RARE-EARTH DATA ON MONZONORITIC ROCKS RELATED TO ANORTHOSITES AND THEIR BEARING ON THE NATURE OF THE PARENTAL MAGMA OF THE ANORTHOSITIC SERIES

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Major and trace elements have been determined in monzonoritic rocks (hypersthene-monzodiorite or jotunite) from two intrusions belonging to the South Rogaland anorthositic complex (Norway). The rare-earth abundance pattern reveals no Eu anomaly, or only a very small one. This fact together with field observations suggest that these rocks represent the parental magma of the anorthositic suite. High Ti and P abundances, low Si content, high Fe/Mg and K_2O/SiO_2 ratios are characteristics of the major element geochemistry. Absolute amounts of some trace elements abundances vary distinctly between the two intrusions. K/Rb ratios as high as 1700 are observed. Partial fusion of upper mantle kaersutite is proposed as a possible mechanism of magma generation. Partition coefficients between plagioclase phenocrysts and liquid are determined.

1. Introduction

Removal of plagioclase is unanimously accepted as the main mechanism of differentiation of the anorhositic suite, but the nature of the parental magma remains a controversial problem. Compositions ranging from gabbroic to quartz-monzodioritic [1] or even granodioritic liquids [2] have been proposed. These estimates are based principally upon imprecise evaluations of volume proportions of the related rocks and the hypothesis of their consanguinity. Criteria of consanguinity and resulting proportions differ considerably. In the deep-seated conditions of emplacement of anorthosite massifs, chilled margins are not frequent and moreover, they can result from consolidation of a residual liquid rather than from a parental magma. The similarity between chemical trends of pyroxenes [3] in different massifs restricts, however, the compositional range of possible parental magmas and calls for intermediate compositions. Green's experimental work [4] on quartz-dioritic compositions (= andesite) has made this hypothesis plausible.

The purpose of this note is to present the chemical characteristics of some monzonoritic (hypersthene monzodioritic of jotunitic) rocks from the South Rogaland anorthositic complex (Norway), to show that their rare-earth element (REE) content indicates that they result from crystallization of parental liquids, and to discuss the possible mode of formation of such liquids.
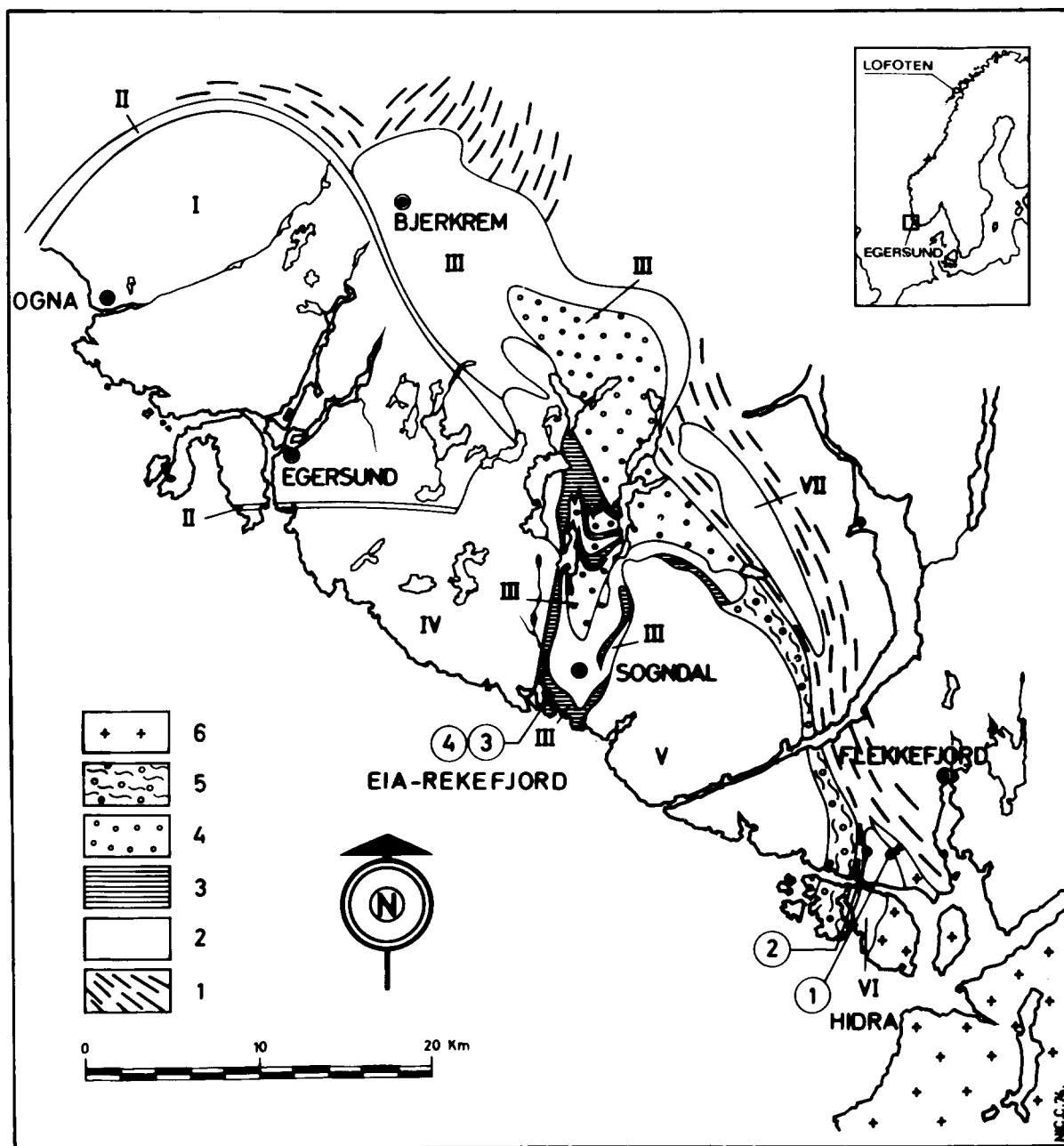
Fig. 1. The South Rogaland igneous Complex (after J. and P. Michot [8]). Legend: 1 = gneisses of the envelope; 2 = anorthosite, leuconorite, norite; 3 = monzonorite (mainly Eia-Rekefjord intrusion); 4 = mangerite; 5 = norito-mangeritic complex; 6 = farsundite.

I = Egersund-Ogna massif; II = Laksevelefjeld-Koldal intrusion; III = Bjerkrem-Sogndal lopolith; IV = Håland-Helleren massif; V = Aana-Sira massif; VI = Hidra massif; VII = Garsaknatt massif.

Encircled numbers: 1 = sample 7234, 2 = sample 7020, 3 = sample 66125, 4 = sample Pa 66/0.

2. Geological situation

The rocks studied belong to two geological units of the province (Fig. 1).

2.1. The Hidra anorthositic massif

The Hidra (HD) massif [5] is made of a coarse-grained leuconorite locally grading into an anortho-

site. At its contact with the gneissic envelope, it is characterized by the occurrence of a fine-grained monzonoritic rock, which is homogeneous (sample 7234) or contains variable amounts of plagioclase phenocrysts (sample 7020). A progressive enrichment of plagioclase phenocrysts and a simultaneous decrease in the matrix proportion towards the centre of the massif are apparent. The genetic relationship between the monzonoritic border and the anorthosito-leuconoritic central part of the body is thus obvious, and therefore the monzonorite and the anorthosite can be considered as comagmatic. Previous studies [5,6] have not determined whether the border rock represents a residual liquid left after the formation of the central part of the body or a parental magma, chilled against the wall rocks.

Sample 7234 and the matrix of 7020 (Tables 1, 3 and 5) contain poorly twinned xenomorphic plagioclase (An_{30-32}), interstitial K-feldspar, subhedral ortho- and clinopyroxene, flakes of biotite, and ilmenite (hematite content from 12 mol.% to less than 7% [7]). Minute idiomorphic apatite crystals are uniformly distributed. Traces of magnetite, sulphides and zircon are also present.

The plagioclase phenocrysts (av. 2–3 cm) contain numerous Fe–Ti oxide inclusions, which give the bluish cast typical for the anorthositic plagioclase. Phenocrysts ranging in composition from An_{48} to An_{43} are usually zoned at the contact with the matrix (down to An_{35}?). The degree of zoning, however, varies from crystal to crystal in the same rock; some individuals are even unzoned. A rim devoid of opaque inclusion is always present.

Separates composed of several phenocrysts coming from different rocks of the border facies have been analysed (Table 2).

2.2. The Eia-Rekefjord quartz-monzonoritic intrusion

Intruded between the anorthositic massif of Håland-Helleren and the southern part of the Bjerkrem-Sogndal lopolith [8], the Eia-Rekefjord intrusion (E-R) is essentially made of quartz-monzonorites (sample 66125) with their variants enriched in quartz or in mafics (sample Pa 66/0) [9]. This intrusion is considered by Michot [9] as representing a part of the

TABLE 1

Chemical compositions, norms (CIPW) and modes of monzonoritic rocks

	Hidra massif		Eia-Rekelfjord intr.	
	7234	7020	66125	Pa 66/0
Chemical composition (wt. %)				
SiO_2	49.8	48.0	51.8	46.6
TiO_2	4.28	4.61	3.46	4.2
Al_2O_3	14.1	14.2	12.10	12.1
Fe_2O_3	2.2	5.0	4.0	4.3
FeO	11.7	10.4	11.1	12.6
MnO	0.17	0.18	0.21	0.24
MgO	4.9	4.6	3.8	5.9
CaO	6.0	6.4	7.1	7.0
Na_2O	3.5	3.6	3.2	3.3
K_2O	1.95	1.08	1.55	1.30
H_2O^+	0.22	0.40	0.14	0.19
H_2O^-	0.10	0.45	0.10	0.08
P_2O_5	0.91	0.81	1.50	2.05
Fe_{total} (as FeO)	13.7	14.9	14.7	16.9
Total	99.83	99.81	100.06	99.86
Norm (CIPW)				
Q	–	2.7	7.5	–
Or	11.5	6.5	9.2	7.7
Plag	46.6	50.3	41.2	42.1
Di	6.2	5.9	10.3	6.9
Hy	21.6	16.5	16.1	23.0
Ol	0.8	–	–	1.8
Mt	3.2	7.3[1]	5.8	6.2
Il	8.1	8.9	6.6	7.9
Ap	2.0	2.0	3.3	4.4
Modal analysis (vol.%)				
Quartz	–	–	9.6	2.0
K-feldspar	7.3	5.3	15.6	15.8
Plagioclase	50.0	56.4	43.7	43.3
Orthopyroxene	18.2	16.2	13.2	17.3
Clinopyroxene	6.4	6.3	5.9	7.8
Biotite	7.9	4.8	–	–
Ilmenite	7.8	8.6	4.8 }	9.5
Magnetite	tr	tr	3.4 }	
Apatite	2.4	2.4	4.0	4.3

[1] Measured Fe_2O_3 and resulting normative magnetite content increased by weathering. 7234: monzonorite – border facies of the Hidra massif (E. Itland). 7020: matrix of a porphyritic monzonorite – border facies of the Hidra massif (W. Itland). 66125: Quartz monzonorite – Eia Rekefjord intrusion (Rekefjord). Pa 66/0: Mafic-rich monzonorite – Eia Rekefjord intrusion (Rekefjord).

TABLE 2

REE and other trace element concentrations (in ppm) in plagioclase phenocrysts from rocks of the Hidra border facies.

	P7020	P251-2/1	P200-2/2	P/199-2/1	Average
La	37.2	19.8	52.3	15.1	31.1
Ce	18.3	35.5	26.3	23.1	25.8
Nd	7.1	15.2	9.6	8.6	10.1
Sm	1.49	2.42	1.27	1.04	1.56
Eu	2.86	4.23	3.03	2.33	3.11
Gd		1.57	0.9	0.81	1.10
Tb	0.16	0.26	0.12	0.08	0.16
Ho		0.30	0.16	0.08	0.18
Tm		0.13			
Yb	0.31	0.82	0.26	0.089	0.37
Lu	0.047	0.12	0.036	0.013	0.054
Eu/Eu*	7.11	7.17	8.04	6.04	6.93
Ca(%)	6.40	6.51	6.37	6.94	6.56
K(%)	0.523	0.315	0.333	0.426	0.399
Rb	12.3	5.4	7.4	8.9	8.5
Sr	784	474	491	759	627
Ba	255–261	250	145	130	196
Cs	0.1				
K/Rb	425	581	450	480	484
An(wt.%)	43.4	45.1	44.2	48.1	45.2
Sc	1.69	3.21	1.57	0.34	1.7
Co	7.3	4.11	12.2	2.3	6.5
Hf	0.6	1.71	0.66	0.11	0.77
Th	0.35	0.17	0.17	0.20	0.22
U	0.10	0.10	0.1	0.1	0.1

REE, Sc, Co, Hf, Th, U, Ba were determined in sample P7020 by NAA (analyst: I. Roelandts) and in the other samples, by INAA (analysts: J. De Winter and J. Hertogen). Rb was determined by isotopic dilution; the other elements including Ba in P7020 by X-ray fluorescence spectrometry.

residual liquid left after the formation of the leuconoritic phase of the Bjerkrem-Sognal body and expelled from the magmatic chamber by the intense deformation of the lopolith [8–10].

The rocks contain quartz and independent microperthitic grains of K-feldspar; plagioclase (An_{30-35}) is an antiperthite locally grading into a mesoperthite. The feldspars exhibit a protoclastic structure contrasting with the poikilitic habit of the orthopyroxene and the interstitial arrangement of the oxides [11] (homogeneous ilmenite and Ti-magnetite) and of the apatite. Biotite is absent and zircon is accessory.

3. Analytical procedures

Major elements were determined by a combination of wet chemical methods and X-ray fluorescence spectrometry. Isotopic dilution was used for Sr and Rb at the Belgian Centre for Geochronology; X-ray fluorescence spectrometry for Sr, Rb, Ba and Zr; emission spectrography for Cu, Ni, Co, V and Cr. REE, Cs, Sr, Ba, U, Th, Hf, Sc, Co, Cr and Ta were determined by neutron activation analysis independently in two laboratories, namely the Mineralogical-Geological Museum, University of Oslo (Radiochemical, Instrumental an Epithermal NAA) and the Institute for Nuclear Sciences, University of Ghent (Instrumental NAA). The NAA procedures employed are described elsewhere [12–16]. BCR-1, AGV-1 and secondary "in house" standards were used. A satisfactory agreement between the different methods (Tables 3 and 5) was obtained (average deviation better than 7%), especially with regard to REE.

TABLE 3

REE concentrations (in ppm) in monzonoritic rocks

	7234		7020	Average on 7234 and 7020	66/125	Pa 66/0
	(a)	(b)	(b)		(b)	(a)
La	35.3	33.4	30.3	32.3	57.7	76.6
Ce	81.9	81.1	75.3	78.4	140	204
Nd	52.9	47.8	46.6	48.5	89.1	141
Sm	11.5	11.44	11.66	11.57	21.52	25.1
Eu	3.31	3.11	3.35	3.28	6.45	7.4
Gd	11.1			11.1		21.2
Tb	1.59	1.58	1.58	1.58	2.76	(3.8)
Dy	8.7			8.7		17.3
Ho	1.9			1.9		3.4
Tm	0.61			0.61		1.23
Yb	3.55	3.45	3.21	3.36	6.27	8.10
Lu	0.52	0.55	0.54	0.54	1.03	1.30
Eu/Eu*				0.91	1	1
La/Yb	9.94	9.68	9.44	9.63	9.20	9.46

(a): INAA (analysts: J. De Winter and J. Hertogen).

(b): RNAA (analyst: I. Roelandts).

4. Results and discussion

4.1. Distribution coefficients between plagioclase phenocrysts and matrix

The distribution coefficients of REE between the phenocrysts and the matrix of rock 7020 are reported in Table 4, together with those based on the average of the homogeneous rock 7234 and the matrix of 7020 (Table 3). It is justified to average 7234 and matrix 7020, which are very similar, and to consider the average as representing the chilled liquid. On the other hand the REE contents vary considerably in the different phenocryst separates. It is difficult to decide whether these discrepancies are due to a variation in the degree of zoning or to some other factors. However, the average distribution factors are very similar to those obtained for the phenocryst-matrix pair of rock 7020. They can therefore be taken as partition coefficients. The values (except for La) fall within

TABLE 4

REE distribution and partition coefficients between plagioclase phenocrysts and matrix

	La	Ce	Nd	Sm	Eu	Eu*	Gd	Tb	Ho	Yb	Lu
Plag. 7020/matrix 7020	1.22	0.24	0.15	0.12	0.85			0.10		0.09	0.08
Av. pheno./av. liquid	0.94	0.32	0.21	0.14	0.95	0.12	0.10	0.10	0.09	0.11	0.10
Range of $D_{Pl/Liq}$[1]	0.28 to 0.49	0.023 to 0.57	0.018 to 0.29	0.024 to 0.20	0.055 to 2.11		0.011 to 0.24	0.12 to 0.21		0.006 to 0.30	0.022 to 0.24

[1] Data from Higuchi and Nagasawa (1969); Schnetzler and Philpotts (1970); Nagasawa and Schnetzler (1971); Dudas, Schmitt and Harward (1971); Philpotts and Schnetzler (1970, 1972); see detailed references in Philpotts and Schnetzler [17].

the range found by several authors – see review of Philpotts and Schnetzler [17] – and they approach those reported for dacites [18]. The light REE values are, however, distinctly higher than the values usually adopted for basic rocks [19,20], which can be due to the deep-seated conditions of crystallization and/or to the chemical peculiarities of these rocks.

4.2. Eu anomaly and parental magma

The salient feature of the chondrite-normalized REE patterns (Fig. 2) is the lack of Eu anomaly in samples from E-R and a very small negative Eu anomaly (measured Eu/interpolated Eu = Eu/Eu* = 0.91) in the Hd border facies (Table 3). On the basis of partition coefficients of Eu and Eu* between phenocrysts and liquid (Table 4) and assuming a Rayleigh fractionation model [23], it can be calculated that subtraction of approximately 10 wt.% of plagioclase from a liquid devoid of an Eu anomaly is sufficient to justify the anomaly in Hd.

It is now well established (see [24,25]) that basic or intermediate undifferentiated magmas display no Eu anomaly. They are indeed generated in the upper mantle where plagioclase – the only phase capable of significantly fractionating Eu with respect to the neighbouring REE – is not stable. Only two exceptions have been reported [26]; two samples from chilled zones of the Stillwater and of the Bushveld display positive Eu anomalies. But it is not certain that these rocks really represent an undifferentiated magma [27].

It thus appears that the monzonorites studied here represent magmas which have not fractionated any plagioclase or only a small amount. Such liquids correspond to the definition of Michot's *plagioclasic magma* [28,10] and can be considered as possible *parental magmas of the anorthositic suite.*

In Hidra the lack of an Eu anomaly (or its very low value) indicates that the border rock is neither a residual liquid nor a cumulate. Its consanguinity with anorthosites being clearly shown by field relation-
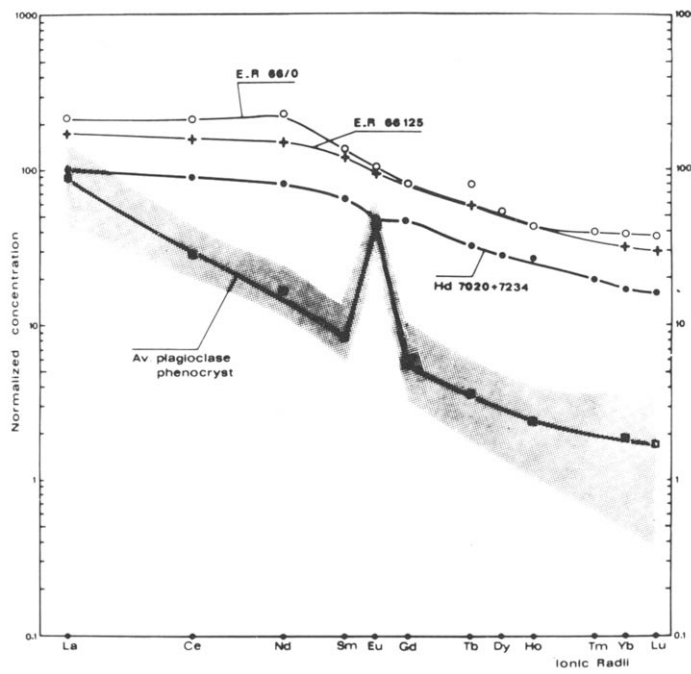

Fig. 2. Chondrite-normalized REE concentrations. O = Eia-Rekefjord monzonorite (Pa 66/0); + = Eia-Rekefjord quartz monzonorite (66125); ● = Hidra border facies (average of 7234 and matrix of 7020); □ = average of the plagioclase phenocrysts. The shaded area shows the range of REE concentrations in the different plagioclase phenocrysts analyzed (Table 2). The normalizing values used for chondrites are taken from Haskin et al. [21]. The ionic radii are taken from Whittaker and Muntus [22].

ships, the monzonorite therefore can be taken as the best representative of the parental magma of the body.

In the E-R monzonorites the lack of an Eu anomaly is difficult to reconcile with the hypothesis [8–10] that these rocks represent a residual liquid left after the formation of the leuconoritic phase of the Bjerkrem-Sogndal massif. Starting from a parental magma without Eu anomaly, the crystallization of plagioclase which has given rise to the leuconoritic phase must produce a negative anomaly in the residual liquids. This anomaly must increase during the differentiation. A decreasing An content of the plagioclase [6] and a decreasing oxygen fugacity [11] within the range of stability of Eu^{2+} and Eu^{3+} [29] have been demonstrated for successive liquids in the massif. The joint effect of these two factors [23,29] increases the positive Eu anomaly in the plagioclase and then also the negative Eu anomaly in the residual liquid. This trend has been confirmed by preliminary REE analyses on plagioclase from this massif [30].

To what extent the E-R monzonorite can give rise to the Bjerkrem-Sogndal series of rocks remains premature to assess without studying the cumulus minerals of this massif. In the present stage of knowledge, E-R could indeed represent either a new intrusion of parental magma posterior to the consolidation of the leuconoritic phase of the Bjerkrem-Sognal massif, or an intrusion completely unrelated to the Bjerkrem-Sogndal differentiation. These possibilities deserve further investigations.

4.3. Mineralogical and major element compositions (Table 1)

The presence of orthopyroxene and quartz in the norm and in the mode indicates that the rocks belong to the subalkaline series. This is confirmed on a regional scale by the mineralogy of the associated rocks; anorthosites and norites contain orthopyroxene, and acidic products, quartz and sometimes orthopyroxene (charnockitic suite).

From the chemical point of view, however, they remain difficult to classify in a classic typology of volcanic rocks (Fig. 3): they appear to be intermediate between the saturated alkaline and tholeiitic series. They display several of the chemical characteristics reported for anorthositic suite [32]: FeO/MgO and K_2O/SiO_2 ratios are high, but enrichment in Al_2O_3
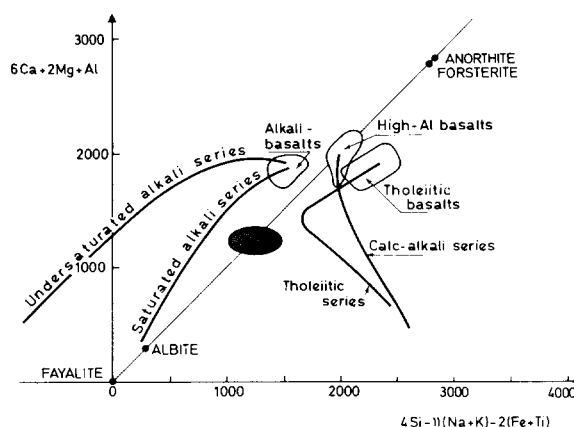

Fig. 3. Schematic representation in the diagram of De la Roche and Leterrier [31] which is a projection of the Cpx–Ol–Q–Ne tetrahedron (basaltic system of Yoder and Tilley) parallel to the critical plane Cpx–Pl–Ol of silica undersaturation. The shaded area comprises the monzonorites here studied. It is situated on the bissectrix line representing the critical plane.

is not apparent. High Ti and P values are characteristic not yet pointed out although it is reflected by the common association of Fe-Ti oxide orebodies (often rich in apatite) with anorthosites and also with the relatively high Ti and Fe contents of the plagioclase of these rocks (purple colour).

The high Ti and P contents conceal the characteristics which would permit to connect them to a known rock type. These rocks could in fact be considered as a mixture of 5–8% ilmenite and of a rock equivalent in composition to low-Si andesite. Indeed, subtraction of an amount of normative ilmenite such that the remaining TiO_2 content be equal to the average value of 0.7% reported for andesites [25], yields a residue of low-Si andesite composition.

4.4 Trace elements

The data (Tables 3 and 5) show important differences between the two intrusions. This feature and the small number of analyzed samples do not permit to deduce whether the parental magmas have basaltic [34] or andesitic [24,33] affinities.

Some pertinent geochemical features are the following:

(1) Sr and Sc show little differences between the two massifs and are similar to basalts [20] and andesite [25].

TABLE 5

Trace element concentrations in monzonoritic rocks

	Hidra massif		Eia-Rekefjord intrusion		Average andesite (27)	Low-Si andesite (33)
	7234	7020	66125	Pa 66/0		
K(%)	1.619	0.897	1.287	1.245	1.33	0.91
Rb	44[a]–42[b]	19.4[a]	7.5[e]	8[b]	31	14
Cs	0.81[e]	0.36[e]	0.02[e]		0.5	0.6
Ba	610[d]–550[e]	500[e]	1050[e]	1025[d]	270	200
Sr	381[a]–383[b]	450[a]	405[c]	420[b]–460[c]	385	430
K/Rb	368–385	462	1716	1557	430	650
K/Ba	27.8	19.4	12.2	12.1	49.3	40.5
La[1]	35.3[d]–33.4[e]	30.3[e]	57.7[e]	76.6[d]	11.9	10.3
Yb[1]	3.55[d]–3.45[e]	3.21[e]	6.27[e]	8.1[d]	1.9	1.5
La/Yb	9.8	9.5	9.2	9.5	6.3	6.9
Ta	1.22[e]	1.02[e]	1.34[e]			
Th	3.81[d]–3.44[e]	1.96[e]	0.45[e]	0.82[d]	2.2	1.34
U	1.31[d]–1.07[e]	0.85[e]	0.23[e]	0.3[d]	0.69	0.43
Zr	310[b]–292[c]	174[c]	521[c]	592[b]–619[c]	110	92
Hf	8.3[d]–6.6[e]	5[e]	13[e]	15.6[d]	2.3	1.7
Th/U	3.21	2.31	1.96	2.7	3.2	3.1
Th/K ($\times 10^4$)	2.10	2.18	0.34	0.66	1.65	1.47
U/K ($\times 10^4$)	0.65	0.95	0.18	0.24	0.52	0.47
Zr/Hf	36	35	40	40	48	54
Sc	20.2[d]–19.9[e]	20.8[e]	27.9[e]	29[d]	30	31
Cu	63[f]	14[f]	18[f]	25[f]	54	60
Co	46.8[d]–46.3[e]	47.7[e]	30[e]–30[f]	36.9[d]	24	28
Ni	55[f]	20[f]	13[f]	12[f]	18	28
V	300[f]	250[f]	133[f]	156[f]	175	200
Cr	31.8[e]	38[e]	2.6[e]	<10[f]	56	85
Ni/Co	1.18	0.42	0.43	0.35	0.75	1.0
V/Ni	5.4	12.5	10.0	13.0	9.7	7.1
Cr/V	0.10	0.15	0.03	0.06	0.32	0.43

a: Isotopic dilution (D. Demaiffe and S. Deutsch, Bruxelles); b: X-ray fluorescence (M. Delvigne and F. Durex, M.R.A.C., Tervuren); c: X-ray fluorescence (J.C. Duchesne and I. Roelandts, Liège); d: Neutron activation (J. De Winter and J. Hertogen, Ghent); e: Neutron activation (I. Roelandts, Oslo); f: Emission spectrography (D. Demaiffe, I.R.C. Tervuren).
[1] Taken from Table 3.

(2) REE, Zr and Ba are distinctly higher in E-R than in Hd and generally higher than basalts and andesites [24–26]. For the REE, this feature is probably connected with the high P content of the E-R rocks. The La/Yb ratio is identical in the two intrusions and similar "continental" basalts [26]. Compared to Hd, the Zr/Hf ratio in E-R is not different while the K/Ba ratio is distinctly lower.

(3) V/Ni and Ni/Co ratios tend to show affinities with andesites [35]. Cr is particularly depleted in E-R with respect to Hd.

(4) The most striking differences between the two massifs appears for Rb, Cs, Th and U which are relatively very low in E-R *. It follows that this massif shows a strikingly higher K/Rb ratio (av. 1636) than Hd where values (av. 420) are closer to Shaw's main K–Rb trend [37]. Contamination by "crustal" material with a lower K/Rb ratio and higher Th and U contents could account for these differences, but conflicts with $^{87}Sr/^{86}Sr$ initial ratios which are higher in E-R (0.7068) [38] than in Hd (0.7052) [5], and also with REE, Ba, Zr and major elements (SiO_2, K_2O, etc.) data.

* Similar values (Th = 0.48 ppm; U = 0.25 ppm) have been measured [36] in a monzonoritic dyke related to the E-R main body.

4.5. Petrogenetic considerations

Further data are needed to clarify the amplitude and origin of the compositional variations between the two massifs befor the origin of the magma can be understood. At this stage certain constraints can be determined.

The lack of an Eu anomaly precludes plagioclase fractionation prior to consolidation. Derivation from high-alumine, alkali and tholeiitic basalts can therefore only proceed from subtraction of mafic minerals. This would yield an Al_2O_3 increase in the resulting material. Such an increase is not observed here, as Al_2O_3 contents are lower or equal to those of basaltic magmas. Therefore, this simple mechanism must be rejected.

Direct formation of this magma through partial melting of the upper mantle must be considered. The high K/Rb values in E-R suggest that, at least in this case, amphibole has played an important role in the magma genesis. This mineral can indeed be present in the upper mantle, especially if it is carried down by a descending slab of oceanic crust [39]. Kaersutite chemistry [40] is characterized by a very high K/Rb ratio (up to 4400), a high TiO_2 content (up to 6%) and a slight enrichment in light REE with regard to heavy REE.

The main features of the behaviour of REE and K/Rb in the partial fusion of upper mantle kaersutite can be qualitatively assessed. For the minerals likely to enter the upper mantle composition (i.e. olivine, pyroxene, garnet, kaersutite) [17,41,42], the partition coefficients for the light REE are lower than those for the heavy REE and they are less than unity (except for the heavy REE in garnet). If it is assumed that kaersutite is the only mineral to melt, the bulk partition coefficients [43] between the liquid and the solid phases will always lead to higher REE contents and higher La/Yb ratios in the liquid than in the solid, irrespective of the mineralogical composition of the starting material, the amount of melt and the melting model. As for Rb and K, the only phase which significantly fractionates the two elements is amphibole. In the fusion of kaersutite the fractionation of K and Rb, i.e. the K/Rb ratio, is entirely controled by the relationship of this mineral with the liquid; the presence of the other minerals will modify the absolute values of K and Rb, not the K/Rb ratio. Distribution factors indicate that K/Rb in the liquid will be lower than in the solid. This qualitative approach thus shows that liquids produced by melting of kaersutite will be enriched in REE, and will have a higher La/Yb ratio and a lower K/Rb ratio than the initial kaersutite. Since kaersutite can have a very high K/Rb value (up to 4.400), it is possible to justify a value of 1700 in the melt. The same considerations can possibly be applied to TiO_2, which varies from about 6% in the kaersutite to lower values in the melt.

This qualitative approach also shows that the E-R and Hd magmas cannot be derived from one and the same starting material, subjected to different degrees of partial melting, because the highest K/Rb values are not found in rocks having the lowest REE contents.

The high Fe/Mg ratio of the magma with respect to kaersutite raises a difficulty which, however, can be overcome by assuming that kaersutite has only been partially melted. It is to be expected that the first liquid to appear will have a higher Fe/Mg ratio than the original mineral.

It is hoped that these results will be an incentive to further geochemical study of monzonoritic rocks related to anorthosites and lead to a better knowledge of the origin of anorthosites.

References

1 Y.W. Isachsen, Origin of anorthosite and related rocks: a summarization, in: Origin of Anorthosite and Related Rocks, Y.W. Isachsen, ed., N.Y. State Mus. Sci. Serv. Mem. 18 (1969) 435.

2 D. de Waard and E.P. Wheeler, Chemical and petrologic trends in anorthositic and associated rocks of the Nain massif, Labrador, Lithos 4 (1971) 367.

3 J.C. Duchesne, Pyroxènes et olivines dans le massif de Bjerkrem-Sogndal (Norvège méridionale). Contrib. à l'étude de la série anorthosite-mangérite, 24th I.G.C. Montréal, Sect. 2 (1972) 320.

4 T.H. Green, High-pressure experimental studies on the origin of anorthosite, Can. J. Earth Sci. 6 (1969) 427.

5 D. Demaiffe, J.C. Duchesne, J. Michot and P. Pasteels, Le massif anorthosito-leuconoritique d'Hidra et son faciès de bordure, C.R. Acad. Sci. Paris 277 (1973) D17.

6 J.C. Duchesne, Le rapport Sr/Ca dans les plagioclases du massif de Bjerkrem-Sogndal (Norvège méridionale) et son évolution dans la cristallisation fractionnée du magma plagioclasique, Chem. Geol. 8 (1971) 123.

7 J.C. Duchesne, Microtextures of Fe–Ti oxide minerals in the South Rogaland anorthositic complex (Norway), Ann. Soc. Géol. Belg. 93 (1970) 527.

8 J. Michot and P. Michot, The problem of anorthosites: the South Rogaland Igneous Complex, Southwestern Norway, in: Origin of Anorthosite and Related Rocks, Y.W. Isachsen, ed., N.Y. State Mus. Sci. Serv. Mem. 18 (1969) 399.

9 P. Michot, La géologie de la catazone: le problème des anorthosites, la palingenèse basique et la tectonique catazonale dans le Rogaland méridional, Norvège méridionale, Norges Geol. Unders. 212g (1960) 1.

10 P. Michot, Le magma plagioclasique, Geol. Rundsch. 54 (1964) 956.

11 J.C. Duchesne, Iron–Titanium oxide minerals in the Bjerkrem-Sogndal massif, Southwestern Norway, J. Petrol. 13 (1972) 57.

12 A.O. Brunfelt and E. Steinnes, Instrumental activation analysis of silicate rocks with epithermal neutrons, Anal. Chim. Acta 48 (1969) 12.

13 A.O. Brunfelt and E. Steinnes, A neutron activation scheme developed for the determination of 42 elements in lunar material, Talanta 18 (1971) 1197.

14 A.O. Brunfelt, I. Roelandts and E. Steinnes, Determination of rubidium, cesium, barium and eight rare-earth elements in ultramafic rocks by neutron activation analysis, Analyst (London) (1974) in press.

15 I. Roelandts, Thesis, Univ. of Liège (in preparation).

16 J. Hertogen and R. Gijbels, Instrumental neutron activation analysis of rocks with a low-energy photon detector, Anal. Chim. Acta 56 (1971) 61.

17 J.A. Philpotts and C.C. Schnetzler, Large trace cation partitioning in igneous processes, 24th I.G.C. Montreal Sect. 10 (1972) 51.

18 M.J. Dudas, R.A. Schmitt and M.E. Harward, Trace element partitioning between volcanic plagioclase and dacitic pyroclastic matrix, Earth Planet. Sci. Lett. 11 (1971) 440.

19 R.A. Zielinski and F.A. Frey, Gough Island: evaluation of a fractional crystallization model, Contrib. Mineral. Petrol. 29 (1970) 242.

20 P.A. Helmke and L.A. Haskin, Rare-earth elements, Co, Sc and Hf in the Steens Mountain basalts, Geochim. Cosmochim. Acta 37 (1973) 1513.

21 L.A. Haskin, T.R. Wildeman and M.A. Haskin, An accurate procedure for the determination of the rare earths by neutron activation, J. Radioanal. Chem. 1 (1968) 337.

22 E. Whittaker and R. Muntus, Ionic radii for use in geochemistry, Geochim. Cosmochim. Acta 34 (1970) 945.

23 J.A. Philpotts and C.C. Schnetzler, Europium anomalies and the genesis of basalt, Chem. Geol. 3 (1968) 5.

24 A.G. Herrmann, Yttrium and Lanthanides, in: Handbook of Geochemistry, II-3, K.H. Wedepohl, ed. (Springer Verlag, Berlin – New York, 1970).

25 S.R. Taylor, A.C. Capp, A.L. Graham and D.H. Blake, Trace element abundances in andesites, II. Saipan, Bougainville and Fiji, Contrib. Mineral. Petrol. 23 (1969) 1.

26 F.A. Frey, M.A. Haskin, J.A. Poetz and L.A. Haskin, Rare earth abundances in some basic rocks, J. Geophys. Res. 73 (1968) 6085.

27 F.A. Frey, Written communication (1974), M.I.T.

28 P. Michot, La géologie des zones profondes de l'écorce terrestre, Ann. Soc. Géol. Belg. 80 (1956) 19.

29 D.F. Weill and M.J. Drake, Europium anomaly in plagioclase feldspar: experimental results and semiquantitative model, Science 180 (1973) 1059.

30 J.C. Duchesne and I. Roelandts (in preparation).

31 H. de la Roche and J. Leterrier, Transposition du tétraèdre minéralogique de Yoder et Tilley dans un diagramme chimique de classification des roches basaltiques, C.R. Acad. Sci. Paris 276 (1973) D 3115.

32 R.F. Emslie, Some chemical characteristics of anorthositic suites and their significance, Can. J. Earth Sci. 10 (1973) 54.

33 S.R. Taylor, Trace element chemistry of andesites and associated calc-alkaline rocks, in: Proc. of the Andesite Conf., A.R. McBirney ed., Oreg. State Dep. Geol. Mineral. Ind., Bull. 65 (1969) 43.

34 M. Prinz, Geochemistry of basaltic rocks: trace elements, in: Basalts: The Poldervaart Treatise on Rocks of Basaltic Composition, 1, H.H. Hess and A. Poldervaart eds. (Interscience Publishers, New York, 1967) 271.

35 S.R. Taylor, M. Kaye, A.J.R. White, A.R. Duncan and A. Ewart, Genetic significance of Co, Cr, Ni, Sc and V content of andesites, Geochim. Cosmochim. Acta 33 (1969) 275.

36 D. Ormaasen, Written communication, Univ. of Oslo (1973).

37 D.M. Shaw, A review of K–Rb fractionation trends by covariance analysis, Geochim. Cosmochim. Acta 32 (1968) 573.

38 J. Michot and P. Pasteels, La variation du rapport (^{87}Sr/ ^{86}Sr) dans les roches génétiquement associées au magma plagioclasique, Ann. Soc. Géol. Belg. 92 (1969) 255.

39 J.G. Fitton, The generation of magmas in island arcs, Earth Planet. Sci. Lett. 11 (1971) 63.

40 S. Kesson and R.C. Price, The major and trace element chemistry of kaersutite and its bearing on the petrogenesis of alkaline rocks, Contrib. Mineral. Petrol. 35 (1972) 119.

41 H. Higuchi and H. Nagasawa, Partition of trace elements between rock forming minerals and the host volcanic rocks, Earth Planet. Sci. Lett. 7 (1969) 281.

42 H. Nagasawa, Rare-earth distribution in alkali rocks from Oki-Dogo island, Japan, Contrib. Mineral. Petrol. 39 (1973) 301.

43 D.M. Shaw, Trace element fractionation during anatexis, Geochim. Cosmochim. Acta 34 (1970) 237.