

Origin and evolution of monzonorites related to anorthosites

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Abstract

Monzonorites from Rogaland are intimately associated with massif-type anorthosites. Together with their related rocks, they show a continuous compositional trend extending to quartz mangerites, i.e. a ferrobasaltic alkali-calcic series.

Sr isotopes show crustal affinities which cannot be explained by simple contamination. Differentiation towards acidic rocks is explained by extraction of anhydrous minerals as in the cumulate rocks of the neighbouring Bjerkreim-Sokndal lopolith. This gives rise to a virtually constant FeO/MgO evolution (Bowen trend).

Monzonorites, though more alkali rich, belong to the ferrobasalt family and their evolution can be compared to HUNTER and SPARKS' (1987) Skaergaard liquid line of descent. The alkali-calcic character of the series is maintained during the evolution due to the high pressure conditions of crystallization. The geochemical similarity of the Rogaland monzonorite series with the Crater of the Moon rocks (Snake River Plain, Idaho) is evident.

Monzonorites are not parental to massif-type anorthosites nor residual after their formation but can result from partial dry melting of basic rocks. This is in good agreement with experimental data (BAKER and EGGLE, 1987). The Crater of the Moon series has a similar origin except that the heat necessary for melting is provided by mafic rocks and not by igneous anorthosites.

Keywords: Magmatic evolution, ferrobasalt, monzonorite, anorthosite, geochemistry, Rogaland.

Introduction

Monzonorites associated with massif-type anorthosites are relevant to the evolution of ferrobasalts. Revival of the Bowen-Fenner debate concerning the Skaergaard liquid line of descent (HUNTER and SPARKS, 1987) has emphasized the need for more quantitative data on the differentiation of ferrobasaltic liquids.

Monzonorites also afford evidence that melting of basic material can give rise to ferrobasaltic liquids. Recent data (DEMAIFFE et al., 1986; DUCHESNE et al., 1989) preclude a direct relationship with massif-type anorthosites and point to an origin as partial melts of basic rocks in granulite facies conditions.

The purpose of the present paper is to review the current state of knowledge on monzonoritic rocks associated with the Rogaland anorthosites (S.W. Norway), to compare them with other occurrences in anorthosites, with other ferrobasalts and with some peculiar volcanic series, and to contribute to the understanding of the mechanisms of formation and evolution of ferrobasaltic liquids from intermediate to acidic rocks.

Geological framework of the Rogaland monzonorites

The Rogaland monzonorite series (RMS) are intimately associated with large massifs of anorthosites. These appear as polybaric intrusions which started crystallizing at 10-12 kb and rised diapirically through the lower crust (MAQUIL and DUCHESNE, 1984; DUCHESNE et al., 1985a). Evidence below the present anorthosite massifs of a lower crust depleted in heat-producing elements is provided by the low heat flow values measured in the anorthosites (SWANBERG et al., 1974). The monzonorites were emplaced later than the oldest anorthosite massifs in the province (the Egersund-Ogna and Åna-Sira massifs) and are older or contemporaneous with the K-rich rocks (mangerites, quartz mangerites and charnockites). They crystallized in granulite facies conditions, as evidenced by WILMART (1988) and WILMART et al. (1990) who measured low fO_2 conditions (close to the $CO_2 = C + O_2$ buffer curve) and a total CO_2 pressure around 8 kb, thus confirming previous determinations on the K-rich rocks by WILMART and DUCHESNE (1987).

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Geochemical characteristics

The RMS occur as dikes, small intrusions and chilled margins to some anorthosite-norite intrusions. The various types of occurrence and petrographic characteristics, first described in MICHOT (1960) and then in various papers reviewed in DUCHESNE et al. (1989), are summarized in Tab. 1.

Geochemically, the RMS form a continuous trend extending from monzonorites (= hypersthene monzodiorites = jotunites, following STRECKEISEN [1974] and LE MAITRE [1989]), with low SiO₂ (43–50%) and MgO (3–5%) contents, high total Fe (15–20% Fe₂O₃t), TiO₂ (3–5%), K₂O (1–2.5%) and P₂O₅ (1–3%) contents, to quartz mangerites, which are moderately high in SiO₂ (66%) and relatively high in K₂O (5%) for low CaO (2%) contents. Al₂O₃ (12–16%) and Na₂O (3–4%) remain virtually constant through the whole trend.

In the AFM diagram (Fig. 1) and in Harker variation diagrams (Fig. 2) three main types can be defined: the Varberg-Tellnes group, comprising most of the occurrences, the Vettaland group, and the Hidra group which comprises the chilled margins of the Hidra massif and of the Bjerkreim-Sokndal lopolith. The groups have a

FeO/MgO ratio of 0.83, 0.90 and 0.76 respectively. In the Varberg-Tellnes group, the FeO/MgO ratio shows little variation with alkali enrichment and thus defines a Bowen trend at a relatively high value of the FeO/MgO ratio.

The RMS are difficult to classify because of their high P₂O₅ and TiO₂ values. They show tholeiitic affinities with their high Fe number, but at the same time, they give rise to substantial amounts of acidic material, a feature they share with calc-alkaline rocks. In the alkali-lime diagram however, the Varberg-Tellnes and Hidra groups distinctly plot in the alkali-calcic field of Peacock, due to relatively high K₂O and low CaO contents for normal Na₂O contents compared to other standard magma series. To sum up, the RMS can be classified as a ferro-potassic alkali-calcic series.

All monzonoritic occurrences have high K/Rb and K/Ba ratios, low U, Th, Ta and transition element contents (Tab. 2). In general, the REE distributions show a (La/Yb)_N ratio about 7–12 with small positive Eu anomalies (Eu/Eu* ≈ 1.0–1.3). Some occurrences, however, differ markedly from the average population: satellite dikes to the Tellnes dike or to the Vettaland dike show strong enrichment in REE and a negative Eu anomaly with high Zr-Hf contents for similar

Tab. 1 Characteristics of the Rogaland monzonoritic series

A. DIKES

Thickness: dm to 100 m / Length: up to 20 km

Composition:

dikes of constant composition:

- monzonorite (Varberg dike)
- monzonite (Vaersland dike)
- ferronorite (Vettaland dike)

zoned dikes: variation along strike:

- from monzonorite to charnockite (Tellnes and Håland dikes)
- from norite to mangerite (Lomland dike)

Texture

subophitic to granular (5–10 mm) with poikiloblastic inverted pigeonite (up to 2 cm in diameter); microgranular in chilled rocks (0.1–0.3 mm) (thin dikes or selvage of large dikes) with minute elongated apatite and Fe–Ti oxides dispersed in all other minerals.

Mineralogy

plagioclase (unzoned) with antiperthite (An₄₀ grading with increasing SiO₂ content to more albitic plagioclase coexisting with K-feldspar, and eventually merging into mesoperthite); simultaneously, opx (inverted pigeonite) varies from En₃₆ down to En₁₇, cpx increases, and Fe–Ti oxides and apatite decrease; quartz (usually < 20% of Q+A+P) is present in quartz mangerites.

B. INTRUSIONS

Elongated intrusions located between the large massifs:

- the Eia-Rekefjord intrusion, at the contact between the southern part of the Bjerkreim-Sokndal lopolith and the two neighbouring anorthosite massifs;
- the Apophys, at the contact between the Åna-Sira anorthosite massif and the metamorphic envelope.

Monzonoritic rocks also occur as chilled margins to some anorthosite-norite massifs: the Hidra massif with a continuous marginal micromonzonorite, the Garsaknatt massif and the Tjörn occurrence along the contact between the Bjerkreim-Sokndal lopolith and its envelope.

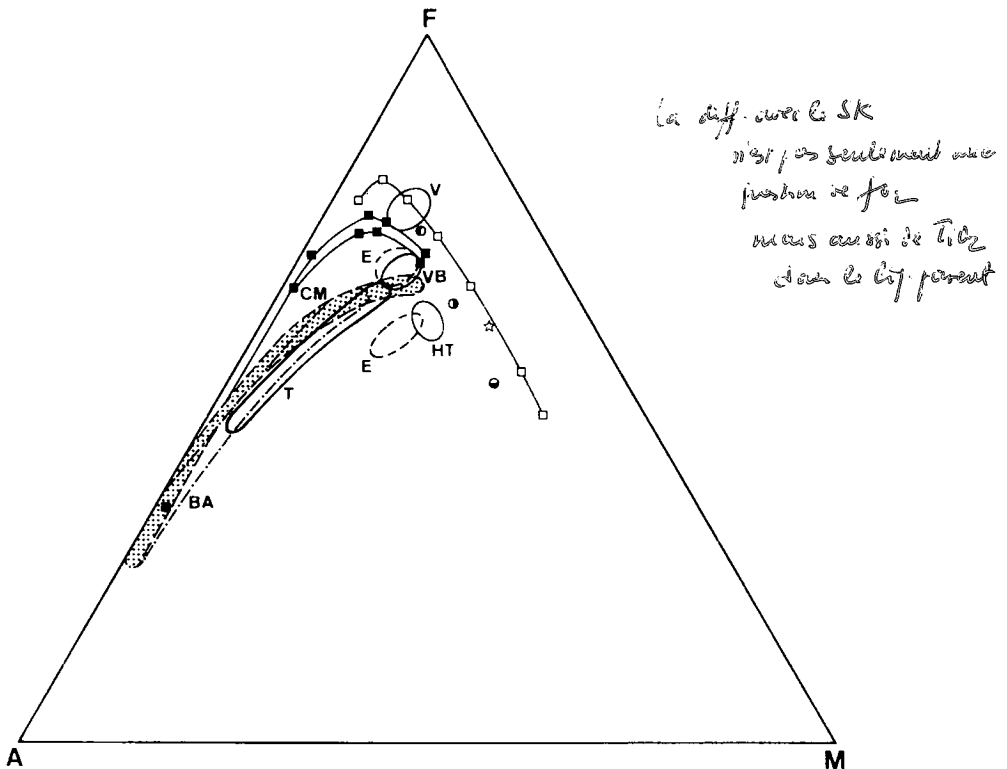


Fig. 1 A ($\text{Na}_2\text{O} + \text{K}_2\text{O}$) - F ($\text{FeO} + 0.9 \text{Fe}_2\text{O}_3$) - M (MgO) diagram for representative monzonorites and related rocks. The clusters enclose the data from the various occurrences. List of abbreviations: Rogaland occurrences: T, Tellnes dike; VB, Varberg dike; V, Vettaland dike; HT, Hydra massif and Tjörn chilled margins. Other occurrences: E (two clusters), Labrador (Harp Lake, Nain) and Grenville Province (Belleau-Desaulniers, Grenville Township, Morin, Lac Croche, Marcy, Snowy Mountain), from EMSLIE (1978); BA, Loch Ba ring dike, Scotland, from SPARKS (1988); CM (dotted cluster), Crater of the Moon, Snake River Plain, Idaho, from LEEMAN et al. (1976); (star), Skaergaard chilled marginal gabbro KT39, from HOOVER (1989); \square (open square), Skaergaard liquid evolution calculated by Wager (WAGER and BROWN, 1968); \blacksquare (full square), Skaergaard liquid evolutions calculated by HUNTER and SPARKS (1987); partial melts from high-alumina basalt obtained by BAKER and EGGLEER (1987): \bullet , high-alumina basalt AT-112; \circ , run number 1098, 6% glass at 8 kb; \odot , run number 953, 44% glass at 8 kb.

major element compositions as in common monzonorites; the south part of the Vettaland dike is strongly depleted in incompatible elements, and shows an umbrella-shaped REE distribution with a distinct positive Eu anomaly (DUCHESNE et al., 1985b, 1989).

Further characterization of the RMS has been obtained with isotopes (DEMAIFFE et al., 1986; DUCHESNE et al., 1989). The Sr initial ratio varies between 0.704–0.710 and $\epsilon_{\text{Nd}(T)}$ between +5.4 and -1. Interestingly, in the Tellnes and Lomland dikes, where a continuous evolution towards acidic rocks is observed, the various rocks define linear trends in $^{87}\text{Sr}/^{86}\text{Sr}$ vs. $^{87}\text{Rb}/^{86}\text{Sr}$ plots, which are isochrons of correct age and thus not mixing

lines. It can be concluded that differentiation took place in a closed system. Lack of correlation between the Sr initial ratio in the various occurrences and elements indicative of crustal contamination (Rb, Ba, Th, K) rules out a single and simple binary contamination process of a mantle-derived magma by crustal material.

Considering the geochemical characteristics of major and trace elements, isotopes, and the degree of evolution in the various occurrences, the monzonorites appear to be composed up of distinct batches of magmas, belonging to the same family, but with distinctive fingerprints for each occurrence, not resulting from fractional crystallization or simple contamination.

Tab. 2 Representative compositions of monzonorites, ferrobasalts and related liquids^{a)}

	VARB	TELLNES		HITJ	HET	CRATER MOON	SKAERG	BAKER & EGGLEER		
	(1)	7252	QMANG	(4)	(5)	69-22	V-31	PARENT	AT112-5	AT1-3
SiO ₂	46.45	47.32	65.87	49.54	49.68	44.40	62.60	50.00	42.80	47.60
TiO ₂	3.70	3.60	1.08	4.17	2.60	4.03	0.73	2.31	5.63	2.07
Al ₂ O ₃	12.83	12.80	13.41	14.06	12.78	13.30	14.80	13.10	12.20	14.90
Fe ₂ O ₃	4.63	4.53	2.82	5.11	7.48		1.79	3.05		
FeO	13.11	11.96	5.10	9.50	12.22	17.12	7.45	14.50	20.00	15.70
MnO	0.23	0.21	0.13	0.16	0.27	0.30	0.20	0.23	0.35	0.31
MgO	3.41	3.44	0.63	4.87	2.09	4.90	0.35	3.84	3.63	5.70
CaO	7.84	7.43	2.18	6.56	7.38	8.53	3.19	8.31	8.20	8.23
Na ₂ O	3.46	3.53	3.20	3.50	2.78	3.34	4.05	3.13	2.27	3.02
K ₂ O	1.77	2.28	5.23	1.41	0.98	1.59	4.67	0.82	2.06	1.16
P ₂ O ₅	2.56	2.74	0.42	1.03	1.67	2.48	0.19	0.65	1.55	0.48
Tot	100.05	99.82	100.08	99.91	100.07	100.00	100.05		98.69	99.17
U	0.30	0.32	0.19	1.13	0.26					
Th	0.71	0.79	0.55	2.75	0.30	3.80				
Zr	305	442	1254	191	1021	857	1830			
Ta	1.80	1.68	1.01	6.0	9.6					
Rb	11.9	16.3	68.9	23.9	5.4	30.0	97.0			
Sr	406	366	152	435	537	330	175			
Ba	1181	1212	1464	576	713	980	3260			
K/Rb	1235	1161	630	490	1524	440	400			
K/Ba	12	16	30	20	11	13	12			
Sc	27.9	26.3	15.4	20.5	28.3	24.0	20.0			
Cr ^(b)	2.9	1.5		17.0	1.3	16.0				
Co	34	36	7	47	28	42				
Ni ^(b)	22	7		34		10				
La	57.8	55.5	37.0	31.6	51.0	85.0	154.0			
[La/Yb] _M	8.9	12.1	5.4	6.6	7.5	6.8	7.9			
Eu/Eu*	1.3	1.1	1.5	1.0	1.0	0.92	0.81			
I _{Sr}		0.7069	0.7069	0.7050	0.7058	0.7081	0.7111			

^{a)} major elements (%), trace elements (ppm)

^{b)} unless specified, less than 20 ppm

1-5 from DUCHESNE et al. (1989): VARB: average analysis from the Varberg dike - TELLNES: 7222, monzonorite; QMANG: average of 7 quartz mangerites from the Tellnes dike - HITJ: aver. of 7 chilled rocks from the margins of Hidra and Bjerkreim-Sokndal - HET: aver. of 5 rocks from the Hetland facies of the Vettaland dike.

6-7 from LEEMAN et al. (1976) Tab. 4

8 from HUNTER and SPARKS (1987) Tab. 2

9-10 from BAKER and EGGLEER (1987) Appendix Tab. 1, 8 kb experiments: AT112-5: run number 1098; AT1-3: run number 934

Mechanism of differentiation towards acidic rocks

Several cases in which immiscibility has been surmised to play a leading role were studied in detail: the Vettaland dike (DUCHESNE et al., 1985b), the Tellnes Fe-Ti orebody (WILMART, 1988; WILMART et al., 1989), the Bakka-Örsland

transition in the Bjerkreim-Sokndal lopolith (DUCHESNE et al., 1987), and the mingling of magmas in the Apophysis (DUCHESNE et al., 1989). In none of the occurrences has immiscibility been confirmed, the major argument against this mechanism being the partitioning of P, REE and Ba between the two liquid candidates. The enrichment in these elements in the Fe-rich

rocks, which is predicted by experimental (WATSON, 1976) and theoretical (RYERSON and HESS, 1978) considerations, is not observed. Moreover, evidence of disequilibrium is common between the two "liquids": these have different isotopic signatures (Apophysis), or crystallize different liquidus phases (Bakka-Örmland).

Magma mixing or assimilation should also be rejected as the mechanism of evolution towards the K-rich rocks observed e.g. in the Tellnes and Lomland dikes. As mentioned, Sr isotopes indicate closed-system differentiation. The linear trends observed in Harker diagrams are thus an intrinsic property of the multi-component phase diagram and do not result from mixing of two end-members. It must also be pointed out that the evolution is not linear in all variation diagrams as a two component mixing array should be: the P_2O_5 vs. SiO_2 diagram definitely shows a curved trend, concave towards the high P_2O_5 values (Fig. 2).

Fractional crystallization is actually the most satisfying mechanism to account for the evolution in a closed system. WILMART (1988) and WILMART et al. (1989) have described the trend in the Tellnes dike by subtracting cumulus extracts made up of minerals found in the cumulate rocks of the Bjerkreim-Sokndal lopolith. The model uses standard least-square calculations constrained by the olivine/liquid partition coefficients of FORD et al. (1983) and mineral/mineral partition coefficients measured in the Bjerkreim-Sokndal cumulates. This approach is also confirmed by trace elements, which behave in excellent agreement with the model.

The nearly constant FeO/MgO ratio observed in the evolution might at first sight seem surprising. Phase relations indeed predict that the various minerals which crystallize in equilibrium with the liquid must continuously change in composition with temperature. Since the FeO/MgO ratio increases in the silicates with falling temperature, one should expect to observe a concomitant change in the bulk cumulate. However, when the role of the Fe-Ti oxides is considered, and particularly the fact that magnetite shows a large increase in Ti and a simultaneous decrease in Fe with decreasing temperature, the FeO/MgO increase is reduced and can eventually stop at a constant value. This effect is particularly well demonstrated in the transition rocks of Bakka-Örmland (DUCHESNE et al., 1987) in the Bjerkreim-Sokndal lopolith. It follows that constancy in the FeO/MgO ratio does not necessarily mean mixing of a basic component with an acidic end-member, as invoked, among others, by ZORR et al. (1989).

Comparison with similar suites of rocks and inference for the ferrobasaltic evolution

The RMS are very similar to other monzonorites, ferrodiorites or jotunitites occurring in other anorthosite provinces such as Labrador, Québec or the Adirondacks (EMLIE, 1978). Figs. 1 and 2 illustrate the comparison. Particularly striking is the similarity with the Hydra group. The conditions of formation of the monzonorites can thus occur in a wide range of environments and are not restricted to the depth of emplacement of the Rogaland anorthosites.

In terms of volcanic rocks, the monzonorites belong to the ferrobasalt family, which according to MCBIRNEY and WILLIAMS (1969) displays an FeO content in excess of 12–13%, MgO content less than 6% and a silica range about 48–50%. It is thus of interest to consider what light RMS can throw on the origin and evolution of ferrobasalts.

Several series of ferrobasaltic rocks have been plotted on Figs. 1 and 2. They include the Loch Ba suite presented by SPARKS (1988) as an example of evolution of a ferrobasaltic magma towards acidic liquids which, according to that author, is a more realistic way of describing the Skaergaard liquid evolution than the classical one calculated by WAGER (WAGER and BROWN, 1968). The latter as well as those calculated by HUNTER and SPARKS (1987) for two possible parental magmas with 50 and 52% SiO_2 respectively, together with the new value for the chilled border gabbro (KT 39) of the Skaergaard, recommended by HOOVER (1989), are also represented. Finally, the unique series of volcanic rocks of Crater of the Moon from the Snake River Plain (TILLEY and THOMPSON, 1970; LEEMAN et al., 1976) is also plotted on Figs. 1 and 2.

All rocks display clear enrichment in alkalis (Bowen trend) for high values of the FeO/MgO ratio. It is well known that subtraction of anhydrous assemblages can explain Bowen trends, without requiring subtraction of an amphibole or mixing with an acidic component. This mechanism has already been invoked for subalkaline magmas intermediate between calc-alkaline and tholeiitic trends (see the review by GROVE and KINTZLER, 1986). The present data on the RMS and particularly the Tellnes case indicate that more alkaline magmas have basically the same behaviour. They also show that alkali-calcic ferrobasalts can evolve through fractional crystallization by decreasing Fe and increasing SiO_2 contents, as suggested by HUNTER and SPARKS (1987) for subalkaline ferrobasalts.

Comparison between Loch Ba and Tellnes is particularly informative in that respect. The two

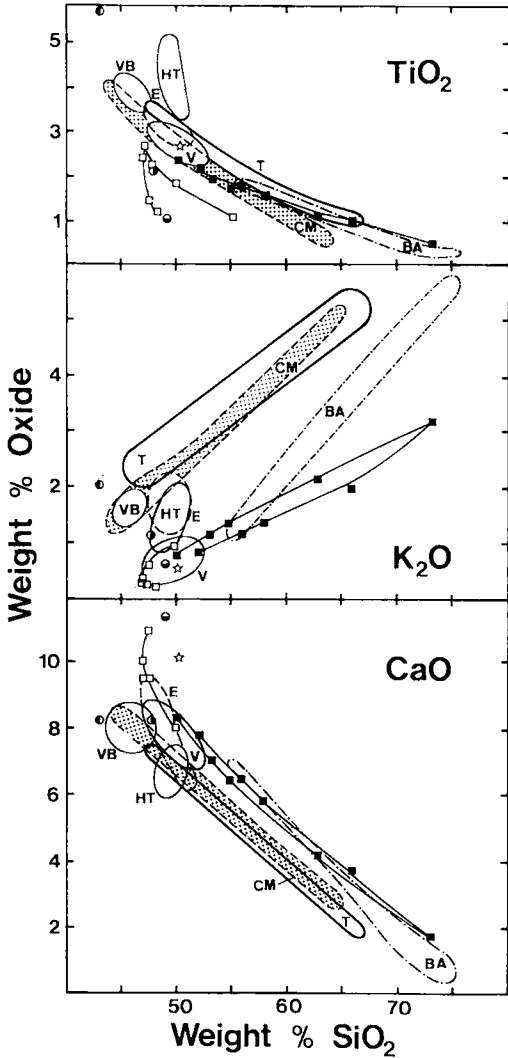


Fig. 2a Variation diagrams for TiO_2 , K_2O and CaO evolution. Same legend as in Fig. 1.

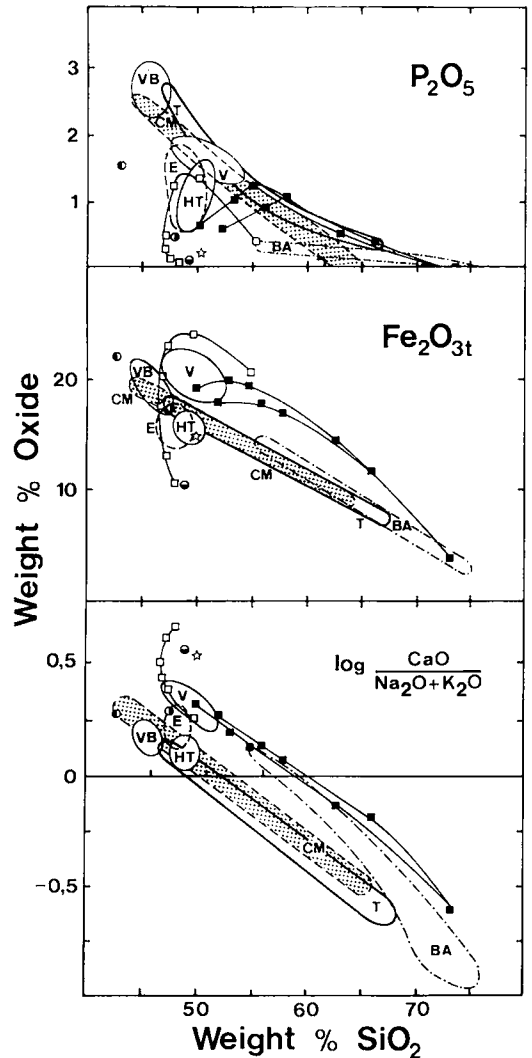


Fig. 2b Variation diagrams for P_2O_5 and Fe_2O_{3t} evolution and Peacock alkali-lime index. Same legend as in Fig. 1.

series have large parts of their trends in common in Harker diagrams (see for example Fe_2O_{3t} and TiO_2 in Fig. 2). However, important differences lie in higher K_2O and lower CaO and P_2O_5 contents for similar SiO_2 values in Tellnes. Interestingly, the arrays in Tellnes and Loch Ba remain quite parallel during the entire evolution in the CaO versus SiO_2 diagram. Such a parallelism can only be achieved if, starting from an alkali-calcic parental liquid (low in Ca), the evolution is controlled by subtraction of a mineral assemblage globally lower in Ca than the Skaergaard cumu-

lates. This is actually the case in Tellnes; for similar Fe numbers, the plagioclase is more albitic in the Tellnes extract than in the Skaergaard rocks. For instance, an orthopyroxene En_{56} coexists with a plagioclase An_{38} (WILMART, 1988; WILMART et al., 1989), while in the Skaergaard An_{50} occurs for a Fe number close to 50 (WAGER and BROWN, 1968). Similarly, in the Bjerkreim-Sokndal lopolith, the most basic cumulate contains An_{50} together with an olivine Fo_{73} (DUCHESNE and HERTOGEN, 1988). Following GREEN (1969), it has been suggested that this

shift towards more alkali-rich compositions reflects the higher pressure conditions of crystallization in Rogaland (DUCHESNE and HERTOGEN, 1988). It follows that crystallization at moderate pressures (ca 8 kb) of an alkali-calcic magma is capable of driving liquids along the same FeO/MgO and SiO₂ paths as in the Skaergaard. It can thus be accepted that the Tellnes liquid line of descent closely resembles the Skaergaard evolution but at a higher pressure and for an alkali-calcic ferrobaltic composition. This gives some support to Hunter and Sparks' view on the Skaergaard trend.

Among the various RMS magma batches, the subalkaline Vettaland dike is the closest in composition to the Skaergaard parental ferrobaltics with 50% SiO₂ of HUNTER and SPARKS (1987) (Tab. 2 and Fig. 2). The Vettaland dike, with its higher Fe number and P₂O₅ content, would represent a more evolved stage (approaching the Skaergaard middle-zone liquid) than the presumed 50% SiO₂ parent liquid. No conclusion can however be drawn regarding further evolution of such liquids because of the restricted interval of major element variation in the Vettaland dike.

The similarity of the RMS with the evolved lavas from the Pliocene-Holocene volcanic province of Snake River Plain (Idaho) is striking, particularly when the Varberg-Tellnes trend is compared to the Crater of the Moon series. In Harker diagrams (Fig. 2), all elements plot in common arrays. The Bowen trend of Crater of the Moon is also obvious in the AFM diagram (Fig. 1), though somewhat more concave towards the M apex than in the Varberg-Tellnes group. The alkali-calcic character of Crater of the Moon clearly appears in the Peacock alkali-lime diagram (Fig. 2). Trace elements (LEEMAN et al., 1976) also strengthen the similarity between the two series (Tab. 2), with high Zr and Ba, low transition elements (Ni, Co, Cr), relatively low (La/Yb)_N ratios (7–8), lack of a significant Eu anomaly throughout the whole series, and high Sr isotopic initial ratios ($I_{Sr} = 0.707$ to 0.712). These features point to identical parental magmas and differentiation mechanisms and strongly suggest that the same magma generation process has taken place in both provinces.

To conclude: (1) the RMS typifies the ferrodiorites associated with massif-type anorthosites; (2) the Tellnes-Varberg group finds a volcanic equivalent in the Crater of the Moon series, both series being distinguishable in the ferrobaltic family by their alkali-calcic character and, for the most basic liquids (ca. 45% SiO₂), by high TiO₂ (4%), P₂O₅ (2.5%) and K₂O (1.5%) contents;

(3) the alkali-calcic character persists throughout the whole evolution towards acidic rocks, possibly because of medium pressure of crystallization; (4) the trends show a continuous decrease in Fe and a large increase in SiO₂, as commonly observed in calc-alkaline trends and invoked in a reinterpretation of the Skaergaard evolution.

Source of the monzonorites

DUCHESNE et al. (1989) have shown that the RMS cannot be accounted for by a unique parental magma, but that several magma batches with contrasted geochemical characteristics (trace elements and isotopes) are required. These differences do not result from fractional crystallization nor is the Sr isotope signature related to simple contamination.

The geochemical characteristics, and particularly the heterogeneity of the population, also preclude a common origin as residual liquids left after the formation of massif-type anorthosites. The decisive argument is the absence of a significant Eu anomaly in the most basic liquids and particularly in the liquids which display an Sr isotope ratio in the range of those observed in the anorthosite (e.g. HIDRA, DEMAÏFFE and HERTOGEN, 1981). There is indeed a consensus among the anorthosite petrologists – see the reviews of EMSLIE (1978, 1985), MORSE (1982) and DUCHESNE (1984) – to locate the source of the anorthosite parental magma in the mantle, which implies a parental magma without any Eu anomaly. Subtraction from this liquid of a huge plagioclase extract would inevitably produce a negative Eu anomaly in the residual liquids.

The role of liquidus apatite has been advocated to counterbalance that of the plagioclase in explaining a REE evolution towards positive Eu anomaly (DUCHESNE et al., 1985b). Indeed, if apatite had begun to crystallize before the emplacement of the most basic "parental" liquid, that is in an intermediate stage of evolution between anorthosite and the observed monzonorites, its influence could have cancelled out a previous negative anomaly.

Actually, such a scenario finds little support here: the Hidra and Bjerkreim-Sokndal chilled marginal monzonoritic rocks have a low P₂O₅ content (1.0% P₂O₅) compared to other liquids of similar SiO₂ content (2–3% P₂O₅) (Fig. 2). Such low P₂O₅ contents indicate saturation at temperatures ca. 900 °C (WATSON, 1979), much lower than the effective liquidus temperature of the other monzonorites (ca. 1050 °C) and than the liquidus temperature of the olivine (ca.

1160 °C) according to FORD et al. (1983). Apatite is also absent from the cumulus mineral assemblages of the Bjerkreim-Sokndal lopolith, in the first two megacyclic units and at the basis of the two following ones (MICHOT, 1965; DUCHESNE, 1987). There is thus good evidence that the Hydra and Bjerkreim-Sokndal magmas were not saturated in apatite when emplaced, and that, as in the Skaergaard trend, apatite appeared later in the evolution.

Conversely, if not residual after the formation of the massif-type anorthosites, to what extent could monzonorites be parental to these rocks? Such an hypothesis is indeed consistent with the mineral composition of the agglomerates of megacrysts of aluminous-orthopyroxene and plagioclase, commonly found in massive anorthosites – andesine plagioclase, Mg number around 0.78–0.64 (EMSLIE, 1985; DUCHESNE and MAQUIL, 1987). It cannot however account for the high Cr content of the mega-orthopyroxene (up to 1200 ppm Cr) compared to that of the monzonorites (< 3–20 ppm) (Tab. 2), because it would imply orthopyroxene/liquid partition coefficients far outside the normal range of variation (DUCHESNE et al., 1985a). Monzonorites and massif-type anorthosites are thus not comagmatic.

Both rock types are however so closely associated that they must be genetically related. It is thus tempting to relate the generation of the two magmas to the same thermal anomaly in the lithosphere, affecting two different sources, or, as an alternative, to consider that the thermal anomaly is produced by the anorthosite diapirs themselves which, when rising through the depleted lower crust, could have retained sufficient heat to melt basic rocks en route to the level of final emplacement. What we know of the depleted nature and thickness of the crust below the Rogaland anorthosites is consistent with such a model.

Whatever the scenario to explain the heat anomaly, strong support to the melting process of basic rocks is provided by the experiments of BAKER and EGGLE (1987). In an attempt to unravel the nature of the anhydrous fractionating crystal assemblage which controls the evolution of island arc andesites, these authors have experimentally produced a variety of liquids by melting different basic and intermediate rocks. The melts obtained from high-alumina basalts are of particular interest: in dry conditions and at intermediate pressures (8 kb), those obtained for low melting rates are higher in P, Ti and Fe and lower in SiO₂ than the starting composition. Two significant melt compositions, produced at 6% and 44% melting rates, are reported in Tab. 2

and plotted in Figs. 1 and 2. The similarity with the basic end of the liquid line of descent of the monzonorites is striking. Also noticeable are the position in the AFM diagram and the alkali-calcic character in the Peacock diagram. The liquid AT 112-5 (6% partial melting) coexists in the experiment with an olivine Fo₅₁ (BAKER and EGGLE, 1987), a value close to that predicted (Fo₄₉) by application of the olivine/liquid element partitioning of FORD et al. (1983). The experiment can thus be considered to have taken place in equilibrium conditions.

Another indication of partial melting of basic rocks is given by the Vettaland dike which displays large variation in trace elements and virtually constant major element composition (DUCHESNE et al., 1989). Though several other mechanisms can also account for these characteristics (see O'HARA and MATHEWS, 1981; LANGMUIR, 1989), the model of eutectic batch melting of a noritic cumulate developed by DUCHESNE et al. (1985b) appears quite satisfying, particularly in view of the experimental data of BAKER and EGGLE (1987).

Melting of basic rocks in dry conditions is also a suitable mechanism to explain the Crater of the Moon parental magma. Geophysical data on the nature of the lithosphere beneath the Snake River Plain-Yellowstone region (WILSON, 1989) indicate a layer of relatively high P-wave velocities (6.5 kms⁻¹), near the upper crust/lower crust boundary, which may represent mafic bodies crystallized from magma chambers similar to that actually present under the Yellowstone hotspot. It is quite conceivable that these mafic intrusions could have provided enough heat to melt basic materials from the lower crust. The occurrence of monzonorite-like volcanism in the recent Snake River Plain lavas does not necessarily imply that massive anorthosites are present beneath that region. It simply means that a high heat source was available at crustal levels and in granulite facies conditions. Massif-type anorthosites are not completely precluded but seem highly unlikely in view of the Proterozoic age which characterizes this rock type.

Conclusions

RMS comprises a variety of rocks from monzonorite to quartz mangerite, which form a ferro-potassic alkali-calcic series. Monzonoritic liquids belong to the ferrobasalt family.

Fractional crystallization (without assimilation) with subtraction of an anhydrous mineral extract can account for the Bowen trend evolu-

tion at a relatively high Fe number. SiO_2 increases and FeO decreases in the evolution as commonly observed in calc-alkaline trends and, particularly, in the Loch Ba ferrobasaltic suite. Though of a more alkaline character, the RMS evolution supports HUNTER and SPARKS' (1987) reappraisal of the Skaergaard liquid line of descent.

The RMS are not comagmatic with massif-type anorthosites, though intimately associated with them. A simple model of contamination of mantle-derived liquids cannot account for their geochemical characteristics (major and trace elements, isotopes). Partial melting of basic rocks in granulite facies conditions and at moderate (crustal) pressure, as evidenced by experimental data, can produce monzonoritic magmas, the necessary heat being provided by the rising anorthosite diapirs.

The Crater of the Moon series in the Snake River Plain is quite comparable to the RMS and thus represents a volcanic equivalent. This strongly points to a similar mechanism of partial melting of basic rocks in a high heat flow environment, and also gives evidence that the monzonorite formation can be decoupled from the anorthosite genesis.

Acknowledgments

The author thanks D. Demaiffe and E. Wilmart for stimulating discussions. The final version of the paper was greatly improved by the reviews of R.S.J. Sparks and S. Ayrton. The work was supported by the Fund for Basic Joint Research (Belgium).

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Manuscript received January 23, 1990; revised manuscript accepted April 4, 1990.