

Geochemical comparisons of coronitic olivine gabbro and eclogites: metamorphic effects and the origin of eclogite protoliths (Flemsøy, Sunnmøre, Western Norway)

MAI BRITT E. MØRK AND ARILD O. BRUNFELT

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Olivine gabbros on the island of Flemsøy (Skuløy) show different degrees of transition to eclogite. Coronitic olivine gabbro and eclogitized parts within the gabbro have been compared with more typical country-rock eclogites for the rare earth elements (REE), K, Rb, Sr, Y, Zr, Ti and Ni. Eclogite transformation *within* the gabbro body has *not* been accompanied by significant changes of Y, Zr, Ni, P and Ti and the REE patterns. The trace element data support the hypothesis of a common origin for the country-rock eclogites and the gabbro. In the country-rock eclogites Y, Zr and Ti have been fairly resistant to metamorphism on a whole-rock (ca. 1 litre) scale. The REE have typically preserved the original compositions of the inferred gabbro protoliths, but may show variable degrees of selective disturbance which tend to 'flatten out' the original LREE enriched patterns. The protoliths are interpreted as continental, low-P gabbro intrusions of tholeiitic to transitional alkaline affinity. High MgO and FeO contents are attributed to accumulation of olivine. REE and P₂O₅ allow distinction of the Flemsøy eclogites from the more alkaline eclogite compositions in the Sunnfjord area, and from the eclogites with more depleted tholeiitic and variable REE patterns in the Stadlandet area. This suggests the presence of provinces with petrogenetically different eclogite protoliths within the Western Gneiss Region.

Mai Britt E. Mørk, *Continental Shelf Institute (IKU)*, P.O. Box 1883 Jarlesletta, N-7001 Trondheim, Norway; Arild O. Brunfelt, *Mineralogisk-Geologisk Museum, Sarsgt. 1, 0562 Oslo 5, Norway*.

Trace elements, and particularly the rare earth elements (REE), can be used to throw light on the origin of eclogite protoliths. In this respect it is important to determine whether the eclogite metamorphism is isochemical or not. Comparison of REE patterns in eclogites with those of various basalt types have been used by some authors to discuss possible basaltic protoliths for eclogites, assuming that high-P metamorphism has not changed the original REE patterns (e.g. Bernard-Griffiths & Cornichet 1985; Bernard-Griffiths et al. 1985; Gebauer et al. 1985).

Eclogites in the Western Gneiss Region (WGR) of Norway (Fig. 1a) show a wide range of basic compositions, and several are interpreted to have formed from low-pressure igneous protoliths on the basis of geochemical studies (Bryhni et al. 1969; Mysen 1971; Garmann et al. 1975; Krogh 1980; Krogh & Brunfelt 1981; Brastad 1985; Carswell & Harvey 1985; Griffin & Brueckner 1985; Gebauer et al. 1985; Erambert 1985;

Jamtveit 1986). Some of the range in composition is illustrated in Fig. 2 and in Griffin et al. (1984, fig. 2).

Gebauer et al. (1985) interpreted the geochemical variations of eclogites in the Stadlandet area in terms of tectonical emplacement of different eclogite protoliths into the gneisses. They used La/Yb ratios of eclogites to argue for ocean basalt and island arc magma types.

Considerations of the effects of metamorphism have led to different conclusions including depletion of K₂O (Bryhni et al. 1969; Mysen 1971) and of La and Ce (Griffin & Brueckner 1985) or local alkali introduction (Krogh 1980; Krogh & Brunfelt 1981). Elsewhere, Hellmann et al. (1979) found that the La/Yb ratio may vary widely due to REE mobility accompanying metamorphism. Thus, clearly, knowledge of the degree to which the trace element patterns have been retained or disturbed during metamorphism is important for the geotectonical use of geochemistry.

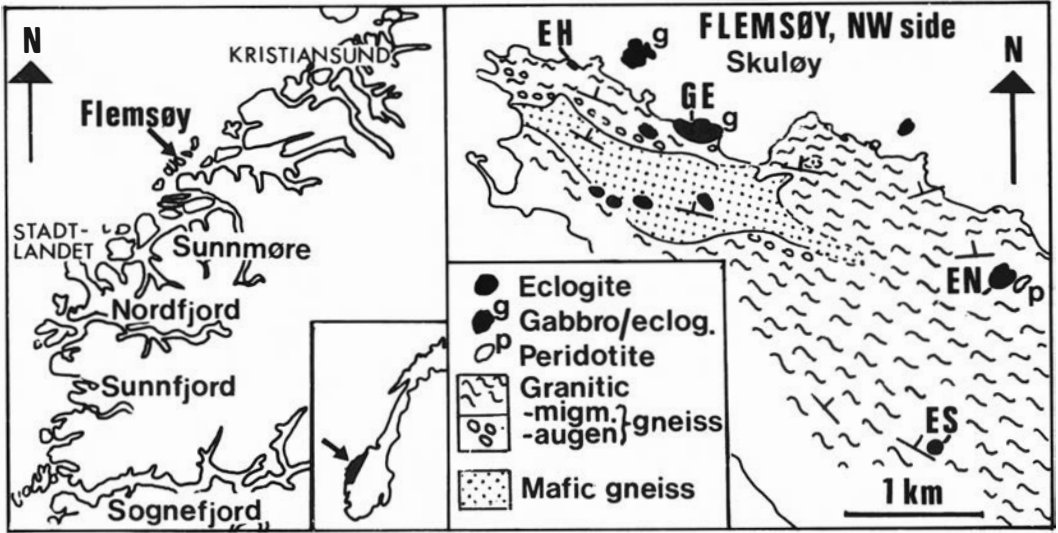


Fig. 1. (a) Map showing the Western Gneiss Region of Norway with the location of some general areas referred to in the text. Small inset shows where the map is located. (b) Geological map of the northwestern part of the island of Flemsøy (Skuløy) showing the locations of country-rock eclogites (EH; east of Hornhamaren, EN; Nogvadalen, ES; Stølshaugane) and a gabbro-eclogite body (GE; Sandvikhaugane).

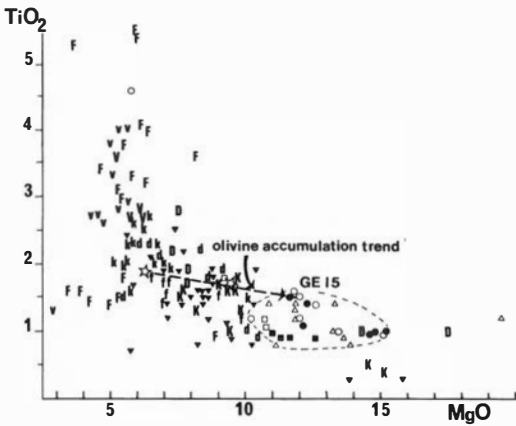


Fig. 2. Comparisons of TiO₂-MgO for coronites and eclogites from this study (encircled area; symbols as in Fig. 4) and some published and unpublished data for eclogites and dolerites from different parts of the Western Gneiss Region. Eclogites: Sunnfjord area: K - Kvineset (Krogh 1980), F - Fureviknipa (Foslie unpubl.). Sunnmøre area: black triangles - Hareidland (Mysen 1971). Northern areas: K - Kristiansund (Griffin & Råheim 1973), f - Frei (Ilebekk 1981), V - Vindøladalen (Tørudbakken 1982). Dolerites: D - Sunnmøre (Gjelsvik 1952), d - Kristiansund (Griffin & Råheim 1973), v - Vindøladalen (Tørudbakken 1982). Asterisk = possible melt composition.

The occurrence of meta-igneous rocks which show different degrees of metamorphic transformation provides a method of identifying possible bulk-rock chemical exchange during metamorphism. This approach is used in the present study which addresses (1) the origin of closely associated eclogites and a corona gabbro on the island of Flemsøy, and (2) whether the metamorphism was isochemical or not.

It has earlier been suggested that the eclogites and the corona gabbro have a common origin, and that eclogitization has not disturbed the major-element compositions of the rocks except for the oxidation of iron (Mørk 1985). In the present study, trace elements (Rb, Sr, Ni, Y, Zr, Sm, Eu, Gd, Tb, Tm, Yb, Lu) and minor elements (TiO₂ and K₂O) are used to test this hypothesis. Furthermore, the metamorphic effects on the trace-element chemistry will be examined by comparative studies of rocks which are situated within the same gabbro body (loc. GE, Fig. 1b), but show different degrees of transition to eclogite.

The first question is whether the corona gabbros have preserved their original trace-element distribution. Comparative studies with the completely

reacted eclogites will then allow conclusions about the effects of metamorphism. Further comparisons with the country-rock eclogites (Fig. 1b) may then be used to test the hypothesis (Mørk 1985) of a common origin with the corona gabbro.

Geology and sampling locations

Mørk (1985) has divided the eclogites into layers and patches within relict coronitic gabbros (type 1 eclogite) and disrupted fold-layers or pods within the migmatitic gneisses (type 2 and 3 'country-rock' eclogites). All the types have shared a similar metamorphic history with a common mineral assemblage garnet + omphacite (Jd₂₄₋₃₃) ± phlogopite ± orthopyroxene ± amphibole ± ilmenite ± rutile.

The locations studied (Fig. 1b) correspond to those described earlier (GE, EH, EN, ES; see Mørk 1985, figs. 1 and 2 for location and geology and fig. 3 for location of sampling profile EH).

The Sandvikhaugane gabbro-eclogite (GE) is dominated by coronitic olivine gabbro with relict igneous structures such as local occurrences of small-scale rhythmic layering and irregular patches and veins of coarse-grained (1–2 cm) plagioclase-rich pegmatitic gabbro (GE3b). The igneous mineralogy (olivine + plagioclase + augite + ilmenite + phlogopite) is best preserved in sample GE15, comprising 56% of the mode. Coronas (garnet + orthopyroxene ± omphacite) and inclusions in plagioclase (spinel) have been attributed to incomplete high-pressure metamorphic transformations (Mørk 1985, 1986). The coronitic samples which have been grouped together for the comparative studies with the eclogites have similar mineralogy to GE15 but show some variations in amount of relict igneous minerals preserved.

In contrast, completely reacted rocks from the same location (GE) are eclogites. They show no relict igneous phases, but may have preserved pseudomorphic igneous textures (e.g. garnet pseudomorphs after plagioclase).

Layered country-rock eclogites (type 2) were selected from an occurrence east of Hornhamaren (EH) where several bodies of complexly folded eclogite occur. Two bodies, 10 m and 5 m across respectively, have been sampled in profiles across the layering and main foliation (Fig. 3; Mørk 1985, fig. 4). The larger body forms a doubly folded structure where the eclogite mineralogy defines an axial-plane cleavage in isoclinal folds.

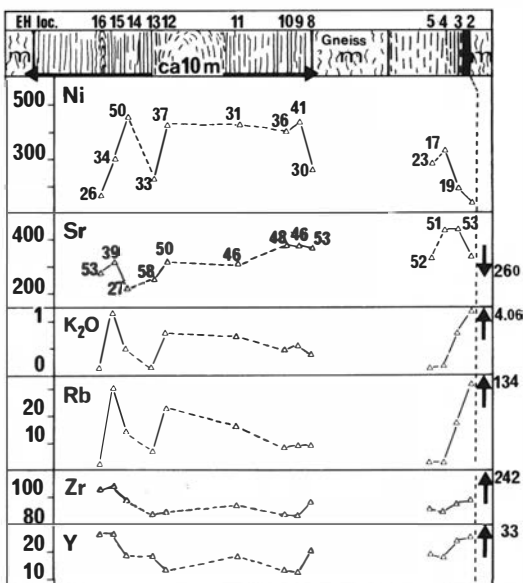


Fig. 3. Trace-element variation (in ppm) across layering and foliation in two layered eclogite bodies (loc. EH) within migmatite gneiss (m). Traces of foliation are indicated by lines, with strongest foliation in areas of high density of lines. '16' is a zone of tight fold-hinges. The black zone at '2' represents the amphibolitized margin of the smaller eclogite lens. Additional information on normative olivine contents and normative plagioclase contents is given by the numbers in the Ni and Sr diagrams respectively. Trace-element concentration values for adjacent gneiss are indicated by the arrows in the right contact area.

A thin layer of migmatite gneiss is infolded in the central part of the body, adjacent to a zone of tight fold-hinges in the eclogite. The sampling is complicated by two scales of layering: a fine-scale layering (a few mm scale) attributed to metamorphic foliation, and a 10–50 cm layering defined by bulk-chemical variations and locally amplified by major foliation planes. Sampling was done to cover the compositional variations of the 'broad' layers. The smaller lens at the EH location is strongly symplectitized, with an increase of amphibole towards the completely amphibolitized margin. The type 2 eclogites are interpreted as disrupted parts of the corona-gabbro body (Mørk 1985). Boudinage, disruption of eclogite fold-structures and complex interfolding with the migmatitic gneisses was initiated during early stages of decompression.

Coarse-grained, orthopyroxene bearing country-rock eclogites (type 3) have been sampled from two locations; Stølshaugane (loc. ES) and in the Nogvadalen hill (loc. EN); Fig. 1b.

Table 1. Whole-rock analyses. Fe₂O₃ calculated from titration analyses.

wt. %	Coronites			Type 1 eclogites		Type 2 eclogites				Type 3 eclogite	Calculated melt composition, using GE15
	GE3b	GE15	GE4c	GE4a	GE7	EH16	EH14	EH9	EH5	EN3	
SiO ₂	45.50	45.22	45.11	44.83	45.02	45.85	41.41	43.37	45.54	45.92	47.15
TiO ₂	4.63	1.48	1.37	1.42	1.06	1.58	1.24	.80	1.28	1.76	1.85
Al ₂ O ₃	14.26	13.87	13.29	13.54	15.85	13.99	8.26	13.80	15.75	15.87	17.34
Fe ₂ O ₃	3.56	2.13	3.05	5.78	5.29	2.20	7.65	10.39	1.53	4.30	—
FeO	10.85	14.10	13.39	10.15	9.93	13.22	12.60	4.95	10.74	9.77	13.08*
MnO	.20	.21	.23	.22	.18	.22	.29	.20	.18	.19	.14
MgO	5.74	12.03	12.59	12.29	12.08	9.11	19.46	13.93	11.89	9.31	6.27
CaO	9.13	7.50	7.36	7.60	7.18	8.19	4.77	6.59	9.63	8.36	9.38
Na ₂ O	3.37	2.35	1.90	2.33	2.79	3.43	1.26	2.31	2.05	2.66	2.94
K ₂ O	1.20	.79	.73	.64	.65	.11	.51	.56	.16	.45	.99
P ₂ O ₅	.46	.22	.20	.21	.22	.22	.24	.15	.21	.24	.28
	98.90	99.90	99.22	99.01	100.25	98.12	97.69	97.05	98.96	98.83	99.42
ppm											
Rb	30	17	18	12	n.a.	2	14	9	3	12	
Sr	393	378	350	343	n.a.	277	217	374	331	378	
Y	49	24	20	19	n.a.	26	18	12	19	26	
Zr	197	105	90	92	n.a.	112	93	65	79	117	
Ni	100	266	280	307	330	167	458	436	284	295	
katanorms (using Fe ₂ O ₃ = TiO ₂ + 1.5)											
'Pl'	59.5	49.81	47.42	49.83	57.44	54.50	30.26	50.27	52.77	57.48	
Ol	6.57	33.12	28.22	31.78	33.55	25.82	49.49	40.88	22.65	19.30	
Cp	18.22	10.08	7.77	9.48	4.38	13.67	5.47	4.95	10.49	8.01	
Op	1.42	1.29	11.21	3.38	—	—	9.60	—	8.95	8.74	
Ilm + Mt	13.29	5.17	4.96	5.08	4.17	5.54	4.68	3.59	4.70	5.95	
Apat	.99	.56	.42	.44	.46	.47	.51	.32	.44	.51	

Protolith relations from major-element chemistry

The total major element variations have been compiled elsewhere (Mørk 1985); some representative analyses with norms are shown in Table 1. The country-rock eclogites overlap compositionally with the corona gabbros and eclogitized gabbros, but they define a larger compositional range totally. All are characterized by high MgO (and FeO) contents compared to eclogites elsewhere in the WGR (Fig. 2). Some of this FeO and MgO enrichment has been attributed to igneous accumulation of olivine (Mørk 1985). A 'melt' composition (Table 1, and Fig. 2; asterisks) closer to the composition of other WGR eclogites has been modelled on the basis of sample GE15, olivine (Fo₇₁) and FeO/MgO olivine – melt equilibrium considerations (Roeder & Emslie 1970) leading to 20% of olivine accumulation for GE15.

Possible fractionation or accumulation

relations between the gabbros and different eclogite types can be indicated by simple least square mixing tests based on the major elements and relict igneous mineral compositions from sample GE15 (Table 2, e.g. GE15–GE3b, GE15–EN3, GE4a–GE15, GE7–EH9). Such tests, however, are only *indicative* for genetic relations.

Analytical techniques

Analyses of Rb, Sr, Ni, Y and Zr were done by means of XRF on pressed pellets. The samples include 7 coronites/partly eclogitized gabbros and 6 eclogites (type 1) from the GE location, 12 type 2 eclogites (loc. EH) and 9 type 3 eclogites (loc. ES and EN). The concentration of La, Ce, Nd, Sm, Eu, Gd, Tb, Tm, Yb and Lu have been measured in selected samples (3 coronites, 2 type 1 eclogites, 4 type 2 eclogites and 2 type 3 eclogites + garnet separate from GE7) by neutron activation technique following the radio-

Table 2. Fractionation test based on major elements.

Product rock	EN3	GE3b	GE3b	EH9	GE15	GE15
Parent rock	GE15	GE15	GE15	GE7	GE4a	GE4a
	1.1585	2.3371	2.3406	.7624	1.0999	1.1002
OL1	-.1358	-.6239	-.6248	.145	-.0278	-.0279
CP1	-.0132	-.5920	-.5936	.0198	-.0314	-.0314
PLVE	-.0045	-.0123	-.0125	.0534	-.0283	-.0284
IL1	.0011	.0225	.0223	-.0005	.0024	.0023
OPX	-.0108	-.1226	.1231	—	—	—
av. difference	.007	.010	.005	.012	.112	.126
S. of squares	.001	.003	.000	.003	.158	.158
% difference	.91	1.52	.11	1.62	3.62	2.86
s. of squares	38.2	132	.34	104	247	167
Excluded elements	Mn K	Mn K	Mn K P	K P	K P	Mn K P

chemical separation method described by Brunfelt et al. (1974) and Krogh & Brunfelt (1981). BCR1 and G2 were used as counting standards. Standard deviations from replicate analyses of the standards are 2.6–5.9% for Sm, Eu, Tb, Yb, 9–10% for La, Sm and 14–18% for Nd, Gd, Tm, Lu. The standard values refer to Brunfelt & Steinnes (1978) and Laul et al. (1982) for Tm. Chondrite values refer to Haskin et al. (1968).

Trace- and minor-element variations (excluding REE)

Total ranges and mean values of Rb, Sr, Ni, Y and Zr for different rock groups are presented in Table 3, and selected elements are shown in two-element variation diagrams (Fig. 4).

Corona gabbros and transitional gabbro-eclogites

Two-element variation diagrams have been plotted using an incompatible element (Zr) and a compatible element (Ni) as abscissa (Fig. 4). Y and Zr show a coherent behaviour, both giving a negative correlation with Ni which is comparable with the inferred fractionation (and accumulation) of olivine. The regular increase of TiO₂ with increasing Zr and with decreasing Ni supports the textural evidence that ilmenite has not been a fractionating phase. Similarly, the increase of P₂O₅ with Zr also suggests that apatite has not been a fractionating phase in the olivine-rich compositions represented by these rocks.

However, these relations may explain the relative enrichments of P₂O₅ and TiO₂ in the *late* crystallized pegmatitic gabbro sample GE3b (Table 1). When only the corona gabbros are considered, K₂O and Rb also increase with Zr. The K/Rb ratio in the corona gabbro samples varies between 330 and 520 within the range of continental basalts (cf. Dostal & Fratta 1977; Carmichael et al. 1974).

From the above it is concluded that the corona gabbros (and transitional rocks; Mørk 1985) may well represent the original igneous compositions and are therefore suitable as reference rocks for comparative studies with the eclogites.

Chemical comparisons between corona gabbros and eclogites

The concentration of K, P, Rb, Sr, Ni, Y and Zr in eclogites within the gabbro body (type 1 eclogite) and in country-rock eclogites (types 2 and 3; except loc. ES) overlap with the corona gabbros, but define a larger compositional range (in total) (Table 3).

Eclogites within the gabbro body are closest to the corona gabbros compositionally. Indeed, Zr, Y, P₂O₅ and TiO₂ have similar concentration values (Table 3) and also yield high correlation coefficients (c) in two-element variation plots which include both corona gabbros and eclogites (Fig. 4, C_{Zr-Y} = 0.95, C_{Zr-P} = 0.89, C_{Zr-Ti} = 0.91, all increasing to 0.98–0.99 if the enriched gabbro pegmatite GE3b is also included). In contrast, K₂O and Rb scatter more irregularly in the eclogites. One sample, GE9, is anomalously enriched in K₂O and Rb, while its other elements fall on the corona gabbro trends in Fig. 4.

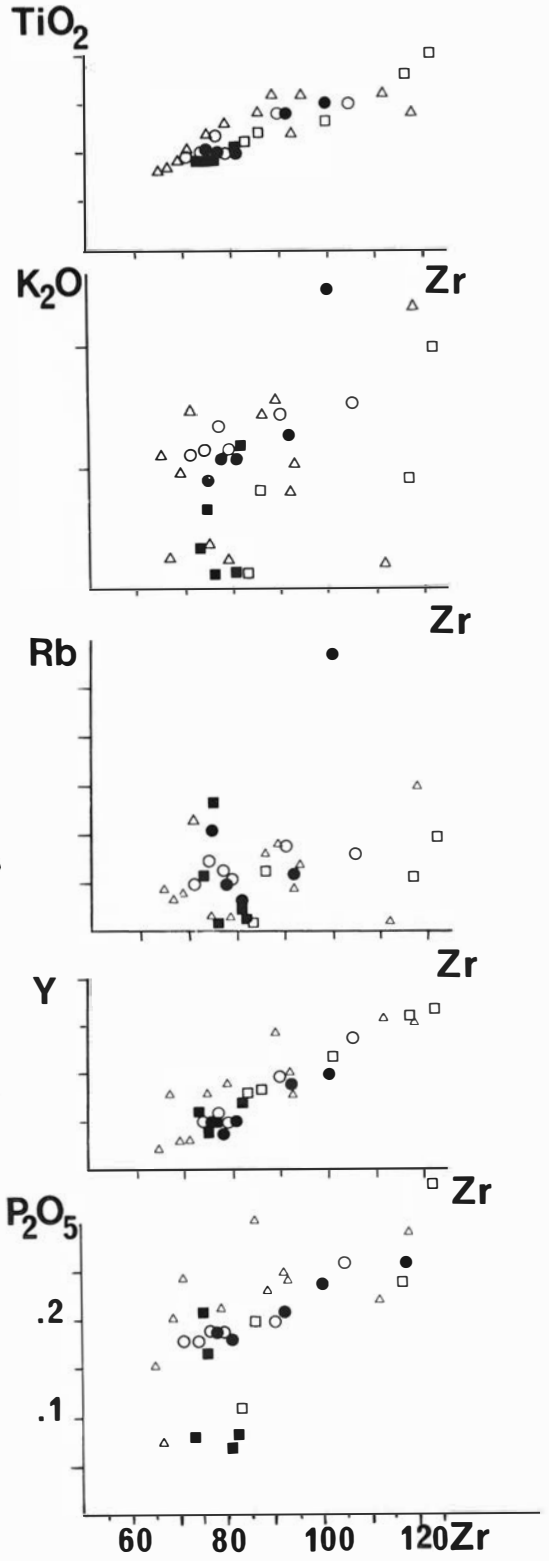
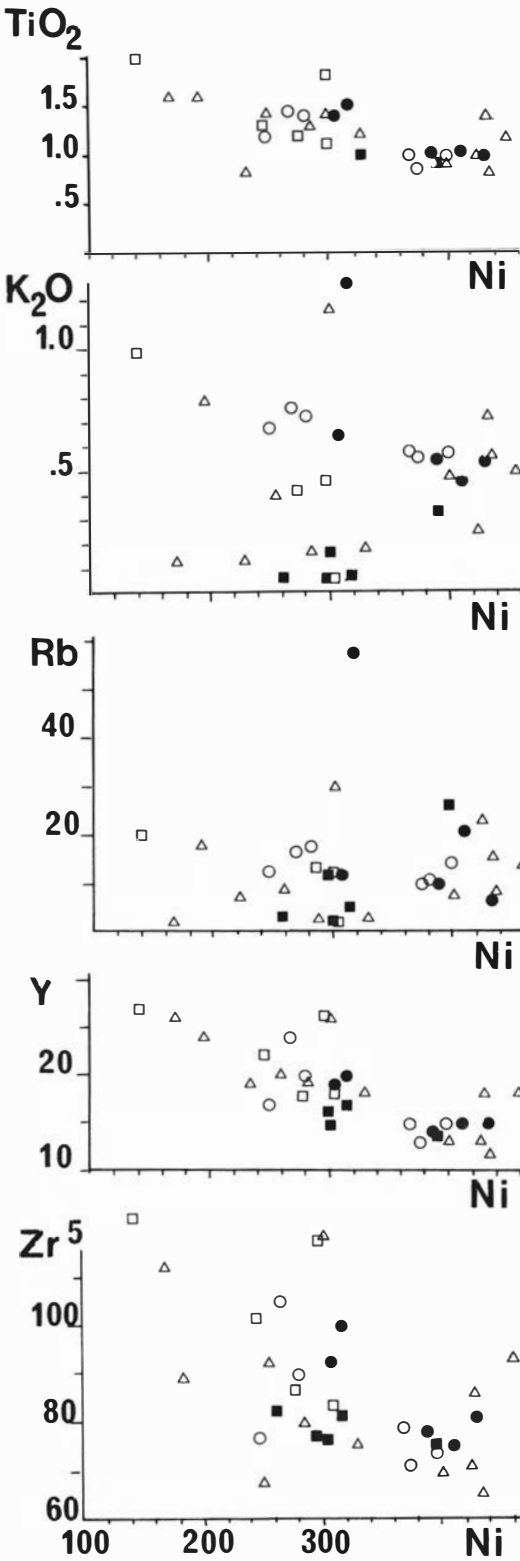


Table 3. Trace-elements and minor-elements in the different eclogite types showing total chemical range and mean value (in parentheses).

Rock type:	Plag coronite	Oliv coronite	Type 1 eclogite	Type 2 eclogite	Type 3 eclogites	
Location:	GE3b	GE	GE	EH	EN	ES
Total no.	(1)	(6)	(6)	(12)	(4)	(5 & 4)
Rb (ppm)	30 —	10–18 (13.9)	7–58 (21.6)	2–30 (11.8)	2–20 (11.6)	2–27 (9.7)
Sr	393 —	350–419 (378)	249–351 (308)	217–440 (336)	149–386 (262)	110–208 (168)
Y	49 —	13–24 (17.2)	14–20 (16.8)	12–26 (18.8)	18–27 (22.2)	13–17 (15.6)
Zr	197 —	74–105 (82.7)	75–100 (85.2)	65–118 (84.7)	83–122 (102)	73–82 (77.4)
Ni	100 —	247–397 (322)	307–434 (364)	134–458 (326)	139–305 (252)	258–388 (312)
% K ₂ O	1.20 —	0.58–0.78 (0.66)	0.45–1.24 (0.68)	0.16–1.17 (0.50)	0.41–0.99 (0.48)	0.05–0.34 (0.16)
% P ₂ O ₅	0.46 —	0.16–0.28 (0.21)	0.18–0.24 (0.21)	0.07–0.30 (0.22)	0.20–0.34 (0.22)	0.07–0.21 (0.16)
% TiO ₂	4.63 —	0.85–1.45 (1.19)	0.96–1.48 (1.16)	0.79–1.58 (1.22)	1.21–2.02 (1.53)	0.89–0.95 (0.93)

Country-rock eclogites (types 2 and 3) also follow the same chemical trends as the corona gabbros for Y, TiO₂, Zr, Ni, while P₂O₅, K₂O and Rb show more irregular scattering. Largest deviations are shown for the type 3 eclogites (loc. ES), with an apparent depletion of P₂O₅, Rb, and K₂O (Fig. 4).

The general similarities between corona gabbros and country-rock eclogites for TiO₂, Zr, Y and Ni support the earlier hypothesis of a common origin. The question is whether the irregular scattering, particularly for Rb, K₂O and Sr, is due to selective disturbances.

The trace-element scattering across the layered country rock eclogites, loc. EH (Fig. 3), is in part related to irregular variations in the normative olivine contents. However, some of this variation cannot be explained in terms of fractionation – accumulation processes. For example, K, Rb, Zr and Y are strongly enriched in EH15 (Fig. 3), while the adjacent layer EH16 has a higher FeO/MgO ratio, similar Zr and Y values, but distinctly lower K and Rb. A secondary redistribution of Rb and K is therefore suggested. This involves enrichment of K and Rb in the strongly foliated

zone EH15 and depletion in the fold-hinge zone EH16. An anomalous depletion of K, Rb and also P may similarly be inferred for EH13.

The samples EH2 to EH5, which represent the smaller eclogite lens, are characterized by lower contents of Ni and normative olivine and higher Sr and normative plagioclase. Rb and K show a strong increase towards the gneiss contact (Fig. 3). This increase is correlated with an increasing degree of retrogression towards the outer amphibolite layer (EH2). The Y, Zr, Rb, K and Sr values of the adjacent migmatitic gneisses (Fig. 3) suggest that the gneisses may be a source for contamination with respect to Y, Zr, Rb and K.

Discussion (excluding REE)

The elements Y, Zr and Ti are often considered as relatively immobile during alterations and metamorphism of basalts (Cann 1970; Pearce & Cann 1973; Winchester & Floyd 1976; Ferrara et al. 1976). The regular and coherent variation recorded for these elements in the present rocks may support this view. On the other hand, it has

Fig. 4. Two-element variation diagrams with (a) Ni and (b) Zr as abscissa. Symbols: Open circles – corona gabbros (incl. transitional gabbro-eclogites) (loc. GE), filled circles – eclogites within the gabbro body (loc. GE; type 1 eclogite), triangles – type 2 eclogites (loc. EH), open squares – type 3 eclogites (loc. EN) and filled squares – type 3 eclogites (loc. ES).

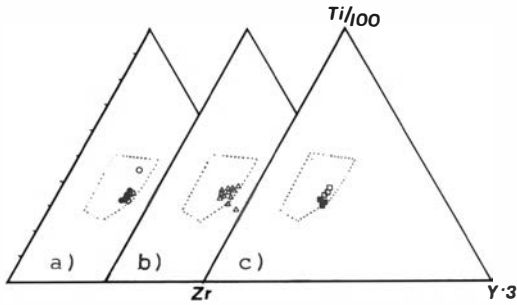


Fig. 5. Ti-Zr-Y for (a) corona gabbros and eclogites within the gabbro (type 1 eclogite) (loc. GE). Note the higher Ti-value of one of the samples; pegmatitic gabbro GE3b. (b) Type 2 eclogites (loc. EH). The sample with lowest Ti is EH13, below the main cluster. (c) Type 3 eclogites (loc. EN and ES). Note the close similarities for corona gabbros and the different eclogite types, with a main clustering in the 'within plate basalt field' of Pearce & Cann (1973).

been argued elsewhere that the high correlation commonly observed for these elements (and P) does not necessarily prove their *immobility*, but rather can be explained by a coherent mobility (Hellmann et al. 1977; Hellmann et al. 1979; Cann 1970). In the present case, however, a coherent *mobility* or removal is not supported, since the rocks showing different degrees of metamorphic transformation (coronites and eclogites within the gabbros) have also preserved the same *absolute* concentration values for Y, Zr, TiO₂ and P₂O₅. This suggests that within the gabbro body these elements have not been affected on a whole-rock scale during the metamorphism. These elements

also appear to have been immobile in the country-rock eclogites, except that P₂O₅ is disturbed in some layers (e.g. EH13). In the Y-Zr-Ti plot (Fig. 5) the eclogites from the different locations cluster in the same area as the corona gabbros in the 'within plate basalt field' of Pearce & Cann (1973). Pegmatitic gabbro (GE3b) and P₂O₅ depleted eclogite (EH13) are slightly above and below the main clusters respectively. The inferred olivine accumulation in the rocks should not have disturbed the original Y-Zr-Ti ratio so that the melt would also fall within the main cluster.

In all eclogite types K and Rb appear to be the most strongly disturbed elements. Sr varies much more irregularly, but with a tendency towards depletion in eclogites compared to the corona gabbros. Such a depletion could be caused by the breakdown of igneous plagioclase to form garnet leading to mobility of Sr. An opposite effect is expected during retrograde breakdown of omphacite with a restabilization of plagioclase (e.g. EH2-EH5). In contrast, K, Rb and Ni are favoured by the eclogite mineralogy with phlogopite and ilmenite.

Rare earth elements

REE have been analysed in selected samples from corona gabbro and the three different eclogite types (Table 4). The samples of type 2 eclogites were chosen in order to cover the compositional range within the EH location.

Table 4. REE element concentrations (ppm).

		La	Ce	Nd	Sm	Eu	Gd	Tb	Tm	Yb	Lu
<i>Sandvikhaugane</i>											
Pl-coronite:	GE3b	19.8	44.5	34.2	9.0	2.09	8.3	1.18	0.48	3.63	0.40
Ol-coronite:	GE15	9.9	24.1	21.0	4.4	1.23	4.0	0.62	0.35	1.89	0.27
Ol-coronite:	GE4c	8.6	30.5	17.9	4.5	1.51	3.2	0.77	0.29	1.95	0.24
Type 1 ecl.:	GE4a	8.1	27.0	18.1	4.0	1.28	3.7	0.63	0.37	1.73	0.15
	GE7	7.9	26.7	17.4	3.7	1.30	3.0	0.61	0.24	1.52	0.22
Type 2 ecl.:											
loc. EH; large lens:	EH16	10.4	23.5	17.3	3.9	1.34	5.4	0.71	0.44	2.27	0.42
	EH14	8.4	21.0	14.5	3.2	0.98	4.2	0.55	0.31	1.72	0.32
	EH9	6.6	16.2	10.6	2.9	1.02	3.6	0.46	0.23	1.22	0.22
small lens:	EH5	6.0	19.3	15.1	3.1	1.32	4.0	0.70	0.33	1.77	0.33
Type 3 ecl.:											
loc. EN	EN3	10.8	32.3	22.2	5.5	1.62	5.4	0.84	0.41	2.32	0.30
loc. ES	ES4	7.1	27.4	14.1	3.6	1.32	3.4	0.60	0.25		0.17
<i>Mineral separates:</i>											
Garnet		0.8	3.5	1.9	1.3	0.94	4.1	0.60	0.50	2.56	0.59

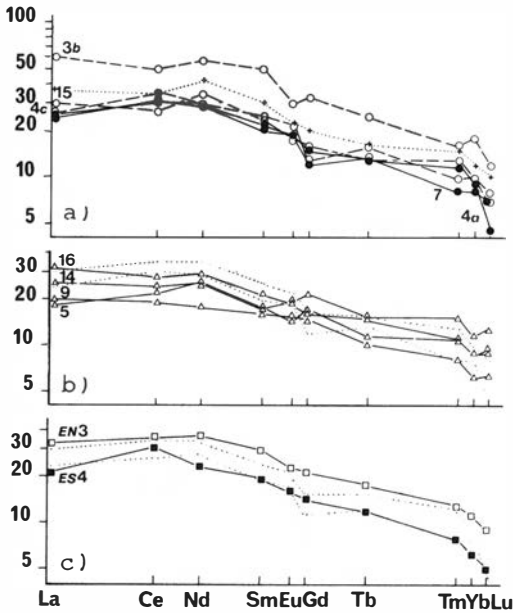


Fig. 6. Chondrite normalized REE plotted against ionic radius. Symbols as in Fig. 3. (a) Overlap between coronitic olivine gabbros (GE4c, GE15) and eclogites within the gabbro (GE4a, GE7). The pegmatitic gabbro GE3b is distinguished by higher REE contents. The position of an inferred melt composition, calculated from GE15 is marked by the crosses. (b) Layered country-rock eclogites (type 2, loc. EH). (c) Type 3 eclogites (EN, ES). In (b) and (c) the location of the coronites and eclogites from the GE location is stippled for comparisons. Note the general similarities for the different locations.

The chondrite normalized patterns (Fig. 6) are all characterized by moderate enrichments of the light REE (LREE) with maximum values for Ce and Nd. Pegmatitic gabbro GE3b is the most heavily REE-enriched sample. When correcting for the inferred 20% of olivine accumulation in sample GE15, the resulting melt composition would fall between the olivine gabbros and sample GE3b in Fig. 6. The patterns would correspond to tholeiitic to transitional basalts, rather than alkali basalts.

The parallel patterns are in accordance with the interpretation of igneous fractionation and accumulation. The very low REE partition coefficients for olivine/basalt melt (Irving 1978; McKay 1986, often ≤ 0.01) imply that the inferred olivine accumulation only contributes a 'dilution effect'; the total REE contents in the olivine at 20% of olivine accumulation would correspond to less than 0.3% of the rock's REE contents.

The relative enrichment of REE in pegmatitic gabbro GE3b is also in accordance with the

enrichments of P and incompatible elements in this sample.

Corona gabbros and eclogites show an overlap also for the REE (Fig. 6a-c). The eclogites within the gabbro are closest compositionally to the corona gabbros (Fig. 6a). The type 2 eclogites show a spread towards lower total contents of REE; this effect is not present in the two selected type 3 eclogites (Fig. 6c). In order to distinguish possible metamorphic effects from the primary igneous variations, both direct comparisons and comparisons based on REE values which have been corrected for normative differences have been done.

Direct comparisons

The similar REE contents in corona gabbros and the eclogites within the gabbros (type 1) suggest that high-P metamorphic transitions within the main gabbro body have not significantly changed the REE distribution and absolute contents. It is however possible that Ce has been disturbed even in the coronite GE15. The other GE samples show a depletion of La relative to Ce (Fig. 6a).

The type 2 eclogites (loc. EH) show a depletion of Ce and Nd and an enrichment of Lu relative to the corona gabbros and the eclogites within the gabbro (excluding Ce value of GE15). However, sample EH16 has the same REE distribution as the corona gabbro GE15 although some other trace elements are disturbed in EH16, (K, Rb, Sr). The sample with lowest concentration of REE in the EH location, EH9, also has relatively low contents of P, Y and Zr, and is enriched in Ni and normative olivine. A natural question is therefore whether most of the REE variations seen in the EH eclogite samples are due to primary igneous processes.

REE test of the inferred fractionation relations

The fractional crystallization relations calculated from major elements (Table 2) have been examined by using the REE data, the total equilibrium model (equation 3 of Zielenski 1975) and published partition coefficients for olivine, clinopyroxene, plagioclase, ilmenite and orthopyroxene (see Zielenski 1975; fig. 4). For the parent-daughter relations GE15-EN3, GE4a-GE15 and EH9-GE7, REE concentrations predicted from the concentrations of REE

Table 5. REE prediction for different rock combinations (using Table 5 results).

	La	Ce	Nd	Sm	Eu	Gd	Tb	Tm	Yb	Lu
GE15										
analysed:	9.9	24.1	21.0	4.4	1.23	4.0	.62	.35	1.89	.27
calc. from GE4a:	8.7	29	19.3	4.2	1.34	3.9	.66	.39	1.79	.15
GE7										
analysed:	7.9	26.7	17.4	3.7	1.30	3.0	.61	.24	1.52	.22
calc. from EH9:	8.2	20.3	13.2	3.6	1.23	4.45	.57	.28	1.48	.27
GE3b										
analysed:	19.8	44.5	34.2	9.0	2.09	8.3	1.18	.48	3.63	.40
calc. from GE15:	22.9	55.8	48.7	10.2	2.85	9.3	1.44	.81	4.38	.63
EN3										
analysed:	10.8	32.3	22.2	5.5	1.62	5.4	.84	.41	2.32	.30
calc. from GE15:	11.5	28.1	24.4	5.1	1.43	4.7	.72	.40	2.20	.31
calc. from GE4c:	11.3	39.9	23.4	5.9	1.98	4.2	1.00	.38	2.55	.31

in the parent rocks are in fairly good agreement with the analysed values (Tables 4, 5); in all cases the best agreement is for the HREE. Six out of 10 calculated REE fall within the error limits for replicate standard analyses for the GE15-EN3 relation, while 7 out of 10 REE are within or reasonably close to these limits for GE4a-GE15 and EH9-GE7. Ce, Eu and Lu are not within the analytical error limits, especially Ce.

Simplified accumulation model

This approach attempts to compare the REE in the different eclogite types with the least reacted rock GE15 by making a simple correction for the differences in major element compositions. In order to compare the REE in relation to the different degree of metamorphic transformations, several assumptions must be made: (1) the major element compositions have not changed during metamorphism, (2) the ratios between the igneous minerals are represented by the norms, and (3) the igneous minerals have similar REE contents in the different rocks. The last assumption requires that the rocks have formed from similar magma reservoirs, and that differences in compositions represent different amounts of accumulation. This is of course an oversimplification, but is still attempted here since all the samples are fairly undifferentiated (excluding GE3b). CIPW normative mineral proportions together with a set of REE partition coefficients (Zielenski 1975) were used to assign a *relative* contribution to the total REE contents of GE15 from the different igneous phases. The bulk REE

content of GE15 was then used to derive an *absolute* contribution from each normative unit for plagioclase, clinopyroxene, orthopyroxene, olivine, ilmenite and apatite. The calculated contents for each mineral were then used to 'predict' the REE contents from the norm of the other eclogite samples. Predicted and analysed values are compared in Table 6.

If the simple model is valid, the differences between the analysed values and those predicted from the less extensively metamorphosed corona gabbro GE15 could reflect changes due to the eclogite formation (excluding Ce). From this, the analysed values would indicate a tendency of relative enrichment of HREE, while LREE are more variable, and the intermediate elements Nd and Sm show a depletion relative to the predicted values (Table 6). The sample with the most significant LREE depletion is EH5. In contrast, EH9, which has the lowest *total* REE contents, is closer to the predicted value, suggesting that the low REE contents in this sample are due to primary igneous differences. The La depletion of EH5 may be a metamorphic effect (compare Griffin & Brueckner 1985). Thus, from this approach, the different samples within the EH eclogite occurrences may show different degrees of metamorphic disturbances of the REE.

Summary and discussion of the REE

- (1) The general similarities of the REE in the two types of country-rock eclogites with the corona gabbro and eclogites within gabbro, and the fractional crystallization relations

Table 6. Calculated REE using GE15 as a normalizing standard.

	La	Ce	Nd	Sm	Eu	Gd	Tb	Tm	Yb	Lu
TE7										
analysed	7.9	26.7	17.4	3.7	1.30	3.0	.61	.24	1.52	.22
calculated	9.1	20.8	17.6	3.5	1.20	3.0	.47	.25	1.24	.17
GE4										
an.	8.1	27.0	18.1	4.0	1.28	3.7	.63	.37	1.73	.15
cal.	8.6	20.2	17.9	3.8	1.19	3.6	.55	.33	1.83	.26
EH16										
an.	10.4	23.5	17.3	3.9	1.34	5.4	.71	.44	2.27	.42
cal.	9.3	22.0	20.0	4.4	1.35	4.1	.63	.38	2.16	.31
EH14										
an.	8.4	21.0	14.5	3.2	.98	4.2	.55	.31	1.72	.32
cal.	8.2	20.3	17.3	3.5	.83	3.3	.52	.32	1.62	.24
EH9										
an.	6.6	16.2	10.6	2.9	1.02	3.6	.46	.23	1.22	.22
cal.	7.0	15.8	13.7	2.8	1.05	2.5	.38	.22	1.15	.16
EH5										
an.	6.0	19.3	15.1	3.1	1.32	4.0	.70	.33	1.77	.30
cal.	8.7	20.6	18.5	4.1	1.28	3.9	.60	.39	2.17	.32

shown by some of the samples, support the earlier interpretation of a common igneous origin for gabbro and the eclogites.

- (2) Metamorphic effects on the general REE trends are small. However, even for the corona gabbros selective REE minor disturbances may be indicated by zig-zag patterns, e.g. Ce is variably disturbed in the samples. On the other hand, olivine gabbro may transform completely to eclogite without changing the REE patterns; eclogites GE4a and GE7 preserve the same REE patterns as the corona gabbros (except that Lu is anomalously depleted in GE4a).
- (3) Some country-rock eclogites may show a spread towards lower total REE contents. Some of this spread can be explained in terms of primary igneous differences (e.g. EH9), while other cases may reflect metamorphic disturbances (e.g. EH5).
- (4) When comparing the REE patterns for country-rock eclogites with the major element variation (represented by CIPW norms), comparisons with the corona gabbro (GE15) suggest a tendency of (a) selective disturbances of LREE, (b) depletion of Nd and Sm and (c) enrichment of the HREE in the country-rock eclogites relative to the corona gabbro.

These effects may be related to metamorphism,

although the present approach is not sufficient to explain all detailed variations.

The gabbro-eclogite transition involves the breakdown of plagioclase to form garnet, and the formation of omphacite and phlogopite after olivine and augite (Mørk 1985). LREE have lower preference for the metamorphic product minerals than for the original plagioclase (cf. Helmke & Haskin 1973; fig. 3, Zielenski 1975; fig. 4). The only phase present that concentrates LREE (including Sm and Nd) is the accessory apatite. The behaviour of this phase during metamorphism is therefore important for the ability to retain the LREE concentrations during the eclogite transitions (see also Mørk & Mearns 1986). HREE would however be preferentially incorporated in the most abundant metamorphic reaction products, garnet (Table 4) and omphacite. Thus a flattening of the original REE patterns when compared with the original gabbro patterns could be explained by selective removal of the LREE and retention of the HREE during the high-P metamorphism (by breakdown of plagioclase and/or dissolution of apatite).

Origin of eclogite protoliths

The eclogites in this study have formed from olivine gabbro protoliths. The olivine gabbros intruded into the granitic gneisses around 1200–

1300 Ma (Mørk & Mearns 1986) and were subjected to high-P metamorphism during the Caledonian continent-continent collision. The intrusive event belongs to a period with widespread igneous activity on the Baltic shield (within-plate continental intrusions); (Mearns 1984; Mørk & Mearns 1986; Patchett 1978; Welin & Lundqvist 1975; Schärer 1980).

The Ti–Zr–Y ratios and the REE distribution patterns are in accordance with the earlier interpretation from major element chemistry of a tholeiitic to transitional alkaline basalt composition, although the total concentrations of these elements in the rocks may have been reduced by the up to 20% accumulation of olivine. The weakly LREE-enriched patterns are similar to those of continental tholeiite basalt (Helmke & Haskin 1973), and the parallel patterns may partly be explained by the dilution effect due to accumulation of olivine. The La/Yb ratio is fairly constant (4.4–5.5) for both corona gabbros and eclogites. EH5 has a ratio of 3.4; the lower ratio is interpreted as a metamorphic effect.

The REE patterns have been compared with available REE data for other eclogites in the WGR (e.g. Krogh & Brunfelt 1981; Garmann et al. 1975; Brastad 1985; Griffin & Brueckner 1985; Gebauer et al. 1985). The eclogites from Sunnfjord (Krogh & Brunfelt 1981) have distinctly higher REE contents than the samples in this study. The present eclogites have REE total ranges and patterns which are intermediate between those from Sunnfjord and eclogites from the Nordfjord–Sunnmøre area described by Garmann et al. (1975), and Brastad's (1985) types b and c. The REE patterns indicate a geographic distribution with more alkaline eclogites in the southern part of the WGR and tholeiitic eclogites further north (cf. Krogh & Brunfelt 1981). Krogh's Sunnfjord eclogites are also characterized by a high phosphorus content, which distinguishes them also from the *late differentiates* in the Flemsøy gabbro (GE3b). This suggests the existence of geochemically different protolith magmas.

The metamorphic effects, as recorded in the present study, are not sufficient to explain the large variations in the La/Yb ratio of the eclogites in the Stadtlandet–Nordfjord area (Gebauer et al. 1985; Griffin & Brueckner 1985; Garmann et al. 1975). Thus, in those areas either the eclogites are derived from a much wider range of unrelated protolith compositions, as suggested by Gebauer

et al. (1985), or some of the eclogites described earlier were subjected to much more severe metamorphic alterations than in the present study. A possible mechanism is by more extreme selective removal of LREE, than in the present case (type 1 REE mobility of Hellmann et al. 1979).

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