluded that it is "... inescapable that the K-feldspar megacrysts enclosing oriented plagioclase grains in the augen gneisses are, in reality, porphyroblasts." However, more recent studies indicate that most augen gneisses are orthogneisses, and that the augen are K-feldspar phenocrysts which have been deformed and chemically equilibrated during metamorphism (Vidal et al. 1980; Harvey 1983; Dusel-Bacon and Aleinikoff 1985; Mehnert and Büsch 1985; Vernon 1986).

The Sveconorwegian Augen Gneisses (distinguished in this text by capitalisation) of the Vest-Agder province of SW Norway (AuGn, Fig. 1) are re-examined here. The two main stages of their history are considered, namely the emplacement of the magmatic precursors and the subsequent metamorphic overprinting. The Augen Gneisses cross the amphibolite-granulite-facies transition and provide an opportunity to study the evolution of mineral chemistry at this transition in a homogeneous rock type. The major and trace element evolution of the feldspars is presented here.

Compositional variations of feldspars have been successfully used to trace the variation of peak-metamorphism temperatures in granulite-facies terranes (Bohlen and Essene 1977). Nevertheless, it has been shown that many granulite-facies feldspar pairs do not represent equilibrium compositions and that they often suffered changes after peak-metamorphism (Brown and Parsons 1981, 1985; Mora and Valley 1985; Fuhrman and Lindsley 1988). In this respect, the augen gneisses are of special interest because they contain two generations of feldspars: megacrysts and groundmass.

Rb/Sr whole-rock and mineral isochrons of the Augen Gneisses have been determined to provide constraints on the closure of the Rb/Sr isotopic system in K-feldspar.

Metamorphic zoning in the Augen Gneisses of Rogaland – Vest-Agder

The Augen Gneisses constitute one of the three major folded lithological units of the Sveconorwegian metamorphic belt in Vest-

Introduction

The K-feldspar (Kfs) megacrysts of augen gneisses have long been considered as porphyroblasts of metamorphic origin (Smithson 1965; Touret 1967a, b). From his petrographic study of the Mandal augen gneisses of SW

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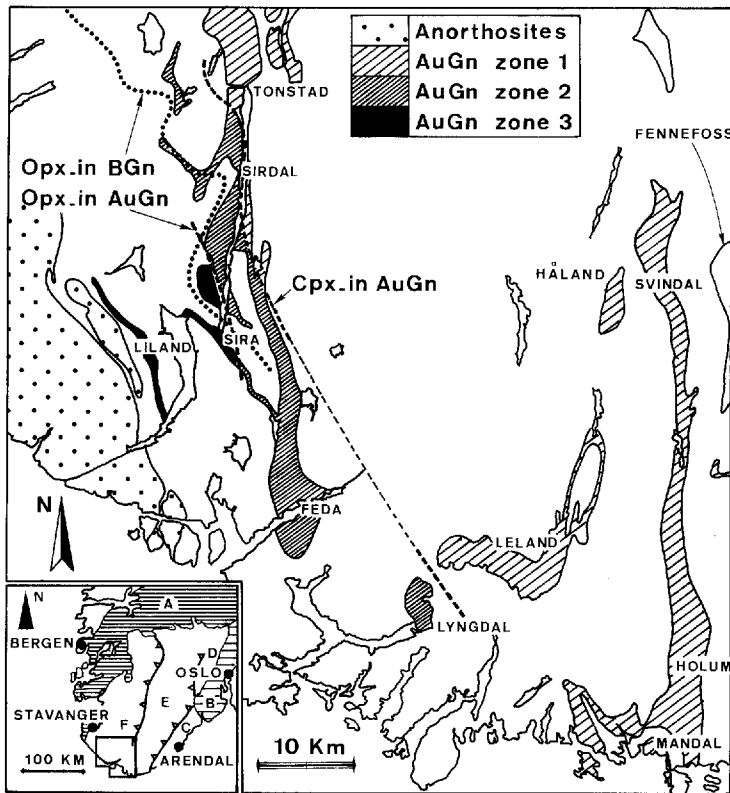


Fig. 1. Sketch map showing the different Augen Gneiss units (*AuGn*, Falkum 1982) as well as the approximate limits of the three metamorphic zones in the Augen Gneisses. *Zone 1*, Bt ± Am; *zone 2*, Bt ± Am ± Cpx; *zone 3*, Bt ± Am ± Cpx ± Opx in granulite-facies. *Opx-in BGn*, *Opx-in* isograd in banded gneisses (Hermans et al. 1975); *Opx-in AuGn*, *Cpx-in AuGn*, *Opx-in* and *Cpx-in* isograds in Augen Gneisses. *Inset*: A, Caledonian orogenic area; B, Oslo graben; C, Bamble sector; D, Kongsberg sector; E, Telemark sector; F, Rogaland – Vest-Agder sector

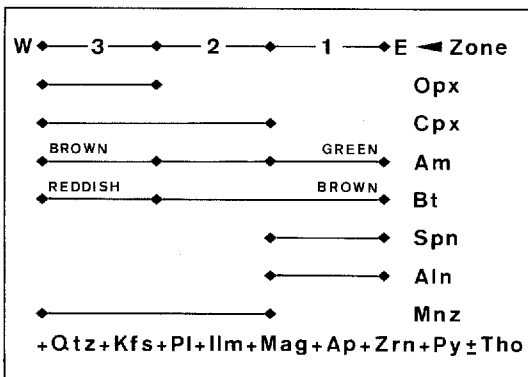


Fig. 2. Summary of the Augen Gneiss mineral associations in the three metamorphic zones. *Abbreviations* for minerals: see Appendix. Qtz, Kfs, Pl, Bt, Ilm, Mag, Ap, Zrn and Py are present in all samples while Opx, Cpx, Am, Spn, Aln and Mnz are present only in some samples of appropriate composition in the corresponding zone. Tho (thorite) is present in trace amounts in some samples

Agder and Rogaland (SW Norway, Fig. 1). The other units are granitic gneisses, and banded gneisses that are often migmatitic and in some places of clearly metasedimentary origin (Falkum 1966, 1982, 1985; Falkum and Petersen 1980). The Rogaland anorthosite complex (Michot 1960; Michot and Michot 1969) occurs at the western extremity of the province. Metamorphic grade increases westwards reaching granulite-facies in the vicinity (10–20 km) of the anorthosite complex. The amphibolite-granulite-facies transition has been mapped at a regional scale by Tobi (1965) and Hermans et al. (1975) on the basis of the appearance of orthopyroxene in banded gneisses (*Opx-in* BGn isograd, Fig. 1). Within the granulite-facies domain, the osumilite-in and pigeonite-in

isograds were retraced by Maijer et al. (1981) and Tobi et al. (1985). These observations underscored the westward increase of metamorphic grade (Jansen et al. 1985).

Between Mandal to the East and the Rogaland anorthosite complex to the West (Fig. 1), the Augen Gneisses outcrop as elongated bodies concordant with the regional structures. On the basis of ferromagnesian mineral associations, three metamorphic zones separated by two isograds can be delineated in the Augen Gneisses (Fig. 2; Bingen 1989). The easternmost zone (zone 1) is characterised by the association Bt + Am (abbreviations for minerals: see appendix). In zone 2, to the West of the *Cpx-in* isograd, Bt + Am + Cpx associations occur, although the Bt + Am association without Cpx still persists. The Bt ± Am ± Cpx + Opx association characterises the granulite-facies Augen Gneisses to the West of the *Opx-in* isograd. The Bt + Am + Cpx and more rarely the Bt + Am associations can still be found in the granulite-facies. The *Opx-in* isograd in the Augen Gneisses is in good agreement with the one mapped in the banded gneisses (Hermans et al. 1975). In the most quartzofeldspathic varieties of Augen Gneisses, biotite is the only ferromagnesian mineral, irrespective of metamorphic zone. Quartz, plagioclase, K-feldspar and biotite are present in all samples. Ubiquitous minor phases are magnetite, ilmenite (with abundant hematite exsolution lamellae), apatite, zircon and pyrite. Biotite is brown in zone 1 and reddish-brown in zone 3; amphibole, of the hornblende type, is green in zone 1 and brown in zone 3 (Dekker 1978). In zone 1, accessory sphene and allanite are common.

Heavy minerals have been separated from ten samples. An electron microprobe examination of zircon fractions shows that monazite occurs in trace amounts (less than 1% of zircon fractions) in all the samples of zones 2 and 3. It is absent in samples of zone 1 where allanite is present in most samples. Trace amounts of thorite are also present in all samples of zones 3, in most samples of zone 2 and in one sample of zone 1.

Three generations of K-feldspar are present in the Augen Gneisses: (1) *mm-sized K-feldspar* of the groundmass, microcline in zone 1 and orthoclase in zones 2 and 3; (2) *medium-sized (1 mm–1 cm) K-feldspar* of the pressure-shadow deformation zones of the

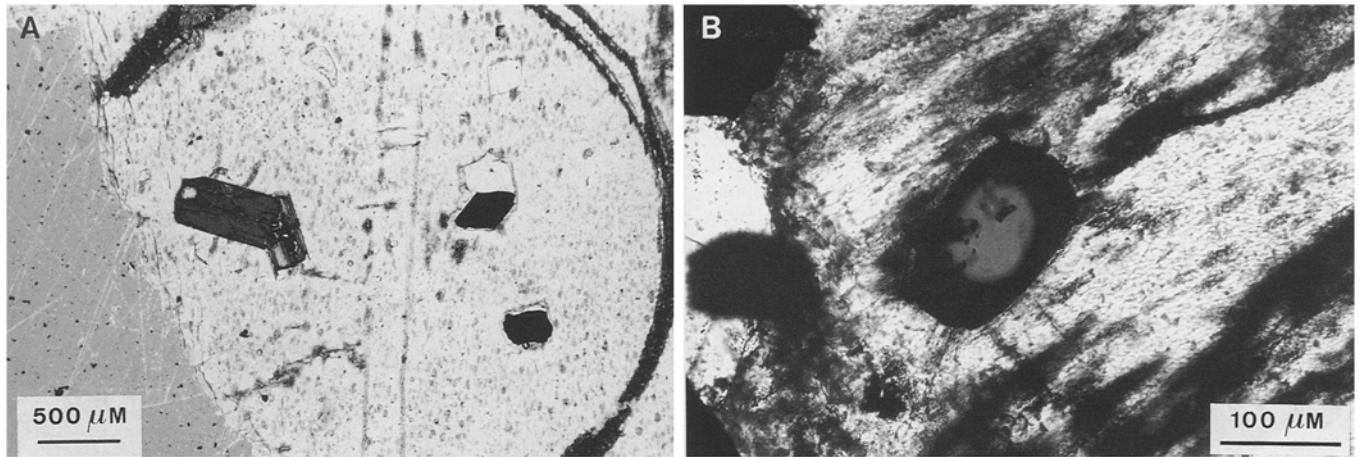


Fig. 3 A, B. Photomicrographs of inclusions in K-feldspar megacrysts. Euhedral inclusions of **A** amphibole, biotite and magnetite

(from left to right); **B** Sphene in sample 379a (zone 2). Sphene is absent from the groundmass of this sample

Table 1. Sample locations and minor mineral contents

Sample	Z	Unit	X	Y	SiO ₂	Opx	Cpx	Am	Spn	Aln	Mnz	Tho
1a	2	Feda	3	70.8	64	62.1	—	+	+	—	—	—
13a	2	Feda	3	73.3	64	60.1	66.8	—	+	+	—	—
18d	2	Feda	3	70.4	64	61.6	—	—	+	—	—	—
28	2	Feda	3	69.5	64	60.9	66.6	—	—	+	s	—
63b	2	Feda	3	70.6	64	54.9	—	—	+	—	—	—
66	1	Håland	4	07.3	64	82.1	67.1	—	—	+	+	—
80b	2	Feda	3	71.6	64	57.2	—	—	+	—	—	—
104	3	Liland	3	55.4	64	77.5	69.8	—	—	—	—	+
107	3	Liland	3	57.0	64	71.8	66.9	+	+	—	—	+
109b	2	Feda	3	70.5	64	61.6	65.1	—	—	+	—	—
111	2	Feda	3	70.2	64	61.6	68.8	—	—	+	—	—
112	2	Feda	3	69.5	64	60.9	64.3	—	—	+	—	—
113c	2	Feda	3	70.8	64	62.1	65.8	—	—	+	—	+
114	2	Feda	3	72.1	64	62.2	66.3	—	—	+	—	+
117b	2	Feda	3	71.4	64	57.3	49.7	—	—	+	—	—
119	2	Feda	3	73.4	64	58.1	64.8	—	—	+	—	—
120a	2	Feda	3	71.0	64	71.7	60.5	—	—	+	—	—
135	2	Feda	3	71.8	64	62.8	73.4	—	—	—	—	—
140a	2	Feda	3	71.5	64	62.8	57.6	—	—	+	—	—
168	2	Feda	3	71.1	64	70.1	62.4	—	—	+	—	—
169	2	Feda	3	72.2	64	70.6	66.1	—	—	+	—	—
171	2	Feda	3	73.4	64	60.4	67.3	—	—	+	—	—
172	2	Feda	3	72.3	64	62.2	—	—	+	—	—	—
179	1	Tonstad	3	68.2	65	09.2	64.1	—	—	+	+	+
185	2	Sirdal	3	65.5	64	93.2	62.9	—	—	+	s	—
189	3	Liland	3	53.8	64	79.9	—	+	+	—	—	—
190a	3	Liland	3	51.6	64	83.1	—	+	+	—	—	—
191	3	Liland	3	51.6	64	83.0	67.8	—	—	—	—	—
195a	3	Liland	3	56.9	64	71.1	66.0	—	—	+	—	—
198	3	Sira	3	62.6	64	79.1	64.9	+	+	—	—	+
204a	1	Mandal	4	15.2	64	35.0	64.7	—	—	+	+	—
206	1	Holum	4	13.2	64	40.6	63.0	—	—	+	+	—
379	2	Feda	3	72.4	64	61.8	—	—	+	—	—	—
D5	2	Lyngdal	3	86.0	64	50.7	61.0	—	—	+	—	—
D6575	3	Liland	3	55.6	64	77.6	68.5	—	—	—	—	—
Pa66L	3	Liland	3	56.1	64	76.5	68.6	—	—	—	—	—

Z, Metamorphic zone; X and Y, grid coordinates of the 1/50000 ordnance map; SiO₂ (wt%), other oxides from Bingen (1989); symbols for minerals: see Appendix; +, present; —, absent; s, secondary; blank (for Mnz and Tho), accessory minerals not separated. Qtz, Kfs, Pl, Ilm, Mag, Ap, Zrn and Py are present in all samples; trace amounts of fluorite are in sample 206; minor amounts of secondary Ep, Cal, Chl are in most samples. Samples 111 and 135 rarely contain phenocrysts; sample 117b is a basic enclave of lamprophyric composition

megacrysts; (3) *the megacrysts* (3–15 cm), generally orthoclase in all three zones, though occasionally microcline in zone 1.

The K-feldspars are micropertthitic with perthite, being coarser and more abundant in the megacrysts and the K-feldspar of the shadow zones than of the groundmass. The megacrysts are not zoned optically. They often show simple Carlsbad twinning, the composition plane being visible in hand specimen; under the microscope, the composition plane is a sinuous rather than a planar surface. The contact between the megacrysts and the groundmass is also sinuous and often outlined by a fringe of myrmekite.

The megacrysts contain numerous inclusions of plagioclase, quartz, biotite, amphibole, magnetite and ilmenite in decreasing order of abundance. Accessory apatite, zircon, sphene and allanite are also present as inclusions. In zone 2, sphene and allanite inclusions are observed in K-feldspar megacrysts, whereas they are absent in the groundmass (Fig. 2). Plagioclase and biotite inclusions are often orientated parallel to the crystallographic planes of the host megacryst and are sometimes arranged in concentric zones. Plagioclase inclusions are often in optical continuity. Where in direct contact with the plagioclase inclusions, the micropertthitic texture of the K-feldspar megacrysts is less apparent (narrow zone, 500 μm –1 mm). Inclusions of amphibole, biotite, apatite, zircon and sphene are sometimes euhedral (Fig. 3).

The mineral content of the samples in this study is summarized in Table 1.

Geological history of the Augen Gneisses

Granodioritic precursor

In the extreme central part of the Feda unit (zone 2), the rocks are almost undeformed and exhibit a typically porphyritic texture of magmatic origin. Chemically, the Augen Gneisses are granodioritic to granitic in composition; they define a high-K calc-alkaline trend (Bingen 1989). The different units recognised in the field define a single trend, implying that they represent a single magmatic episode of regional extent. They contain a few K-rich basic enclaves of calc-alkaline lamprophyric composition (Bingen 1989), a classic association in calc-alkaline series (Rock 1984).

Petrographic and field observations show that the K-feldspar megacrysts initially crystallised as phenocrysts: (1) they display simple Carlsbad twinning; (2) they are more abundant in granodioritic varieties than in SiO_2 -rich granitic ones, which shows that their repartition is correlated to the magmatic facies; (3) plagioclase and biotite inclusions are often orientated parallel to crystallographic planes, a feature which is commonly explained by synneusis occurring in the magma (Vance 1969); (4) some biotite, amphibole, zircon, apatite and sphene inclusions have euhedral shapes which show that they crystallised and grew in a magma together with the K-feldspar megacrysts and were incorporated at this stage (Vernon 1986; Flood and Vernon 1988).

There is thus good evidence that the Augen Gneisses were emplaced as phenocryst-bearing granodiorites. The presence of amphibole and biotite inclusions in the megacrysts indicates that the rocks were originally amphibole and biotite bearing.

New Rb/Sr isotopic data were obtained on Augen Gneiss samples from the three metamorphic zones (Table 2). In spite of the small range of $^{87}\text{Rb}/^{86}\text{Sr}$ ratios

Table 2. Rb-Sr isotopic data

Sample		Rb	Sr	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr} \pm 2\sigma$	
13a	WR	126	988	0.3690	0.70894	0.00002 ^a
13a	Gr	106	933	0.3287	0.70851	0.00002 ^a
13a	Kfs	302	1475	0.5926	0.71177	0.00002
13a	KfsGr	326	1909	0.4942	0.71033	0.00002
104	Gr	120	477	0.7284	0.71502	0.00002
					0.71507	0.00002
104	Kfs	344	755	1.3201	0.72227	0.00004
104	KfsGr	359	863	1.2051	0.72045	0.00003
107	WR	127	796	0.4618	0.71081	0.00003
107	Kfs	312	1148	0.7869	0.71477	0.00002
111	WR	121	857	0.4086	0.70965	0.00003 ^a
113c	WR	101	859	0.3402	0.70884	0.00004 ^a
113c	Gr	87	821	0.3066	0.70815	0.00004 ^a
113c	Kfs	284	1349	0.6094	0.71187	0.00015
113c	KfsGr	296	1716	0.4992	0.71044	0.00004
113c	Pl	9	795	0.0327	0.70481	0.00005
113c	Ap	17	645	0.0762	0.70524	0.00004
117b	Kfs	272	5560	0.1415	0.70561	0.00002
117b	Ap	36	2120	0.0491	0.70447	0.00003
120a	WR	110	1008	0.3157	0.70828	0.00002 ^a
120a	Gr	109	930	0.3391	0.70840	0.00003 ^a
120a	Kfs	249	1548	0.4655	0.71007	0.00003
135	Gr	143	369	1.1226	0.72046	0.00004 ^a
135	Kfs	290	461	1.8239	0.72906	0.00003
140a	WR	82	1215	0.1952	0.70662	0.00003 ^a
140a	Ap	16	893	0.0518	0.70474	0.00002
179	Gr	156	741	0.6094	0.71275	0.00003 ^a
179	Kfs	488	1067	1.3251	0.72200	0.00003
191	WR	141	481	0.8490	0.71794	0.00025
					0.71796	0.00002
198	WR	125	991	0.3650	0.70909	0.00002 ^a
198	Kfs	350	1451	0.6983	0.71322	0.00003
204a	WR	133	1014	0.3795	0.70907	0.00007 ^a
206	WR	136	1092	0.3604	0.70905	0.00002 ^a
206	Kfs	283	1645	0.4979	0.71039	0.00003
Pa66L	WR	123	844	0.4217	0.71002	0.00015
D6575	WR	46	451	0.2965	0.71059	0.00006

WR, Whole rock; Gr, groundmass; Kfs, K-feldspar megacryst; KfsGr, groundmass K-feldspar; Ap, apatite; Pl, plagioclase + quartz

^a Data used for the 1040 Ma isochron (Fig. 4); Rb and Sr in ppm by XRF

(<1.2) due to the high Sr contents (900 ppm on average), whole-rock and groundmass values for the Augen Gneisses from Sira (zone 3), Feda (zone 2) and Tonstad and Mandal (zone 1) appear to define a good isochron (13 points; MSWD=1; Fig. 4). This isochron gives an age of 1040 ± 44 Ma (2σ) and a Sr isotopic initial ratio (I_{Sr}) of 0.7036 ± 2 . A Rb/Sr whole-rock isochron (7 samples) on the Fennefoss Augen Gneiss (West Telemark, Fig. 1) yielded a similar age of 1035 ± 65 Ma (2σ) (Pedersen 1980).

Two main arguments indicate that the 1040 Ma event represents the age of the magmatic emplacement of the granodiorite precursors of the Augen Gneisses:—

1. Samples from the different units, situated in the three metamorphic zones, fall on the same isochron. The distance between the Mandal and Sira units is greater than 50 km. A metamorphic isotopic re-homogenisation on such a large scale seems unrealistic.

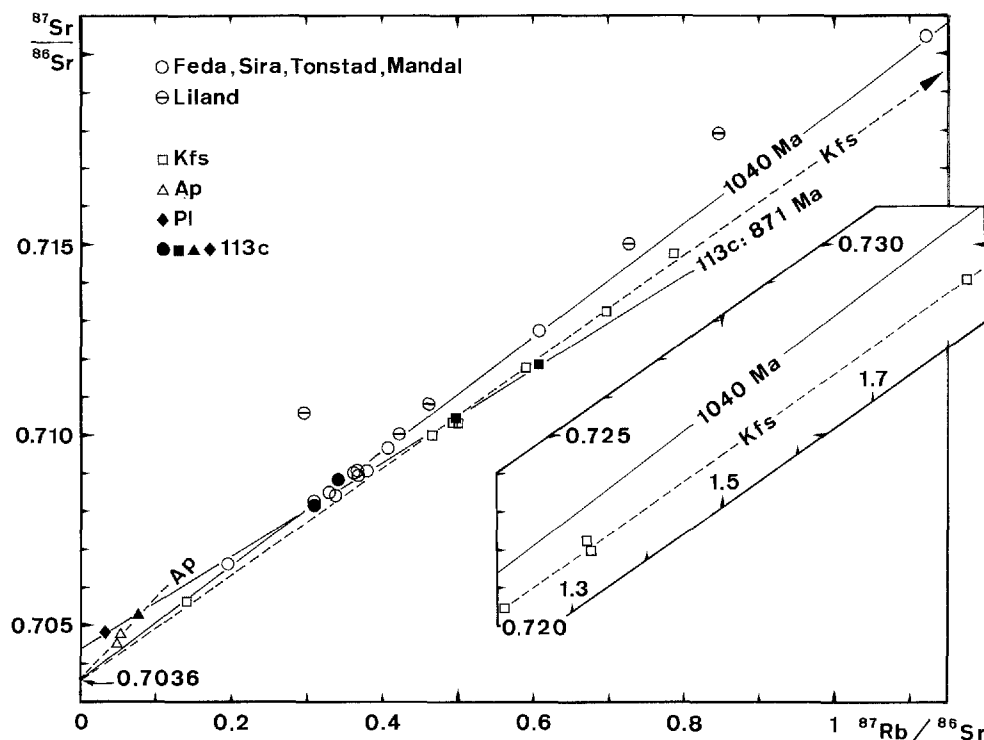


Fig. 4. $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{87}\text{Rb}/^{86}\text{Sr}$ diagram. The samples of Fedra, Sira, Tonstad, Mandal Augen Gneisses (zones 1, 2, 3) define an isochron of 1040 ± 44 Ma (2σ , MSWD=1, with $I_{\text{Sr}}=0.7036$). The three samples of Liland Augen Gneiss from near the anorthosite contact (<2 km) plot above the isochron. The minerals of sample 113c (Fedra) define an 871 ± 35 Ma (2σ) internal isochron. The K-feldspars of all samples define a linear array (explanation: see text and Fig. 13)

Indeed, Versteve (1975) and Wielens et al. (1981) have shown that the banded gneisses of the same area, which are clearly older than 1100 Ma (Menuge 1988), only locally achieved metamorphic homogeneity. The regional data on banded gneisses scatter on an isochron plot. Furthermore, the development of a regional homogeneity would certainly have increased the Sr isotopic ratio of the Augen Gneisses by the addition of more radiogenic Sr from the surrounding banded gneisses [average $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 150 banded gneisses at 1040 Ma is 0.720: data of Versteve (1975), Pasteels and Michot (1975), Wielens et al. (1981) and D. Demaiffe (unpublished)]. On the contrary, magmatic rocks are often isotopically homogeneous on a large scale. The low I_{Sr} (0.7036) deduced from the Augen Gneisses isochron is most probably a primary magmatic value; it is, moreover, close to the "undepleted" mantle value at 1040 Ma.

2. The Rb/Sr age is concordant with published zircon U/Pb ages. Zircon concentrates from four samples provided U/Pb discordia upper intercepts (Pasteels and Michot 1975; Wielens et al. 1981): zone 1 in Tonstad: $1030 \pm 45 - 40$ Ma (8 zircon fractions); zone 2 in Sirdal and Fedra: $1030 \pm 35 - 30$ Ma (4 fractions) and $1045 \pm 30 - 25$ Ma (6 fractions); zone 3 in Liland: $1017 \pm 26 - 24$ Ma (2 fractions). Zircon is a refractory mineral that generally loses only part of its radiogenic lead during amphibolite to granulite-facies metamorphism (Lancelot and Allegret 1982; Black et al. 1986; Schärer et al. 1986): the presence of well-defined upper intercepts at 1030–1040 Ma in several Augen Gneiss samples thus points to a magmatic event.

Deformation

The Augen Gneisses occur as elongate bodies (up to 50 km long, Fig. 1; Falkum 1982) concordant with regional structures. Nevertheless, the large unit of Fedra is nearly undeformed in its central sections. The penetrative deformation seems partially concentrated in thin zones of metric to decametric thickness. The contact between the Augen Gneisses and the adjacent units is gradational.

The Augen Gneisses can be considered to have been a pre-(or early)tectonic intrusion, deformed in most places but undeformed

in the centre. However, some features of the Augen Gneisses can also be interpreted in terms of syntectonic magmatic emplacement. Indeed, Hibbard (1987) showed that syntectonic granitoids outcrop as elongate concordant units guided by regional deformation, while Bouchez and Guineberteau (1984) pointed out that deformation in a partially crystallised granite may be irregularly distributed and concentrated in planar shear zones.

Metamorphism

The metamorphic overprinting (lower amphibolite- to granulite-facies) was a prograde event on the granodioritic precursors of the Augen Gneisses. This is shown by two petrographic observations: –

1. In metamorphic zones 2 and 3, the pyroxenes often contain amphibole inclusions or occur as rims to amphiboles; the pyroxene clearly crystallized after the amphibole. Pyroxene inclusions have not been observed in K-feldspar megacrysts of any zone. The pyroxenes are thus clearly of metamorphic origin, whereas amphibole and biotite belong to the magmatic association. Amphibole is interpreted as a major reactant in the pyroxene-forming reactions.

2. In zone 2, sphene and allanite are absent from the groundmass of the Augen Gneisses but occasionally appear as inclusions in megacrysts. The euhedral shape of some sphene inclusions (Fig. 3) suggests that sphene was ubiquitous during the magmatic stage but disappeared during the subsequent prograde metamorphism in zones 2 and 3, except where it was sheltered as inclusions in the megacrysts.

The Augen Gneisses of the three metamorphic zones define a single trend in binary and ternary chemical diagrams (Bingen 1989). Granulite-facies Augen Gneisses

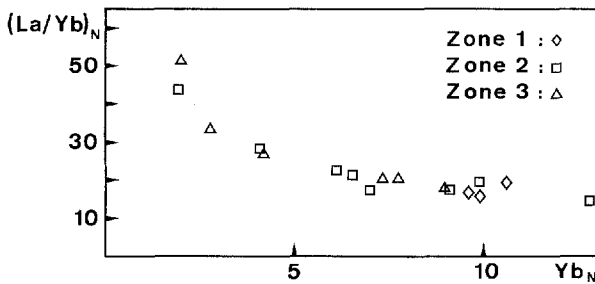


Fig. 5. $(La/Yb)_N$ vs Yb_N diagram. The Augen Gneiss whole-rock values of the three metamorphic zones define a single curve. Diamonds, Zone 1; squares, zone 2; triangles, zone 3

are not depleted in K and Rb relative to their amphibolite-facies equivalents (average $K/Rb=290$ in zones 1 and 2 and 310 in zone 3, Bingen 1989). The REE and Th contents are also independent of the metamorphic zonation: Augen Gneisses of the different units plot on a single curve in the $(La/Yb)_N$ vs Yb_N diagram (Fig. 5). Metamorphism can thus be considered as isochemical (Bingen 1989).

The 1040 Ma emplacement age of the Augen Gneisses represents an upper limit for the main Sveconorwegian (Grenvillian) tectono-metamorphic event in Rogaland and Vest-Agder (the M2 phase of Majjer et al. 1981). This event is bracketed between 1040 Ma and 980 Ma. The lower limit is given by the emplacement of the first post-tectonic granite (Holm granite; Wilson et al. 1977; Falkum and Pedersen 1979). This order of events is consistent with regional geochronological syntheses (Demaiffe and Michot 1985; Verschure 1985).

Two of five samples from the Liland Augen Gneiss (zone 3, Fig. 1, Table 2) fall close to the 1040 Ma isochron, while the other three plot distinctly above it (Fig. 4). A cogenetic link between the Liland Augen Gneiss and the other Augen Gneisses is suggested by the position of two samples on the isochron. The isotopically disturbed samples (104, 191, D6575) are those situated close (<2 km) to the contact with the anorthosite complex. The emplacement of the nearby high-temperature Bjerkreim-Sokndal lopolith and the Garsaknatt leucocratic body at 950–930 Ma (Pasteels et al. 1979) may have induced a local (<a few kilometres) isotopic disturbance in the Augen Gneisses, after the main regional metamorphic event. This thermal event could correspond to the late M3 metamorphic phase of Majjer et al. (1981).

Feldspar

Chemical data

Plagioclase (groundmass and inclusions in megacrysts), the three groups of K-feldspar (megacrysts, groundmass, shadow zone) and the ferromagnesian minerals of the Augen Gneisses were analysed with a CAMEBAX electron microprobe (CAMST, Univ. Catholique de Louvain). Several groups of groundmass crystals were ana-

Table 3. Molar compositions of groundmass K-feldspar and plagioclase (microprobe analyses)

Sample	Z	Kfs			Pl		
		Or	Ab	An	Or	Ab	An
66	1	0.899	0.100	0.001	0.012	0.765	0.223
179	1	0.864	0.134	0.002	0.014	0.746	0.240
204a	1	0.905	0.095	0.000	0.012	0.750	0.238
206	1	0.833	0.166	0.001	0.016	0.756	0.228
1a	2	0.835	0.155	0.010	0.018	0.717	0.265
13a	2	0.848	0.146	0.006	0.016	0.708	0.276
18d	2	0.813	0.174	0.013	0.017	0.741	0.242
28	2	0.805	0.183	0.012	0.014	0.734	0.252
63b	2	0.836	0.159	0.005	0.025	0.702	0.273
80b	2	0.837	0.155	0.008	0.016	0.708	0.275
117b	2	0.894	0.102	0.004	0.012	0.704	0.284
185	2	0.830	0.160	0.010	0.019	0.754	0.227
D5	2	0.882	0.118	0.000	0.019	0.743	0.238
104	3	0.827	0.148	0.025	0.021	0.723	0.256
189	3	0.798	0.188	0.014	0.017	0.716	0.267
190a	3	0.837	0.151	0.013	0.012	0.716	0.272
191	3	0.864	0.128	0.008	0.013	0.717	0.270
198	3	0.835	0.146	0.019	0.020	0.715	0.265

Ab, Or, An, Mole fraction recalculated to 1. Z, metamorphic zone

lysed in the same thin section; for each feldspar crystal, two or three analyses for major elements and Ba were performed with an enlarged beam. Eighteen samples were selected: 4 in zone 1, 8 in zone 2 together with 1 basic enclave and 5 in zone 3. Selected analyses of groundmass K-feldspar and plagioclase are presented in Table 3.

Concentration profiles of major elements and Ba were measured in eight megacrysts along sections through their cores; four Ba profiles are shown in Fig. 6. As no significant optical and chemical zonation was observed, except in the outer 3 mm, one megacryst was separated from each of 22 samples: 2 in zone 1; 15 in zone 2 with an additional 1 from a basic enclave; 4 in zone 3. Their inclusions (mainly plagioclase and quartz) were removed by grinding and processing with heavy liquids. Groundmass K-feldspars were also purified in two of those samples. The purity of final K-feldspar concentrates is better than 99% as shown by cobaltinitrite staining. The elements Si, Al, K, Fe, Rb, Sr and Pb were measured by X-ray fluorescence spectrometry (XRF), Na and Ca by atomic absorption and Ba by inductively coupled plasma atomic emission spectrometry (ICPAES; analyst: J. Navez, MRAC Tervuren). The Ba, REE, Th and U contents of 11 megacrysts were measured by instrumental neutron activation analysis (INAA). The Ba values obtained by INAA are systematically 10% higher than the ones obtained by ICPAES. The results are given in Tables 4 and 5. Microprobe analyses of the megacrysts (average of concentration profiles, Fig. 6) tend to be slightly more potassic than analyses of concentrates (Fig. 8B).

All the K-feldspar analyses (microprobe and mineral concentrates) are plotted on a ternary Or–Ab–An diagram (Figs. 7, 8). Groundmass K-feldspars are richer in Or and poorer in An than the megacrysts (Fig. 8A, B): groundmass K-feldspars fall in the range Or_{77} – Or_{94} and An_0 – An_2 , while the megacrysts are in the range Or_{66} – Or_{77} and An_1 – An_3 . In the two analysed samples, the average composition of pressure shadow zone K-feldspar is similar to that of the adjacent megacryst (Fig. 6).

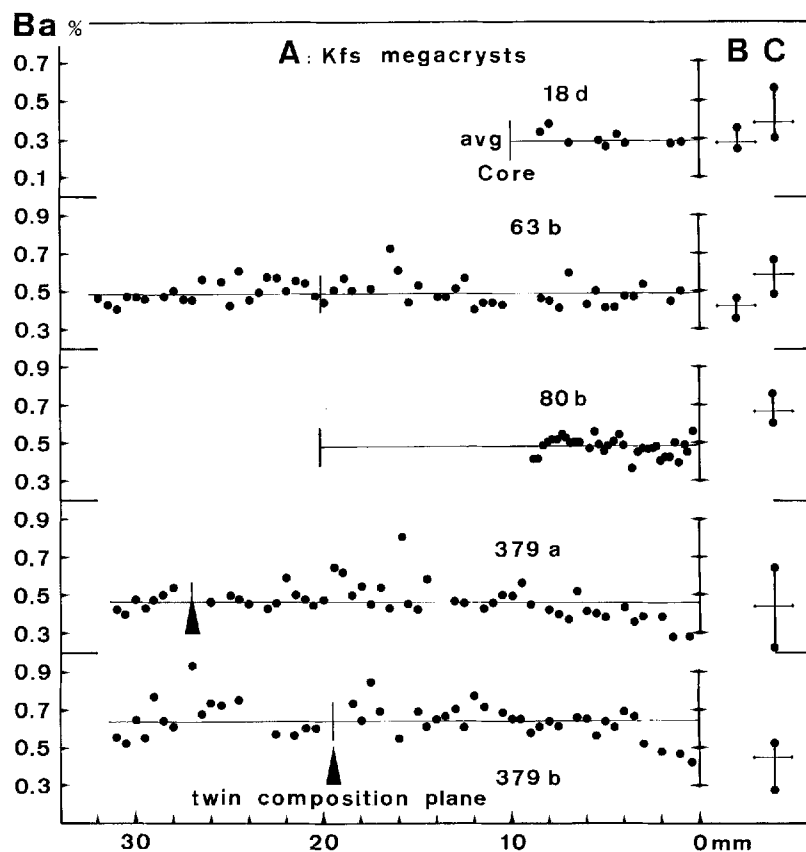


Fig. 6A–C. Ba microprobe profiles in K-feldspars. A Megacrysts: each symbol represents one analysis ($50 \times 50 \mu\text{m}$); Omm represents the edge of the megacrysts; arrows point to the position of the twin composition plane, vertical line to the approximate position of the crystal core; avg, average value; width of the megacrysts; 18 d, 2 cm; 63 b, 4 cm; 80 b, 4 cm; 379 a, 6 cm; 379 b, 5 cm. B Compositional range in shadow zone K-feldspar. C Compositional range in groundmass K-feldspar

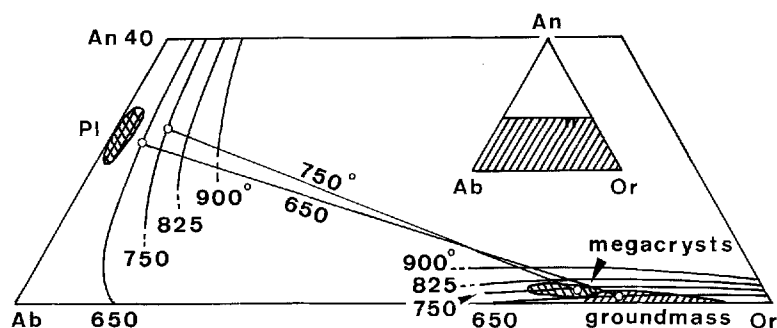


Fig. 7. Analyses of plagioclases and K-feldspars of the Augen Gneisses on a ternary feldspar diagram with solvus isotherms (at 5 kbar) from Fuhrman and Lindsley (1988). Plagioclase field: groundmass plagioclases and inclusions in the megacrysts. Two experimental tie-lines at 650°C and 750°C are shown (explanation in the text)

Plagioclase compositions all plot in a narrow field: $\text{An}_{22}\text{--An}_{29}$ and $\text{Or}_1\text{--Or}_3$ (Figs. 7, 9A). A few larger crystals (± 1 cm) are situated in the An-rich, Or-rich corner of the compositional field. In a given sample, plagioclase inclusions in K-feldspar megacrysts and groundmass plagioclase have the same composition (Fig. 9B).

K-feldspar megacrysts: phenocrysts equilibrated during the metamorphic overprinting

Petrographic observations show that the K-feldspar megacrysts initially crystallised as phenocrysts from a magmatic liquid of granodioritic composition. These rocks subsequently underwent a prograde metamorphic overprinting. The K-feldspar megacryst compositions will now be considered as a function of the metamorphic grade.

The Na and K contents of megacrysts do not show

a well defined correlation with metamorphic zonation; on the contrary, the Ca content does change with metamorphic grade (Fig. 8D). It increases from an average of 1600 ppm Ca (equivalent to $\text{An}_{1.1}$) in zone 1 (amphibolite-facies) to 2700 ppm ($\text{An}_{2.0}$) in zone 2 and up to 3500 ppm ($\text{An}_{2.6}$) in zone 3 (granulite-facies).

K-feldspar megacrysts are situated between the 650 and 825°C solvus isotherms (at 5 kbar pressure) computed by Fuhrman and Lindsley (1988) using the experimental data of Seck (1971) (Figs. 7, 8D). In contrast, their plagioclase inclusions fall well below the 650°C isotherm, in the same field as groundmass plagioclase. The 750°C and 825°C experimental tie lines are not compatible with the respective positions of the megacrysts and their inclusions (Fig. 7). Thus inclusions are not in equilibrium with the whole mass of the host megacryst but were equilibrated at a lower temperature, with the narrow (mm-sized) rim of the megacryst in direct contact with the inclusion, where perthites are optically

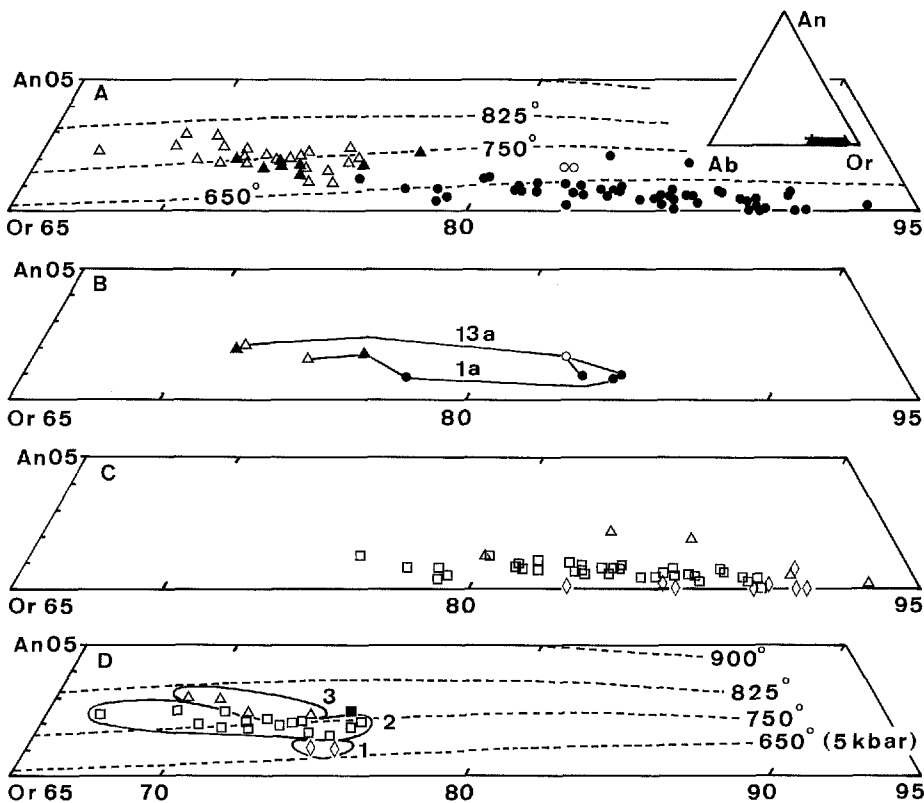


Fig. 8A–D. K-feldspar compositions (microprobe and bulk mineral) in Or–Ab–An diagram. **A** All analyses: *triangles*, megacrysts; *dots*, groundmass K-feldspar; *open symbols*, analyses of concentrates; *filled symbols*, microprobe analyses. **B** Comparison of megacryst and groundmass K-feldspar compositions in samples 13a and 1a (symbols as in Fig. 8A). **C** Groundmass K-feldspar of the three metamorphic zones; *diamonds*, zone 1; *squares*, zone 2; *triangles*, zone 3. **D** Analyses of megacryst concentrates; *diamonds*, zone 1; *squares*, zone 2 (filled square: basic enclave); *triangles*, zone 3. The isotherms of the disordered ternary feldspar solvus at 5 kbar (Fuhrman and Lindsley 1988) are shown in Fig. 8A and D

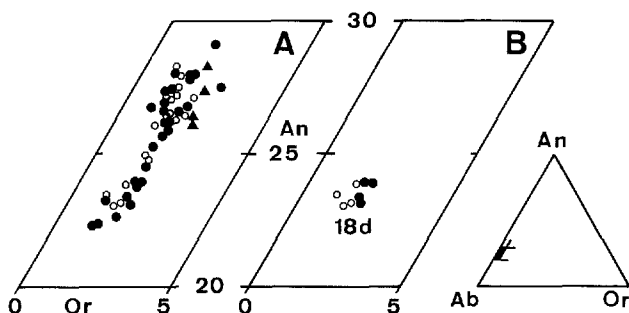


Fig. 9A, B. Plagioclase compositions (electron microprobe) on Ab–Or–An diagram. **A** All analyses: *dots*, groundmass; *triangles*, small megacrysts (± 1 cm); *open circles*, inclusions in K-feldspar megacrysts. **B** Comparison of groundmass plagioclase and inclusions in K-feldspar megacryst, sample 18d

less abundant. Consequently it is not possible to calculate equilibrium temperatures for the plagioclase inclusion/K-feldspar megacryst pairs. Nevertheless, these temperatures can be roughly estimated by plotting the megacryst compositions directly on a ternary solvus diagram. Estimated temperature intervals are 650–700°C in zone 1, 700–800°C in zone 2 and 750–825°C in zone 3 (Fig. 8D). These temperature are approximate due to the uncertainty in the pressure correction and due to the analytical errors on the Ca concentrations. Nevertheless, the 750–825°C temperature interval in granulite-facies is compatible with estimates deduced by Jansen et al. (1985) from other metamorphic formations in the same area.

The observed variation of the Ca content of megacrysts with metamorphic grade is a strong indication

that the megacrysts equilibrated (with plagioclase) during metamorphism.

The iron content of the megacrysts ranges from 700 to 2300 ppm with an average of 1100 ppm, the highest content (1100–2300) being observed in the samples of the granulite-facies. Iron is mainly located as Fe^{3+} in the T1 and T2 sites of alkali feldspars (Smith 1974; Petrov and Hafner 1988). The highest iron contents could reflect either an increase of metamorphic temperature or of oxygen fugacity; Bingen (1988) showed that the magnetite content and the whole-rock (WR) $\text{Fe}^{3+}/\text{Fe}^{2+}$ ratio of the Augen Gneisses increase with metamorphic grade ($(\text{Fe}^{3+}/\text{Fe}^{2+})_{\text{WR}} = 0.46$ in zone 1, 0.55 in zone 2 and 0.60 in zone 3).

Ba content profiles in megacrysts

Because Ba, Rb and Sr have large K-feldspar/whole-rock (WR) concentration ratios ($K^{\text{Kfs/WR}} > 1$), a large proportion of the total content of these elements is carried in the K-feldspar. Their abundance in megacrysts is hence mainly determined by the whole-rock content and by the modal proportion of K-feldspar and other minerals rich in these elements, but not by metamorphic conditions. The $K^{\text{Kfs/WR}}$ ratios are not correlated with metamorphic grade (Fig. 10); average values are nearly constant for Rb (2.5) and Sr (1.47) but some scatter is observed for Ba (3.2).

Ba content profiles in five megacrysts are shown in Fig. 6. Three of them (18d, 63b, 80b) are flat. The other two (379a, b) display a small decrease in the outer 4 mm. Some of the scatter can be explained by the presence of the exsolution lamellae. Mehnert and Büsch (1985) showed that, as a rule, megacrysts of augen gneisses

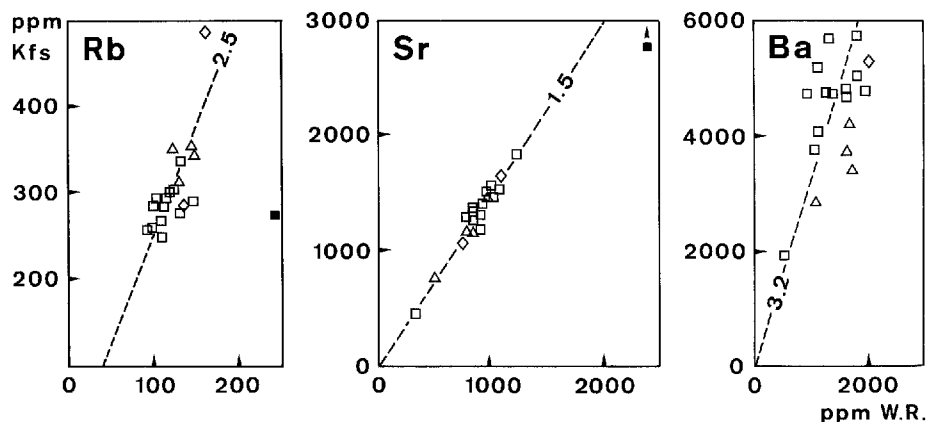


Fig. 10. Distribution of Rb, Sr and Ba between K-feldspar megacrysts and whole-rocks. *Diamonds*, zone 1; *squares*, zone 2; *filled square*, basic enclave of zone 2; *triangle*, zone 3. Average concentration ratios are 2.5, 1.5 and 3.2 for Rb, Sr and Ba respectively. (Ba, ICPAES values)

display flat or smooth profiles. On the contrary, three distinct zones are generally observed for phenocrysts in granites: a Ba-rich core, grown in an early magmatic stage, an intermediated shell with an irregular Ba distribution and a rim having a lower Ba content comparable to the groundmass K-feldspar (Kuryvial 1976; Kawachi and Sato 1978; Ivanov and Chubarov 1982; Mehnert and Büsch 1981, 1985). These zones were not observed in the K-feldspar megacrysts of the Augen Gneisses (Fig. 6). Any initial Ba zoning, if present, must have been obliterated during metamorphism.

Rare earth elements in megacrysts

Rare earth element (REE) patterns of K-feldspar megacrysts are shown in Fig. 11. K-feldspar REE content is low compared to the whole-rock: La_N ranges from 10 to 45 and $K_{La}^{Kfs/WR}$ from 0.04 to 0.4. Contents of HREE are low and often below the detection limit of INAA so that the $(La/Sm)_N$ ratios (instead of $(La/Yb)_N$) are used to quantify the slope of the REE patterns, which varies from 14 to 210. The megacrysts exhibit a large positive Eu anomaly.

The REE patterns of five megacrysts from zone 2 are nearly identical (Fig. 11) despite the fact that SiO_2 and La_N abundances of the analysed whole-rock samples range from 60% to 73% and from 80 to 200 respectively. The K-feldspar megacryst of the potassic basic enclave ($SiO_2 = 50\%$ and $La_N = 800$) also displays a similar REE pattern. The REE contents of zone 1 megacrysts are significantly lower than those of zone 2 (Fig. 11). In zone 3, the La content is highest and the slope is steepest: compare a $(La/Sm)_N$ value of 14 to 30 in zone 2 with values between 50 and 210 in zone 3. The REE patterns of megacrysts are thus correlated with the metamorphic zoning.

The increase of the REE content of the megacrysts between zones 1 and 2 is most likely related to the change in the nature of the REE-rich accessory minerals. Allanite and sphene disappear between zones 1 and 2, while minute amounts of monazite appear at this transition. Because the whole-rock chemistry of the Augen Gneisses is independent of metamorphic grade (Bingen 1989; Fig. 5), and because allanite and sphene carry an important fraction of the REE content of the whole-

rocks (Fourcade and Allègre 1981; Gromet and Silver 1983), their disappearance implies a redistribution of REEs among the minerals of the rock. The modal abundance of allanite and sphene were estimated at 0.06% and 0.7% respectively by point counting in sample 206 (45,000 points). A simple mass-balance calculation, using REE analyses of sphene and allanite in granodiorites (Gromet and Silver 1983), shows that these minerals contain between 40% and 60% of the total REE content of the rocks. Redistribution of the REEs contained in these minerals can account for the higher REE content observed in the K-feldspar megacrysts of zone 2 relative to zone 1 (as well as for the occurrence of minute amounts of monazite).

To explain the higher $(La/Sm)_N$ ratios and the lower HREE content in the megacrysts at the granulite-facies transition (between zones 2 and 3), one could invoke a change of the REE distribution coefficients among the minerals, due to the increase of metamorphic conditions or due to the dehydration of metamorphic fluid. Indeed, the REE content of apatite is higher in granulite-facies rocks (B. Bingen, in preparation): for example, the average $K_{Sm}^{Ap/WR}$ varies from 55 in zone 2 to 110 in zone 3 corresponding to an increase of the proportion of total Sm contained in apatite from 40% to 70%. A large proportion of REE contained in K-feldspar (and in the other minerals) may thus have been transferred to the apatite (and zircon?). As apatite is especially rich in middle REE, the coexisting K-feldspar may display high $(La/Sm)_N$ ratios.

The behaviour of Eu is intermediate between that of Sr and of the other REEs. In zones 2 and 3, the Eu content of megacrysts is linked to the whole-rock content, with an average $K_{Eu}^{Kfs/WR}$ of 1.2. In zone 1, Eu content is markedly lower, with a $K_{Eu}^{Kfs/WR}$ of 0.6.

The Th content of the megacrysts is correlated with the metamorphic zoning: in the granulite-facies (zone 3), the megacrysts contain less than 0.19 ppm Th ($K_{Th}^{Kfs/WR} = 0.03$) while in amphibolite-facies (zones 1, 2), the Th content ranges from 0.24 to 0.88 ppm ($K_{Th}^{Kfs/WR} = 0.08$). Like the REE, the Th content of megacrysts is controlled by accessory minerals. Thorite is present in trace amounts in all the samples of granulite-facies. However, in zone 2, thorite is present only in the samples containing >5 ppm Th. The Th content of apatite is higher in the granulite-facies: $K_{Th}^{Ap/WR} = 15$ in zone 2, 28 in

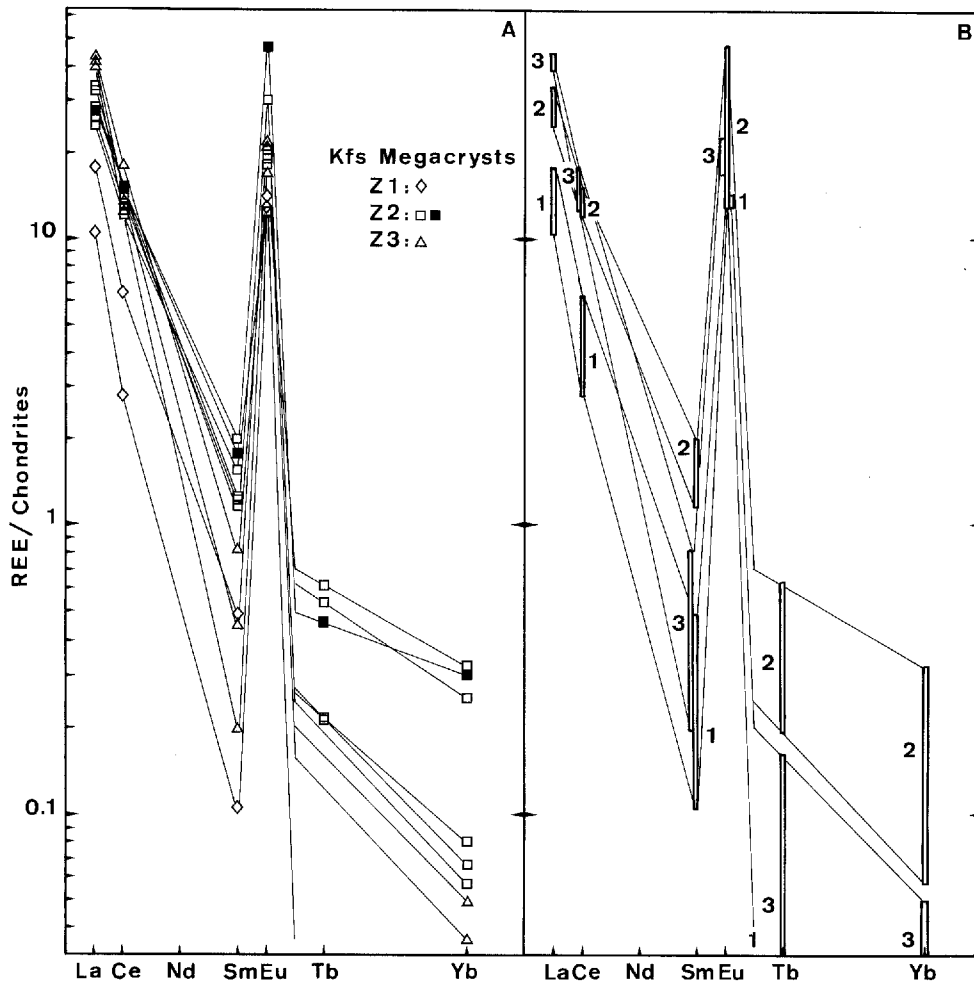


Fig. 11 A, B. Chondrite-normalised rare-earth contents of K-feldspar megacrysts. A individual analyses; B analyses grouped for each metamorphic zone. For symbols, see Fig. 10

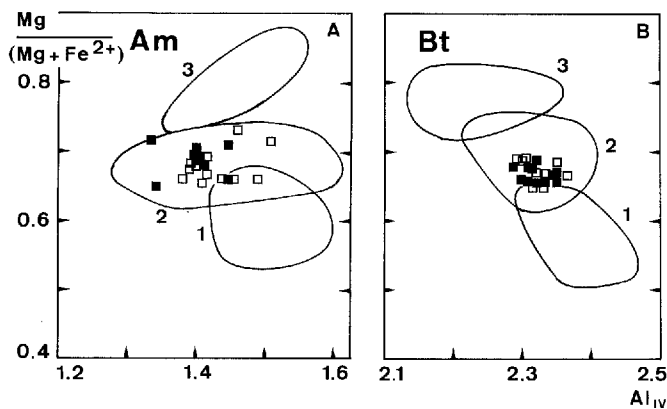


Fig. 12 A, B. Comparison between amphiboles and biotites of the Augen Gneiss groundmasses and these mineral inclusions in K-feldspar megacrysts (sample 379b, zone 2). Filled squares, Groundmass minerals; open squares, included minerals. Compositional fields of amphiboles and biotites of the three metamorphic zones are shown. Al_{IV} , Tetrahedral Al calculated on the basis of 23 oxygens for amphibole and 22 for biotite

zone 3 (B. Bingen, in preparation) corresponding to an increase of the proportion of total Th in apatite from 10% to 25%. This increase, as well as the crystallisation of thorite in granulite-facies, points to a transfer of Th from major minerals (for example K-feldspar) to accessory minerals (apatite, thorite and zircon?).

Ferromagnesian-mineral inclusions in the K-feldspar megacrysts

The composition of groundmass amphibole and biotite in the Augen Gneisses is correlated with metamorphic grade: Mg/(Mg + Fe) ratio increases, whereas tetrahedral Al content is constant or slightly decreases with metamorphic grade (Bingen 1988; Fig. 12). The composition of amphibole and biotite inclusions in megacrysts of the Feda Augen Gneiss (zone 2) is the same as that of the groundmass minerals: the inclusions are located in the compositional fields of zone 2 amphiboles and biotites (Fig. 12), despite the fact that they are sheltered in the megacrysts and that some of them have retained their primary shapes (Fig. 3).

These inclusions, which initially crystallised during the magmatic stage, were chemically modified during metamorphism. Nevertheless, metamorphic minerals did not develop inside the megacrysts (i.e. the absence of pyroxene inclusions in megacrysts).

Groundmass K-feldspars: late-metamorphic changes

Relationships between phenocryst and groundmass K-feldspar have been studied in many granites. As a rule, groundmass K-feldspar is richer in Or than the pheno-

crysts. Rb contents are also higher in megacrysts, whereas Sr and Ba contents are lower (Emmermann 1969; Saint-Joanis and Mergoïl-Daniel 1978; Sultan et al. 1986). In granites, it is generally accepted that groundmass K-feldspar, together with phenocryst rims, is late crystallising from a differentiated magma enriched in K and Rb and impoverished in Sr and Ba.

In the Augen Gneisses under study, groundmass K-feldspars are also rich in Or and poor in An relative to megacrysts (Figs. 7, 8A, B). In some samples, the Ba content is higher in groundmass K-feldspar whereas in others, it is the same or even lower (Fig. 6, Table 4). In two samples where both K-feldspars were separated (13a, 113c, Table 4), Fe, Rb, Sr and Pb contents are higher in the groundmass K-feldspar (1800 ppm Sr and 69 ppm Pb) than in the megacrysts (1400 ppm Sr and 50 ppm Pb). For Sr and Pb this is contrary to what is generally observed in granites.

Groundmass K-feldspar compositions are independent of metamorphic zoning: all analyses, except a few, fall in the same compositional range (Fig. 8C), around or below the 650°C isotherm (Fig. 8A). The respective positions of groundmass plagioclase and K-feldspar are compatible with the tie-lines of Fuhrman and Lindsley (1988) (Fig. 7). Equilibrium temperatures were not calculated, because such a low-temperature domain for Barich feldspars is outside the field of application of current calibrations of ternary feldspar thermometry.

These apparent temperatures are distinctly lower than those of the megacrysts and characterize the late metamorphic history of the rock (i.e. the beginning of uplift). They represent the closure of Na-K-Ca exchange on a millimetre scale. Alkali-interdiffusion distances can be roughly estimated in K-feldspar using simplified equations (Freer 1981) and published diffusion coefficients (Foland 1974; Brady and Yund 1983). At 600°C, estimated K diffusion and Na-K-interdiffusion distances in Or₇₅ are 1 mm in 1 Ma and 2–4 mm in 10 Ma; cm-sized megacrysts were thus not re-equilibrated with plagioclase at these temperatures during uplift while mm-sized groundmass K-feldspars were.

Mineral age and closure of Rb/Sr system in the K-feldspar megacrysts

An internal Rb/Sr isochron was obtained on sample 113c of Feda (zone 2). In increasing order of Rb/Sr ratio, plagioclase + quartz, apatite, groundmass, whole-rock, groundmass K-feldspar and K-feldspar megacryst were analysed. This isochron (MSWD=1.6) gives an age of 871 ± 35 Ma (2σ) with $I_{Sr} = 0.7044$ (Fig. 4).

On a $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{87}\text{Rb}/^{86}\text{Sr}$ diagram, K-feldspars of ten samples from the three metamorphic zones (9 megacrysts, 1 megacryst of basic enclave, 3 groundmass K-feldspar) define a good linear array (MSWD=0.4) which has the same origin as the whole-rock isochron ($I_{Sr} = 0.7036$) but a lower slope corresponding to a "younger age" of 975 ± 22 Ma (Fig. 4). However, this linear array does not correspond to an isochron. It can be explained by means of a diagram (Fig. 13) which schematically represents the situation of the Rb/Sr

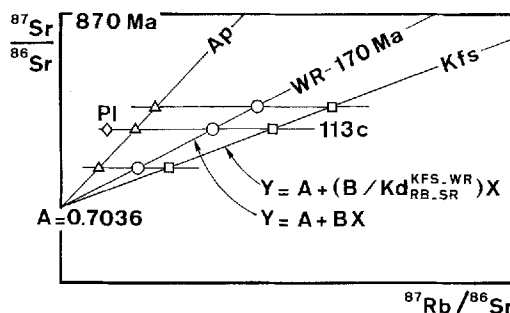


Fig. 13. Schematic $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{87}\text{Rb}/^{86}\text{Sr}$ diagram at 870 Ma ago. Whole-rock values define an isochron $Y = A + BX$ with $A = 0.7036$ and a slope (B) corresponding to an age of 170 Ma. K-feldspar define a linear array with the same origin (A) and a lower slope: $B/K_{\text{Rb-Sr}}^{\text{Kfs,WR}}$ (average $K = 1.7$ in Augen Gneisses) (see Fig. 4 for symbols)

isotopic system in the Augen Gneisses and their minerals 870 Ma ago (the age given by the internal isochron obtained on the minerals of sample 113c). In this diagram, whole-rock and groundmass values define an isochron of 170 Ma ($170 = 1040 - 870$); the minerals of sample 113c plot on a horizontal line (zero Ma) corresponding to a homogeneous Sr isotopic composition, implying that the Sr isotopic system was open on the mineral scale. Minerals of the other samples also theoretically define horizontal segments with variable $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for each rock, depending on the $^{87}\text{Rb}/^{86}\text{Sr}$ ratio of the rock. The position of a K-feldspar megacryst relative to the host whole-rock on the horizontal line depends on the Rb/Sr repartition coefficient between K-feldspar and whole-rock: $(\text{Rb}/\text{Sr})_{\text{Kfs}}/(\text{Rb}/\text{Sr})_{\text{WR}} = K_{\text{Rb-Sr}}$. If this ratio remains constant, the K-feldspar of the different samples will define a linear array with an origin identical to that of the whole-rock isochron but with a different slope. If the isochron equation for the whole-rocks is given by $Y = A + BX$, then the equation of the K-feldspar megacryst line can be written as $Y = A + (B/K_{\text{Rb-Sr}})X$. The K_{Rb} and K_{Sr} values between K-feldspar megacrysts and whole-rock are nearly constant (Fig. 10) and independent of the metamorphic zone. $K_{\text{Rb-Sr}}$ is thus also constant: the average value for 18 samples is 1.7 ± 0.3 (2σ). As the whole-rocks define an 170 Ma isochron in Fig. 13, the K-feldspar megacryst linear array must give a fictitious age of 100 Ma. This fictitious age is in very good agreement with the 104 Ma ($104 = 975 - 871$) obtained by the 13 points linear regression of the K-feldspar (Fig. 4) which, moreover, has exactly the same I_{Sr} as that of the whole-rock isochron (0.7036).

We can thus deduce that the 870 Ma age not only characterises the closure of the Rb/Sr isotopic system on the mineral scale in sample 113c (plagioclase, apatite, K-feldspar) but also the closure of the Rb/Sr system in K-feldspar, especially megacrysts, in the different samples from the whole region. This age is equivalent to, or slightly older than, the biotite/whole-rock Rb/Sr ages in two samples of the Tonstad Augen Gneisses: 858 and 855 Ma (Wielens et al. 1981). It is, moreover, similar to the average (872 Ma) of nine brown biotite/whole-rock Rb/Sr ages in other metamorphic formations in the same area (Verschure et al. 1980).

Table 4. Analyses of K-feldspar megacrysts and two groundmass K-feldspars

Sample	Z	SiO ₂	Al ₂ O ₃	Na ₂ O	K ₂ O	Ca	Fe	Rb	Sr	Ba	Pb	Tot	Or	Ab	An
179	1	64.34	19.06	2.65	12.19	1550	730	488	1067	5600	56	99.32	0.743	0.246	0.011
206	1	64.99	19.17	2.58	12.38	1600	900	283	1645	5280	55	100.25	0.751	0.238	0.011
1a	2	64.50	18.79	2.65	12.23	2300	1210	294	1320	3790	47	99.24	0.740	0.244	0.016
13a	2	64.51	19.32	2.85	11.83	2950	770	302	1475	4830	51	99.74	0.717	0.262	0.021
13a Gr	2	64.43	19.19	1.74	13.73	2400	1170	326	1909	5050	69	100.39	0.824	0.159	0.017
80b	2	64.19	19.22	2.74	11.81	2850	840	278	1419	4510	49	99.15	0.724	0.255	0.021
109b	2	64.17	19.67	3.29	10.79	3150	950	337	1258	4110	49	99.10	0.668	0.309	0.023
112	2	63.69	19.28	2.46	12.54	2700	1250	267	1177	4710	52	99.19	0.756	0.225	0.019
113c	2	65.11	19.72	2.88	11.51	3300	980	284	1349	5200	49	100.56	0.707	0.269	0.024
113c Gr	2	64.38	19.30	1.73	13.92	2300	1080	296	1716	4410	68	100.50	0.828	0.156	0.016
114	2	64.02	19.40	2.80	11.66	2400	820	293	1333	4780	51	99.03	0.720	0.263	0.018
117b	2	63.48	19.57	2.39	12.07	3300	1640	272	5560	7210	77	99.67	0.750	0.226	0.024
119	2	64.01	19.51	3.04	11.32	3400	770	260	1282	4810	52	99.16	0.693	0.283	0.025
120a	2	63.75	19.31	2.62	12.06	2900	940	249	1548	5720	50	99.11	0.736	0.243	0.021
135	2	65.17	19.03	2.97	11.83	2500	1090	290	461	1960	50	99.78	0.711	0.271	0.018
168	2	64.84	19.54	2.67	11.97	2700	1490	256	1834	5810	57	100.48	0.732	0.248	0.020
169	2	64.74	18.89	2.53	12.63	2500	920	277	1457	4790	51	99.98	0.753	0.229	0.018
171	2	65.04	19.19	2.74	12.02	2650	920	282	1405	4740	49	100.19	0.729	0.252	0.019
172	2	64.73	19.49	3.00	11.54	2650	850	281	1582	5340	53	100.04	0.703	0.278	0.019
185	2	64.66	19.17	2.56	12.26	2300	830	300	1526	5050	56	99.83	0.747	0.237	0.016
104	3	63.92	19.18	2.90	11.62	3850	1850	344	755	2860	50	98.83	0.705	0.267	0.028
107	3	64.15	18.97	2.80	11.72	3200	2270	312	1148	3740	54	98.97	0.717	0.260	0.023
195a	3	64.45	19.18	2.64	12.30	3150	1890	352	1140	3420	51	99.80	0.737	0.241	0.022
198	3	64.55	19.32	3.01	11.45	4000	1100	350	1451	4230	54	99.69	0.694	0.277	0.029

Gr, Groundmass K-feldspar; Z, metamorphic zone. SiO₂, Al₂O₃, Na₂O, K₂O in wt%; other elements in ppm; Ba by ICPAES; Na, Ca by atomic absorption; other elements by XRF; Tot, total of all oxides; Or, Ab, An, mole fractions recalculated to 1

Table 5. Trace element analyses of K-feldspar megacrysts

Sample	Z	Sc	Ba	La	Ce	Nd	Sm	Eu	Tb	Yb	Th	U
179	1	0.031	6326	6.1	5.8	<2	0.102	1.13	<0.01	<0.02	0.27	0.31
206	1	0.013	6160	3.6	2.5	<2	0.022	1.05	<0.006	<0.02	0.3	<0.15
113a	2	0.066	5438	9.7	12.6	<2	0.42	1.66	0.032	0.072	0.59	0.62
113c	2	0.043	5467	11.6	12.6	<2	0.24	1.53	0.011	0.015	0.49	<0.1
114	2	0.063	5175	8.9	11.9	<2	0.26	1.54	<0.01	0.040	0.58	0.40
117b	2	0.073	8662	9.9	13.4	<2	0.37	3.76	0.024	0.068	0.88	0.79
120a	2	0.041	6480	11.2	13.1	<2	0.26	2.43	0.011	0.018	0.24	0.08
135	2	0.061	2120	8.3	10.8	1.2	0.32	1.01	0.028	0.057	0.71	0.47
104	3	0.057	3208	14.4	15.8	<2	0.169	1.36	<0.006	0.011	0.19	<0.1
107	3	0.031	4116	13.9	12.1	<2	0.093	1.68	<0.005	0.008	0.19	<0.1
198	3	0.018	4881	13.8	11.0	<2	0.041	1.68	<0.004	<0.006	0.09	<0.1

Z, Metamorphic zone; Elements in ppm by INAA

Diffusion of Sr in K-feldspar is fast (Misra and Venkatasubramanian 1977); at 600° C, the calculated diffusion distance is 30 mm in 10 Ma. The closure temperature of the Rb/Sr isotopic system is thus far below 600° C. Hanson and Gast (1967) showed that it is situated between 450° C and 350° C for biotite (in a contact metamorphic aureole) and is slightly lower than in K-feldspar. Our results are in agreement with this last observation, but the resolution is not sufficient to distinguish K-feldspar- from biotite-cooling ages.

Summary and conclusions

The Augen Gneisses of Rogaland – Vest-Agder were emplaced as amphibole-biotite granodiorites with large K-

feldspar phenocrysts. A Rb/Sr whole-rock isochron based on regional sampling gives an emplacement age of 1040 ± 44 Ma concordant with zircon U/Pb upper-intercept ages. The K-feldspar megacrysts crystallised as phenocrysts:

1. In the least deformed Augen Gneisses (central parts of the large units), they have a prismatic habit with simple Carlsbad twinning
2. Their abundance is correlated to the magmatic facies
3. Plagioclase, biotite and amphibole inclusions are often orientated parallel to crystallographic planes and are sometimes euhedral.

The granodiorite precursors of the Augen Gneisses underwent a prograde metamorphic overprinting (lower amphibolite- to granulite-facies) after their emplacement. Their emplacement age (1040 Ma) thus represents

an upper limit for the main Sveconorwegian metamorphic event in Rogaland – Vest-Agder, which certainly took place between 1040 Ma and 980 Ma (first post-tectonic granite). Three metamorphic zones were defined in the Augen Gneisses: zone 1 = Bt + Am zone to the East; zone 2 = Bt + Am ± Cpx zone; zone 3 = Bt ± Am ± Cpx ± Opx zone in granulite-facies, to the West, in the vicinity of the Rogaland anorthosite complex.

K-feldspar megacrysts have been partially deformed and chemically equilibrated during the main metamorphic event:

1. They display flat or slightly convex Ba profiles, whereas phenocrysts of granites always show zoning. Any original zoning, if present, must have been obliterated during metamorphism.
2. The Ba and Rb concentrations are not very different in megacrysts compared to groundmass K-feldspars, whereas in megacrysts of granites, Ba content is higher and Rb lower.
3. The Ca content of megacrysts increases with metamorphic grade, corresponding to a probable increase of metamorphic temperatures.
4. REE patterns of megacrysts are dependent on the metamorphic grade. The important increase of REE content between zones 1 and 2 is attributed to metamorphic destruction of sphene and allanite in the rock giving rise to a redistribution of REE among the minerals. The Th content of megacrysts is lower in the granulite-facies.
5. Amphibole and biotite inclusions in megacrysts of zone 2 have the same composition as those of the groundmass minerals.

Groundmass K-feldspars are richer in orthoclase component than megacrysts. Due to their small size, they were chemically equilibrated to lower temperatures during uplift.

The closure of the Rb/Sr isotopic system on a mineral scale is given by an internal isochron (plagioclase, apatite, K-feldspar) giving an age of 870 ± 35 Ma. On a $^{87}\text{Sr}/^{86}\text{Sr}$ vs $^{87}\text{Rb}/^{86}\text{Sr}$ diagram, the K-feldspar megacrysts define a good straight line with the same origin as that of the whole-rock isochron but with a lower slope. This line does not correspond to an isochron but shows that the 870 Ma event represents the closure of the Rb/Sr system in the megacrysts over the whole region. The biotite cooling age is equivalent to or slightly younger than the K-feldspar megacrysts cooling age.

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

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