

ISOTOPIC CONSTRAINTS ON THE GENESIS OF THE ROGALAND ANORTHOSITIC SUITE (SOUTHWEST NORWAY)

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Abstract

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Isotopic data were obtained on the Sveconorwegian (1200-900 Ma) anorthosites and associated norites and charnockites of the Rogaland igneous complex (SW Norway).

The isotopic data ($I_{Sr} = 0.703-0.7077$; $\epsilon_{Nd} = +0.4$ to $+5.5$; $^{238}U/^{204}Pb$ (μ_1) $\simeq 8.1-8.2$; $\delta^{18}O = +5.2$ to $+6.6\%$) suggest an upper-mantle origin for the parental magma of the anorthosites and related norites and jotunitites or an origin in the lower crust by melting of mantle-derived basic rocks shortly after their formation. In two well-documented cases (the Egersund-Ogna and the Hydra bodies) a progressive contamination by U-depleted but not Rb-depleted lower-crustal material is apparent during the differentiation process; the late-stage liquids have higher I_{Sr} (up to 0.7086), lower (but still slightly positive) ϵ_{Nd} , less radiogenic Pb isotopic composition.

The intrusive acidic rocks, some of them of the charnockitic type, display variable isotopic data ($I_{Sr} = 0.7055-0.709$; $\epsilon_{Nd} = +0.5$ to -0.8 ; Pb isotopic compositions comparable to that of some of the surrounding gneisses), suggesting that there are, in general, no direct cogenetic relations between the anorthosites and the charnockites. Our data point to an origin of some of these acidic rocks by anatexic melting of the surrounding high-grade metamorphic gneisses.

1. Introduction

The existence of large, batholithic size, anorthositic bodies constitutes a major constraint for the Earth's evolution during the Mid-Proterozoic (1700-900 Ma). These bodies, together with the spatially and temporally associated charnockites and rapakivi granites define one or two broad belts on the Proterozoic supercontinent (Herz, 1969; Bridgwater and Windley, 1973; Piper, 1976). The most documented

anorthosites occur in the North Atlantic Craton: in the Grenville, Churchill and Nain Provinces of North America and in the Sveconorwegian province of the Baltic Shield. Buddington (1939) and P. Michot (1939) have pioneered the study of the anorthosites in the Adirondacks Mountains (New York) and in the Rogaland Complex (S. Norway), respectively.

Several reviews on the anorthosite problem have been recently published (Isachsen, 1969; J. Michot, 1972; De Waard et al., 1974; Duchesne and Demaiffe, 1978; Morse, 1982;

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Duchesne, 1984; Emslie, 1985; Duchesne et al., 1985a). A general consensus is far from being attained. This paper, focused on the Rogaland Complex of south Norway, is meant to contribute to the anorthosite debate by using Sr, Pb and Nd isotopes as petrogenetic constraints.

2. The Rogaland Complex

The Rogaland igneous complex of southwestern Norway (Fig. 1) is a composite intrusive massif belonging to the Sveconorwegian orogenic belt, which is considered as the European counterpart of the Grenville Province (Berthelsen, 1980).

A review of the geochronological evolution of that part of the Baltic Shield has been published recently (Demaiffe and Michot, 1985; and references therein). Two high-grade metamorphic episodes — at ~1200 and 1050–1000 Ma, respectively — have been documented; the occurrence of a pre-Sveconorwegian (=pre-Grenvillian) basement is clearly recognized in the eastern part of the belt (Bamble and

Østfold sectors) while it is less obvious in the western part (Rogaland, Agder). The emplacement of the anorthosites and related plutonic rocks ended with the closure of the orogeny.

Detailed field, petrological and geochronological investigations have given a relatively clear picture of the geological evolution of the Rogaland magmatic complex (P. Michot, 1960; J. Michot and Michot, 1969; Duchesne et al., 1986). In the last 15 years, geochemical and isotopic data (J. Michot and Pasteels, 1969; Duchesne and Demaiffe, 1978; Demaiffe and Hertogen, 1981; Duchesne et al., 1985a,b) have put additional constraints on the genesis of the parental magma (or magmas?) of the anorthosite suite of rocks, on the differentiation process and on the petrogenetic relations between the anorthosites and the related acidic rocks (mostly of charnockitic type). Despite their monotonous mineralogy, the anorthosite bodies and associated noritic and charnockitic rocks can be classified in three distinct, partly overlapping magmatic series — the basaltic, jotunitic and acidic series — each starting from

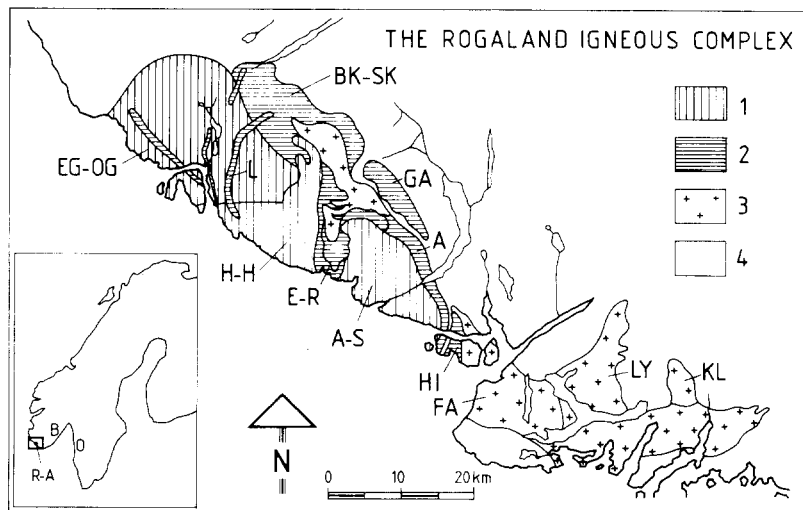


Fig. 1. Schematic geological map of the Rogaland Complex (from J. Michot and Michot, 1969, modified), showing the different intrusions belonging to the three magmatic series (1 = basaltic series; 2 = jotunitic series; 3 = charnockitic series; 4 = gneisses). EG-OG = Egersund-Ogna; H-H = Håland-Helleren; A-S = Åna-Sira; BK-SK = Bjerkreim-Sokndal; GA = Garsaknatt; HI = Hydra; A = apophysis; L = Lomland dyke; E-R = Eia-Rekefjord; FA = Farsund; LY = Lyngdal; KL = Kleivan. Inset map: main geological provinces of south Norway (O = Østfold; B = Bamble; R-A = Rogaland-Agder).

a distinct parental magma and displaying typical associations and features (Duchesne, 1984; Duchesne et al., 1985a).

2.1. *The basaltic series*

The three large massif-type anorthositic bodies (Egersund–Ogna, Håland–Helleren and Åna–Sira) belong to that series. They consist essentially of coarse-grained anorthosites containing large (up to 1 m) plagioclase and Al_2O_3 -rich orthopyroxene megacrysts and blocky inclusions of banded and/or gneissic leuconorites–norites. Late-stage residual liquids appear as crystal-laden leuconoritic to noritic dykes. The origin of the blocky inclusions is still controversial. For J. Michot (1961), the composite Håland–Helleren body results from the partial melting (basic palingenesis) of a previous anorthositic–leuconoritic basement, partly preserved in the Håland layered unit and in the blocky inclusions; the anatectic melt which still contains residual (unmelted) plagioclase has given rise to the Helleren diapiric intrusion. A similar model was also suggested by Anderson and Morin (1969). For Duchesne (1984) and Maquil and Duchesne (1984), the blocky inclusions are fragments of inner margins of the massifs themselves, deformed by the diapiric emplacement of the central part of the massif (synemplacement deformation).

As chilled margins have not been observed in these bodies, only indirect evidence can be used to constrain the nature of the parental magma. A *basaltic magma* has been suggested on the basis: (1) of the high transition-element contents, especially Cr (400–1200 ppm), of the orthopyroxene megacrysts (Maquil and Duchesne, 1984); and (2) of overall geochemical similarities of these megacrysts in other provinces and especially in Labrador where chilled margins of basaltic composition have been found (Emslie, 1985).

2.2. *The jotunitic series*

A fine-grained chilled margin of jotunitic (= hypersthene monzodiorite = monzonorite)

composition has been observed in the Hydra and Garsaknatt leuconoritic massifs (Duchesne et al., 1974; Demaiffe and Hertogen, 1981) as well as in the Bjerkreim–Sokndal layered lopolith. Jotunites also occur as large dykes cutting across the massif-type anorthosites and as intrusions (Eia–Rekefjord, and Apophysis) emplaced along the contacts of the latter massifs. When differentiated, i.e. as in Hydra and Bjerkreim–Sokndal (P. Michot, 1965), the jotunites give rise to leuconoritic and noritic cumulates with subsidiary amounts of true anorthositic cumulates (no Al_2O_3 -rich orthopyroxene megacrysts) and to residual acidic liquid (quartz mangerite, charnockite) usually contaminated by the surrounding granulite-facies gneisses (Pasteels et al., 1970; Demaiffe et al., 1979).

2.3. *The charnockitic series*

Three acidic massifs, penecontemporaneous with the anorthositic plutonism, occur at the southeastern extremity of the igneous province (Falkum et al., 1979): the Farsund charnockite, the Lyngdal granodiorite and the Kleivan granite. These rocks show chemical similarities with the quartz mangerites of the upper part of the Bjerkreim–Sokndal lopolith but, contrarily to these ones, do not show any relationships with noritic cumulates. The acidic rocks can differentiate from charnockitic to granitic rocks as particularly well displayed in the Kleivan granite. Anatexis of crustal material, differentiation of basaltic or jotunitic magmas, or a combination of both processes through contamination (Demaiffe et al., 1979; Petersen, 1980a,b) have been invoked to account for their formation.

3. Analytical methods

Sr was separated by conventional cation-exchange techniques and its isotopic composition was measured by thermo-ionisation either on the Varian® TH5 or on the Finnigan® MAT

260 mass spectrometers of the Belgian Centre for Geochronology. On the MAT 260 machine, the NBS 987 standard has a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.71024 ± 0.00003 ($2\sigma_m$) normalized to $^{88}\text{Sr}/^{86}\text{Sr} = 8.3752$. For the Pb analytical procedure, see Weis (1986 in this special issue). The Nd was separated from the other rare-earth elements (REE) using HDEHP on Teflon[®] powder (for detailed procedure, see Weis and Deutsch, 1984). Nd was measured on double Re filament as Nd ions on the Finnigan[®] MAT 260 mass spectrometer.

For the Nd standard solutions (Wasserburg et al., 1981), the following values were obtained: $^{143}\text{Nd}/^{144}\text{Nd} = 0.51200 \pm 0.00004$; $^{145}\text{Nd}/^{144}\text{Nd} = 0.34834$, normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. Because of systematic and reproducible differences with the Caltech values (0.51193 and 0.34832, respectively), all measured $^{143}\text{Nd}/^{144}\text{Nd}$ ratios were lowered by $8 \cdot 10^{-5}$.

4. Isotope geochemistry

Trace elements, especially the REE, have been used to model the differentiation process in several massifs, especially those belonging to the jotunitic series (Duchesne and Demaiffe, 1978; Demaiffe and Hertogen, 1981; Duchesne et al., 1985b). Detailed studies have been published on specific intrusions: the Bjerkreim-Sokndal lopolith (Roelandts and Duchesne, 1979), the charnockites (Demaiffe et al., 1979), the Hidra body (Demaiffe and Hertogen, 1981) and the jotunitic dykes (Duchesne et al., 1985b). These studies have permitted better definition of the characteristics of the three parental magmas. Complementary isotopic studies have thrown some light on the nature of the possible source-regions of these three magmas. Three main reservoirs with distinct geochemical (Rb/Sr, Sm/Nd, U/Pb, Th/Pb) and consequently isotopic ($^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$) signatures can be the source of igneous rocks: the upper mantle with its depleted uppermost layer, the lower continen-

tal crust (mainly in the granulite facies) and the upper crust.

In the case of the Rogaland anorthosites, as elsewhere in the Grenville Province, the upper continental crust can be ruled out as a source-region. Indeed, the igneous rocks were emplaced at a depth of 22–28 km (Wilmart and Duchesne, 1986) in high-grade granulite facies terranes (Jansen et al., 1985). It is thus excluded that the crust lying above the depth of emplacement could have been involved in the formation of the magmas. There are only two possibilities left: the upper (depleted) mantle and the lower crust. The large-ion lithophile (LIL) depleted nature of granulite-facies rocks have been recognized in a number of cases (see Newton, 1985) but is far from being admitted as a general phenomenon (Ben Othman et al., 1984) or as having affected all LIL elements to the same degree (Rollinson and Windley, 1980). If the depletion has taken place, it has induced isotopic convergences between the upper mantle and the lower-crust reservoirs for both strontium and oxygen isotopic systems.

4.1. Sr isotopic composition

Selected Rb–Sr isotopic results are given in Table I and in Fig. 2. In each magmatic series, a wide spectrum of rocks and minerals was analysed: anorthosite, leuconorite, orthopyroxene and plagioclase megacrysts, norites, jotunites, charnockites. Preliminary data have been published and discussed by Michot and Pasteels (1969), Demaiffe et al. (1974) and Duchesne and Demaiffe (1978).

The plagioclase-rich rocks generally have very low Rb/Sr ratios (typically < 0.01) so that it is usually not possible to draw Rb–Sr isochrons. For most Rogaland massifs, the initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios consequently have been calculated assuming an age of 1 Ga. The initial ratios show large between-plutons variations, from 0.7030 for both plagioclase and orthopyroxene megacrysts of the Egersund–Ogna massif up to 0.7077 for the Lomland jotunitic dyke;

TABLE I

Rb-Sr isotopic and composition data for selected samples of the Rogaland Complex

Sample No.	Mineralogy	Rb (ppm)	Sr (ppm)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}$		$I_{\text{Sr}}, t = 1000 \text{ Ma}$
					x	$\pm 2\sigma$	
ANORTHOSITIC ROCKS							
<i>Egersund-Ogna:</i>							
83-0	plagioclase	1.9	913.8	0.0060	0.70347	± 0.00003	0.7034
83-0-1D	orthopyroxene	0.97	27.7	0.1013	0.70563	± 0.00007	0.7041
75-09-1	plagioclase	1.13	933.7	0.0035	0.70338	± 0.00008	0.7033
66-119-2B	orthopyroxene	0.8	6.9	0.3356	0.70925	± 0.00013	0.7044
5/75	anorthosite	0.9	425	0.0061	0.70450	± 0.00020	0.7044
66/46	leuconorite	2.4	299.3	0.0231	0.70509	± 0.00005	0.7047
<i>Håland-Helleren:</i>							
60/64	anorthosite	0.4	677	0.0017	0.70512	± 0.00005	0.7051
19E	leuconorite	2.2	813	0.0078	0.70556	± 0.00004	0.7054
91C	banded leuconorite	2.6	597	0.0126	0.70557	± 0.00005	0.7054
89C	leuconorite	0.2	592	0.0010	0.70620	± 0.00010	0.7062
162B	anorthosite	1.8	797	0.0065	0.70585	± 0.00005	0.7057
<i>Hidra (1):</i>							
058-1/1	anorthosite	3.4	722	0.1363	0.7077	± 0.0003	0.7057
249-1/1	leuconorite	7.7	438	0.0510	0.7062	± 0.0004	0.7055
065-1/1	plagioclase	4.4	915	0.0138	0.7055	± 0.0004	0.7053
200-2/2	jotunitite	2.3	372	0.1789	0.7087	± 0.0002	0.7061
283-2/2	charnockite						0.7086*
JOTUNITIC DYKES (2)							
Vettaland dyke							0.7060*
Lomland dyke							0.7080*
ACIDIC ROCKS							
Bjerkreim-Sokndal quartz mangerites (3)							0.7085*
Lyngdal granodiorite (4)							0.7054*
Farsund charnockite (2, 4)							0.709*
Kleivan granite (5)							0.7055*
GNEISSES							
Migmatites, granitic gneisses (6)							0.707-0.715
Liland augen gneiss (6)							0.705

References: 1 = Demaiffe and Hertogen (1981); 2 = Duchesne et al. (1985b); 3 = see discussion in Duchesne and Demaiffe (1978); 4 = Pedersen and Falkum (1975); 5 = Petersen and Pedersen (1978); 6 = D. Demaiffe (unpublished data, 1985).

*Initial ratio deduced from Rb-Sr whole-rock isochrons for the acidic rocks or assuming an age of 950 Ma (U-Pb zircon age) for the jotunitic dykes.

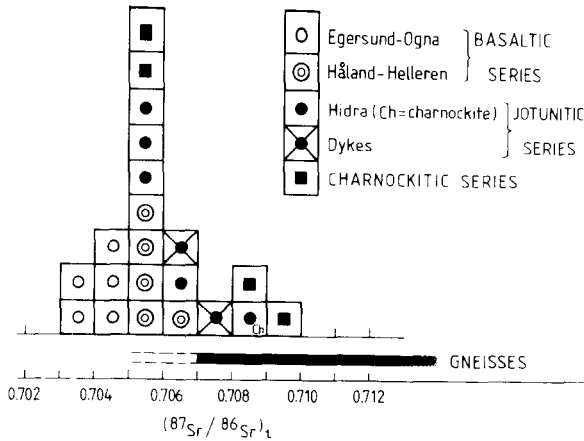


Fig. 2. Initial Sr isotopic composition for selected rocks of the three magmatic series (for the acidic rocks, the initial ratio is deduced from Rb-Sr whole-rock isochrons).

many values including those for Håland-Helleren, Hydra, Garsaknatt and the lower part of Bjerkreim-Sokndal are close to 0.7055 ± 0.0005 . Intra-plutonic isotopic variations have been observed in Egersund-Ogna: the increase of $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.7033 in the central part to 0.7045 in the border leuconorites (which also have higher Rb contents) has been ascribed to contamination by the surrounding gneisses. However, the high Sr content of these rocks, together with the low Rb/Sr ratios could imply that the contamination occurred in the melt before crystallization of the Sr-rich plagioclase.

The lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (Egersund-Ogna megacrysts: ~ 0.7030) is compatible with a mantle origin for the parental magma of Egersund-Ogna at 1 Ga but does not rule out a process of partial melting of a strongly Rb-depleted lower crust. Most other values, in the range of 0.7050–0.7077 are significantly higher than mantle values. A direct mantle origin is thus unlikely and the data point to either the contamination of a mantle derived magma with crustal material or direct partial melting of lower crust, i.e. less LIL depleted than the source of the Egersund-Ogna massif. In the Rogaland Complex, contrarily to what is observed in the Adirondacks, there is no regional metamorphic overprint, so that the

increase of the initial ratio cannot be due to a metamorphic recrystallization of the rocks. The contamination process is difficult to ascertain; bulk assimilation appears unlikely for the anorthosites because of field, mineralogical and chemical similarities between “uncontaminated and contaminated” anorthositic samples. Interaction with fluids derived from the country rocks and/or selective contamination cannot be discarded but it must be recalled that anorthosites are essentially “dry rocks”. It is to be noted, in this respect, that, while most rocks fall in a narrow range of $\delta^{18}\text{O}$ -values: $+5.2$ to $+7\text{‰}$ (Demaiffe and Javoy, 1980), small departures from the normal mantle range ($+5.5$ to $+6\text{‰}$) call for some kind of interaction with country rocks.

The acidic rocks also display quite a large range of $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios (deduced from Rb-Sr whole-rock isochrons). The late-stage liquid of the differentiation process in the Hydra body, occurring as a stockwork of charnockitic dykes, and the quartz mangeritic unit of the Bjerkreim-Sokndal lopolith have higher Sr isotopic initial ratio than in the associated plagioclasic cumulates: 0.7086 for Hydra and 0.7080 for Bjerkreim-Sokndal. However, it is not a general rule: in the Lomland dyke, the most SiO_2 -rich rocks have the same Sr isotopic composition as the associated, less-differentiated norites.

The Lyngdal and Kleivan granites have similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, around 0.7055 (Pedersen and Falkum, 1975; Petersen and Pedersen, 1978). An initial ratio of 0.713 has been reported (Pedersen and Falkum, 1975) for the Farsund charnockite; it is deduced from an ill-defined isochron which gives a much younger age (834 Ma) than the zircon U-Pb age (930 Ma; Pasteels et al., 1979). Recalculated at 930 Ma, the initial ratio is close to 0.709. As various types of gneisses from the metamorphic envelope show a range of Sr isotopic composition, from 0.7050 for an augen gneiss, up to 0.715 for charnockitic migmatites (Verstevee, 1975; D. Demaiffe, unpublished data, 1985), an origin of the mag-

matic acidic rocks by anatectic melting cannot be ruled out.

4.2. Pb isotopic composition

Pb isotope composition has been measured for more than 100 samples of the different units of the Rogaland Complex and the surrounding gneisses. Discussion of the data for two restricted cases (Hydra body and the granulite facies gneisses) have been published previously (Weis and Demaiffe, 1983a,b). A detailed discussion of all these data is presented by Weis (1986 in this special issue). Only the points relevant to the discussion in this paper are presented here.

In two well-documented cases (Fig. 3), the Hydra jotunite and the megacrysts (Opx and Plag) in Egersund-Ogna have the most radiogenic initial Pb isotopic composition: according to Zartman and Doe's (1981) plumbotectonics model, these initial ratios corresponding to a μ_1 ($^{238}\text{U}/^{204}\text{Pb}$) value of 8–8.2 are much closer to that of the mantle ($\mu_1 = 8.5$)

at that time (1 Ga ago) than to that of the lower crust ($\mu_1 = 6$). These data thus suggest an origin in the mantle. Nevertheless, it is not possible to exclude an origin by remelting of mantle-derived basic rocks shortly after their formation. In the $(^{207}\text{Pb}/^{204}\text{Pb})_i$ vs. $(^{206}\text{Pb}/^{204}\text{Pb})_i$ diagram (Fig. 3), linear arrays appear for both the Hydra and Egersund-Ogna bodies: the end-products of the differentiation process (Hydra charnockitic dyke and Egersund-Ogna noritic dyke) have clearly less radiogenic Pb isotopic compositions, closer to those of the surrounding granulite-facies gneisses (Weis and Demaiffe, 1983a). As developed by Weis (1986 in this special issue), these linear arrays could correspond to mixing lines showing the progressive contamination of a mantle-derived magma by crustal material during the differentiation process.

The average Pb isotopic compositions of the Lyngdal and Kleivan granites are comparable to those of the country-rock gneisses while the Farsund charnockite and the Bjerkreim-Sokndal quartz mangerites are more radi-

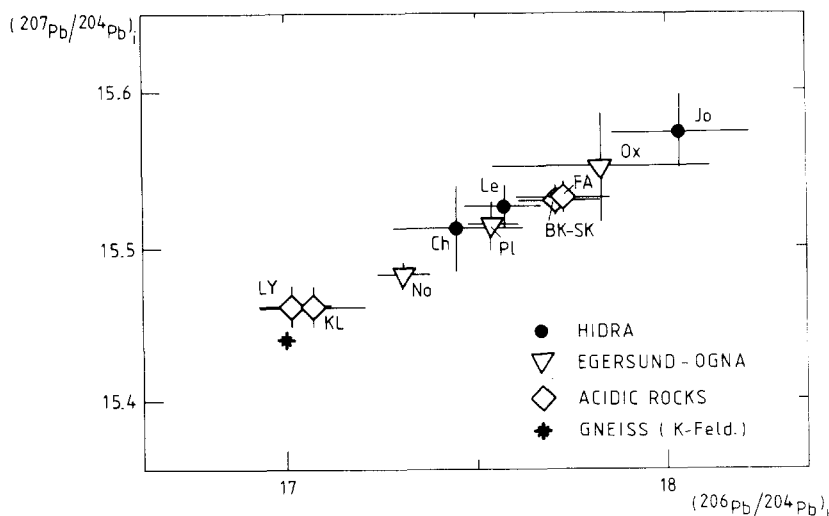


Fig. 3. Initial Pb isotopic composition of the main units of the Rogaland Complex. Each point corresponds to the average of several data on several samples. The error bars are given at the $2\sigma_m$ level of the mean (see Weis, 1986 in this special issue for the detailed data). Hydra: Jo = jotunite; Le = leuconorite; Ch = charnockitic dyke. Egersund-Ogna: Ox = orthopyroxene megacryst; Pl = plagioclase megacryst; No = late-stage norite. The different units in the acidic rocks are: Fa = Farsund charnockite; BK-SK = Bjerkreim-Sokndal quartz mangerites; KL = Kleivan granite; LY = Lyngdal granite.

ogenic and close to each other. The former intrusions could represent the products of anatectic melting of actually exposed gneisses or their equivalents at depth while the origin of the latter two is not well constrained by the Pb data. It must be recalled that these two bodies also have rather comparable Sr isotopic ratios, suggesting a similar origin. Both Sr and Pb isotopic systems lead to an ambiguous answer regarding a pure anatectic mode of formation of these rocks.

4.3. Nd isotopic composition

Few preliminary Nd isotopic data are reported in Table II and in Fig. 4, in terms of ϵ'_{Nd} -values (DePaolo and Wasserburg, 1976), deviations in parts per 10^4 from the value of $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of the chondritic uniform reservoir (CHUR) at the age t .

In contrast with the Sr isotopic composition, the Nd isotopic composition can provide an unambiguous criterion for the origin of a magma in the lower crust or in the upper mantle: indeed, the general light rare-earth element (LREE) enriched trend for crustal rocks [$\text{Sm}/\text{Nd} < (\text{Sm}/\text{Nd})_{\text{chondrites}}$] yields negative ϵ'_{Nd} -values while the upper mantle gives positive ϵ'_{Nd} when depleted, or zero value when less depleted or undepleted.

The "initial" Nd isotopic compositions, expressed as ϵ'_{Nd} -values, at $t = 1$ Ga, are positive for the large massif-type anorthosites of the basaltic series (Fig. 4): +1.9 to +4.6 for the orthopyroxene and plagioclase megacrysts in Egersund-Ogna and for two facies of the Håland body (Menuge, 1983). Positive $\epsilon'_{\text{Nd}}^{935}$ -values, +1.8 to +5.5, are also found in the Hydra jotunitic series. These values are in good agreement with the data reported by Ashwal and Wooden (1983a,b, 1985) for some anorthosites of the Grenville Province (Adirondacks, St. Urbain, Mealy Mountains).

These positive values strongly suggest that old crustal materials with LREE enrichment can be ruled out as potential sources for the

parental magmas of both the basaltic and the jotunitic series. Possible source materials are necessarily characterized by LREE depletion, that is by a time-integrated Sm/Nd ratio higher than in the chondritic reservoir: this condition is fulfilled by a depleted mantle source like the mid-ocean ridge basalt (MORB) type source or by pyroxene-rich mafic to ultramafic cumulates. Interestingly, a similar source material has recently been proposed (Duchesne et al., 1985b) to explain the REE patterns of a large jotunitic dyke of the province.

Nd isotopic data could be useful to test the leuconoritic anatexis model of J. Michot (1961). Plagioclase-rich cumulates typically have LREE-enriched patterns (e.g., Duchesne and Demaiffe, 1978; Simmons and Hanson, 1978): the $^{147}\text{Sm}/^{144}\text{Nd}$ ratios for anorthosite, leuconorite (= gabbroic anorthosite) and separated plagioclases fall in the narrow range 0.09–0.13 (Ashwal and Wooden, 1983a; Menuge, 1983; this paper), much lower than in the chondritic reservoir ($^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$). Remelting of such cumulates should give negative ϵ'_{Nd} -values except if the remelting process takes place not later than 200 Ma after the primary crystallization. Indeed, suppose a leuconoritic body with an average $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of 0.12, emplaced at 1.5 Ga and derived from a depleted mantle source with an ϵ'_{Nd} -value of +4 (DePaolo, 1981). If this body is substantially melted at 1 Ga, that is after 500 Ma of ^{147}Sm decaying, the $\epsilon'_{\text{Nd}}^{1000}$ of the newly formed melt is close to -1. If the melting event occurs only 200 Ma after the magmatic crystallization, the $\epsilon'_{\text{Nd}}^{1000}$ -value is reduced to +2 from its original +4 value 200 Ma before. The rather high positive $\epsilon'_{\text{Nd}}^{1000}$ -values, around +4, observed for the anorthositic bodies imply that, if the basic pal-ingensis has been operative, the original material should have an ϵ'_{Nd} -value close to +6 (if melting occurs 200 Ma after crystallization) or as high as +9 (if melting occurs 500 Ma after crystallization): this last value appears much too high for Proterozoic (1500–1000 Ma) depleted sources (DePaolo, 1981). Thus, if basic

TABLE II

Sm-Nd isotopic and concentration data for selected samples from the Rogaland Complex

Sample No.	Petrography	Sm (ppm)	Nd (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$		ϵ_{Nd}^t
					x	$\pm 2\sigma$	
ANORTHOSITIC ROCKS							
<i>Egersund—Ogna:</i>							
							$t = 1000 \text{ Ma}$
83-0	plagioclase megacrysts	0.48	2.35	0.1235	0.51235 ± 0.00006		+3.7
83-0-1D	orthopyroxene megacrysts	0.27	0.74	0.2206	0.51299 ± 0.00010		+3.7
75-09-1	plagioclase megacrysts	0.17	0.84	0.1238	0.51240 ± 0.00013		+4.6
<i>Håland—Helleren*:</i>							
							$t = 1000 \text{ Ma}$
R11.4	} pyroxene-poor anorthosite	0.234	1.452	0.0976	0.51217 ± 0.00002		+3.5
R11.9		0.234	1.447	0.0979	0.51220 ± 0.00002		+4.0
R12.1	} pyroxene-rich anorthosite	0.924	4.696	0.1190	0.51223 ± 0.00001		+1.9
R12.2		0.593	3.155	0.1136	0.51205 ± 0.00002		0.0
<i>Hidra:</i>							
							$t = 935 \text{ Ma}$
058-1/1	anorthosite	3.56	20.69	0.1040	0.51236 ± 0.00006		+5.5
249-1/1	leuconorite	1.494	7.01	0.1290	0.51246 ± 0.00006		+4.7
065-1/5	plagioclase	0.611	3.985	0.0927	0.51209 ± 0.00012		+1.8
200-2/2	jotunite	6.402	29.51	0.1311	0.51237 ± 0.00002		+2.7
283-2/2	charnockite	19.69	108.5	0.1021	0.51214 ± 0.00002		+1.6

*In Menuge (1983) the samples were reported as belonging to the Egersund-Ogna massif but they actually come from the Håland massif (J. Menuge, pers. commun., 1985).

palingenesis is to be accepted, the time of formation of the banded basement was relatively close (< 200 Ma) to the time of its remelting and final emplacement.

In the differentiated Hidra leuconoritic body, the $\epsilon_{\text{Nd}}^{935}$ -values and the initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are negatively correlated (Fig. 5): the charnockitic dyke has the lowest ϵ_{Nd} -value (+1.6) and the highest $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio. This could result either from progressive contamination of the depleted parental material (high ϵ_{Nd}) with high-Rb/Sr, low-Sm/Nd crustal material (fractional crystallization-assimilation process) or from mixing between a crustal melt and

the residual liquid of the anorthosite differentiation.

The acidic rocks have ϵ_{Nd}^t -values closer to zero or slightly negative (Fig. 4b): +0.5 to +0.8 and -0.5 to -0.8 for the Farsund charnockite and for Lyngdal granite, respectively (Menuge, 1983). These data show that there are, in general, no direct comagmatic relations between the anorthosites and the charnockites. From petrological and geochemical data, it appears unlikely that the acidic rocks were derived from an undepleted chondritic reservoir. As shown in the Nd-Sr diagram (Fig. 5), it seems more plausible that they result from the partial melt-

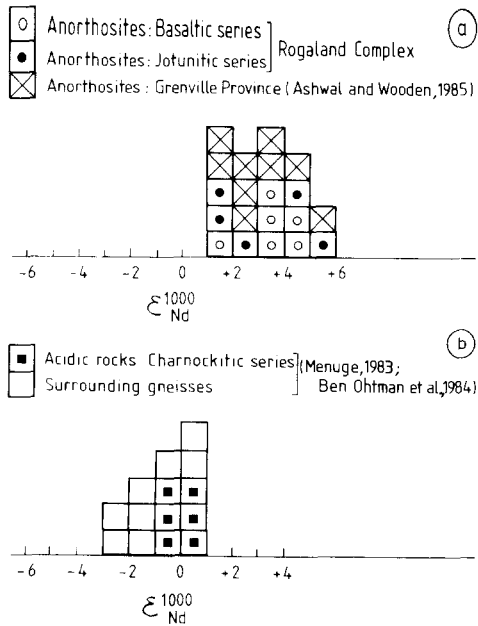


Fig. 4. a. Histogram of the ϵ_{Nd}^{1000} -values for the anorthosites of the basaltic and jotunitic series, including the data of Menuge (1983). The data obtained by Ashwal and Wooden (1985) for the anorthosites of the Grenville Province are reported for comparison.

b. Histogram of the ϵ_{Nd}^{1000} -values for the acidic rocks of the charnockitic series and for surrounding gneisses (from Menuge, 1983; Ben Othman et al., 1984).

ing of crustal materials rather than from a contamination process. The ϵ_{Nd}^{1000} -values of surrounding granulite- to amphibolite-facies gneisses fall in the narrow range of +0.9 to -2.3 (Menuge, 1983; Ben Othman et al., 1984).

5. Conclusions

(1) The anorthosites and related norites from both the basaltic and jotunitic series have isotopic signatures suggesting an origin in the depleted upper mantle or by melting, in the lower crust, of basic rocks (pyroxene-rich cumulates) with time-integrated LREE depletion and derived from the mantle shortly before, for the following reasons: (a) the model μ_1 ($^{238}\text{U}/^{204}\text{Pb}$) value is close to 8–8.2; (b) the ϵ_{Nd}^t -values are positive, in the range +1.9 to +5.5; and (c) the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio is 0.7030.

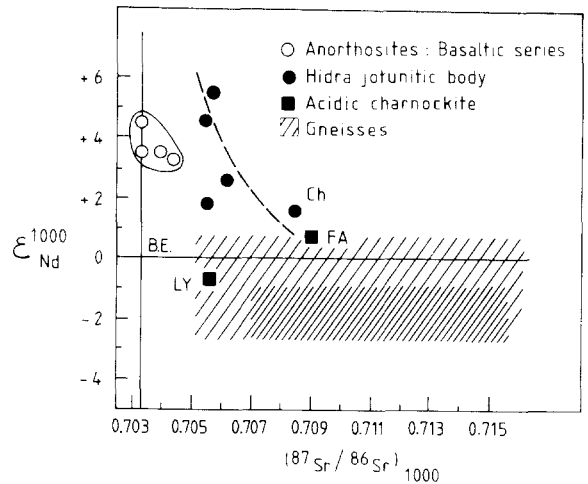


Fig. 5. Nd-Sr isotopic diagram. The dashed line is a hypothetical mixing line drawn through the Hydra data (*Ch*=charnockitic dyke). *FA*=Farsund charnockite; *LY*=Lyngdal granite. Most gneisses (Menuge, 1983) fall in a narrow band (heavily hatched) corresponding to $\epsilon_{Nd}^{1000} = -1.0$ to -2.8 and $(^{87}\text{Sr}/^{86}\text{Sr})_{1000} = 0.707$ – 0.715 . Two samples with higher ϵ_{Nd} -values (+0.2 and +0.9) and one sample with a lower $(^{87}\text{Sr}/^{86}\text{Sr})_{1000}$ of 0.705 have been reported and indicated as lightly hatched zone. *B.E.* corresponds to the bulk-earth values at 1000 Ma.

(2) During the differentiation process, progressive contamination of the primary magmas by U-depleted, but not Rb-depleted, granulite-facies gneisses can take place (but is not a general rule): the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio increases while the Pb isotopic compositions became less radiogenic, the ϵ_{Nd}^t -values decrease (from +5.5 to +1.6 in Hydra).

(3) The large acidic bodies display variable $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, their ϵ_{Nd}^t -values are close to zero or slightly negative; their Pb isotopic compositions are variable but tend to be relatively unradiogenic in comparison with those of the anorthosites. An anatectic origin is favoured for the Lyngdal and Kleivan granites, but the isotopic data (especially the Pb data) give ambiguous results for the Farsund charnockite and the quartz mangerites of the Bjerkreim–Sokndal lopolith.

(4) Although few isotopic data (especially Nd and Pb) have been published on Proterozoic massif-type anorthosites, our conclusions

for the Rogaland Complex of SW Norway are in good agreement with the recent data of Ashwal and Wooden (1983a,b, 1985) on some Grenville anorthosite bodies. However, the negative ϵ_{Nd}^t -values obtained for the Harp Lake and Kiglapait bodies of the Labrador Province (Ashwal and Wooden, 1983a; DePaolo, 1985) show that there is probably not a unique model of anorthosite petrogenesis.

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