Rare earth element contents of Norwegian greenstones and their geotectonic implications

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The rare earth elements (REE) La, Ce, Nd, Sm, Eu, Tb, Dy, Yb, Lu and the elements Sc, Hf, Th were determined by instrumental neutron activation analysis in 18 Ordovician greenstones of the Norwegian Caledonian geosyncline south of Trondheim. The greenstones are enriched in REE by a factor of 10 to 30 compared to the average chondrites. Post-crystallization redistribution of the REE has taken place in individual pillows. REE are not insensitive to secondary alterations. The REE contents of the least altered unpillowed massive greenstones give evidence to support the opinion that the Støren greenstones were formed in an Ordovician island arc.

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In central Norway a 2000 m thick sequence of metamorphosed basic volcanic rocks represents the basal filling of the Caledonian geosyncline (Fig. 1). The rocks are mostly pillow lavas and are known as 'Støren greenstones'. The degree of metamorphism represents a transition between the pumpellyite-prehnite-quartz facies and the beginning of the greenschist facies. The major and trace element geochemistry has been recently described by Gale et al. (1974) and Loeschke (1976a, b). Since only two analyses of the REE of the Støren greenstones are available (Dypvik et al. 1976), 18 samples of the Støren greenstones were analysed by instrumental neutron activation analysis to determine the contents of La, Ce, Nd, Sm, Eu, Tb, Dy, Yb, and Lu. The REE are some of the most diagnostic elements for the identification of past geotectonic environments of metamorphosed basic volcanic rocks in an orogenic domain, since they allow a fairly good discrimination between basic volcanic rocks of oceanic, continental, and island arc environments (Frey et al. 1968, Herrmann et al. 1970, Jakes et al. 1970, Nakamura et al. 1971, Schilling 1971, Kay et al. 1973, Herrmann et al. 1974).

The columnar section of Fig. 1, which is a simplified version of the stratigraphy in the area south of Trondheim (Vogt 1945, Chaloupsky 1969, Oftedahl 1974 and others), shows the stratigraphic succession of the early Palaeozoic rocks of the Caledonian geosyncline south of Trondheim. The contact between the Støren greenstones and the underlying Cambrian sediments is of tectonic character (Oftedahl 1974) and the whole section of the Støren greenstones and the above-lying andesites, rhyolites, and clastic sediments form a far-travelled allochthonous unit, called the Støren nappe (Gale et al. 1974). The major element chemistry and some trace element data (Ti, Zr, Y) reveal that the volcanic rocks of the Støren nappe were probably formed in an Ordovician island arc (Loeschke 1976 b). The following article deals with the distribution of the REE in individual pillows and pillow lava flows and with their implications for the identification of the original tectonic setting of the Støren greenstones. The samples were taken from a road-cut near the lake Benna south of Trondheim and from a second road-cut north of Støren (for a detailed petrographical description see Loeschke 1976a).

Analytical methods

100–200 mg of the samples were irradiated for two days with 8×10^{13}n/cm^{2}sec in the FR-2 reactor in Karlsruhe (Germany) together with single element standards and the U.S.G.S. standard rocks BCR-1 and G-2. γ-ray spectra were obtained in two runs with a planar 200 mm^2 Ge-detector and in one run with a coaxial 40 cm^3 Ge(Li)-detector. The first counting period with the planar Ge-detector 9 days after irradiation yielded the contents of Nd, Sm, and Dy (Dy-166). The second determination with the coaxial Ge(Li)-detector 12 days after irradiation yielded

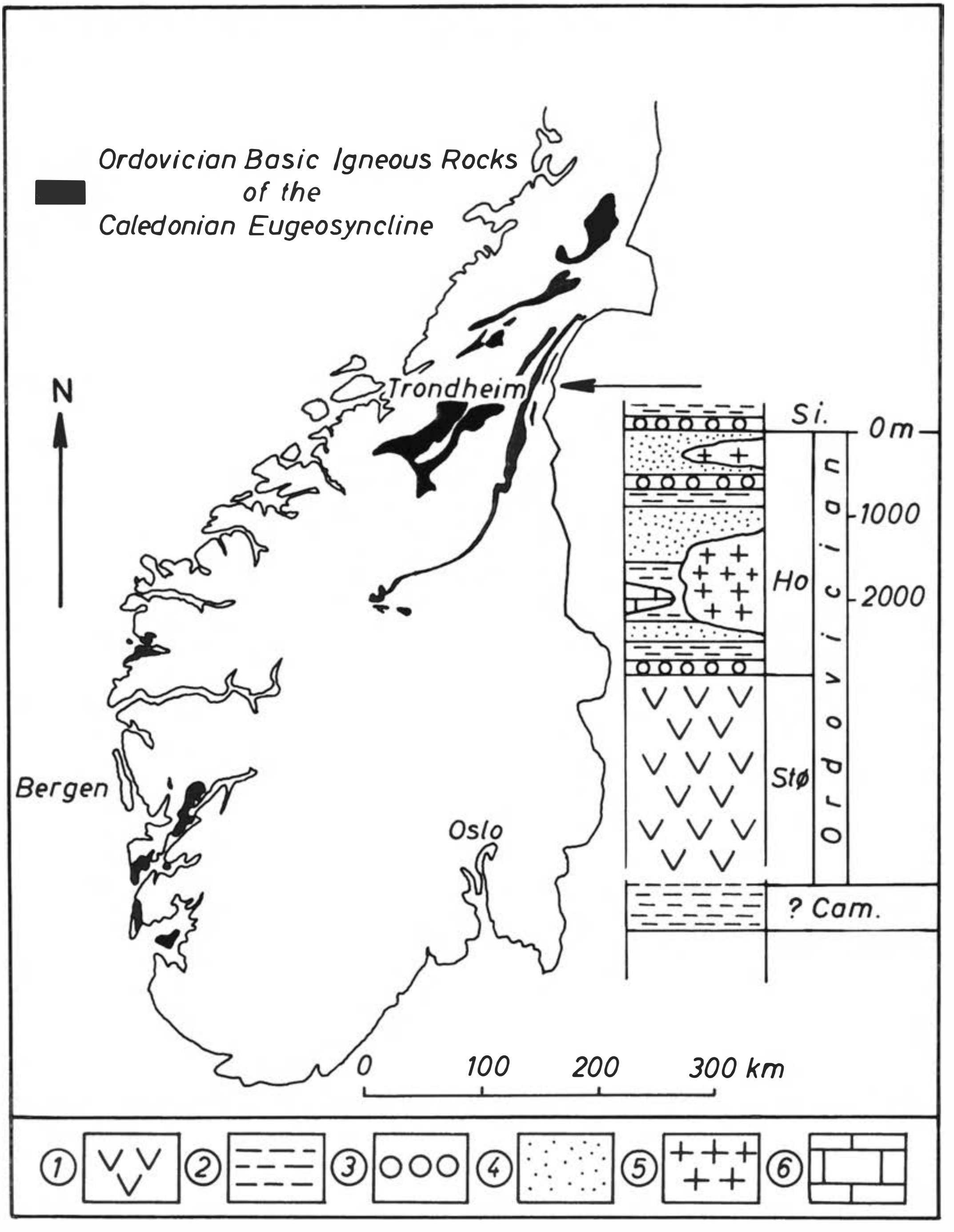

Fig. 1. Geological sketch map of southern and central Norway and simplified columnar stratigraphic section showing the regional distribution and the stratigraphic position of the Støren greenstones south of Trondheim (Norway). Stø = Støren Group (greenstones), Ho = Hovin Group (clastic sediments, andesites, rhyolites). 1 = Basic igneous rocks, 2 = Schists, shales, 3 = Conglomerates, 4 = Sandstones, 5 = Intermediate to acidic igneous and pyroclastic rocks, 6 = Limestones. Simplified and redrawn after Gale et al. (1974) and Oftedahl (1974). A detailed description of the stratigraphy is given by Vogt (1945), Chaloupsky (1969), Oftedahl (1974) and others.

Table 1. Rare earth element contents and Sc, Hf, Th values (ppm) of 18 Støren greenstones south of Trondheim, Norway. M = Massive lava parts of the interior of thicker pillow lava flows, PS = Pillow selvedge, PR = Inner rim of pillow, PC = Pillow core, MP = Matrix between pillows. Analyst: H. H. Schock.

	M	M	PS	PR	PC	PS	PR	PC	MP
	N 12	N 16	N 21a	N 21b	N 21c	N 24a	N 24b	N 24c	N 29
La	10.0	6.2	6.7	4.4	5.0	7.3	4.5	4.9	8.6
Ce	24.9	16.9	16.2	13.3	14.6	16.5	12.5	14.5	21.1
Nd	21.0	14.5	11.9	10.7	15.7	16.0	11.9	14.2	17.4
Sm	6.7	4.64	4.37	3.52	4.15	4.95	3.60	3.90	5.72
Eu	2.13	1.47	1.23	1.26	1.36	1.55	1.27	1.25	2.11
Tb	1.23	0.89	0.80	0.76	0.79	0.90	0.71	0.79	1.08
Dy	7.7	6.0	4.8	4.1	5.9	5.0	4.4	5.0	6.2
Yb	5.16	3.63	3.12	3.09	3.30	3.73	2.87	3.17	4.22
Lu	0.82	0.61	0.45	0.47	0.51	0.61	0.45	0.49	0.63
Sc	40.3	39.3	38.7	28.8	35.9	46.8	31.2	32.6	45.6
Hf	4.4	3.0	2.8	2.3	2.6	3.1	2.3	2.6	3.0
Th	0.39	0.31	0.42	0.27	0.43	0.40	0.33	0.43	0.38

	M	MP	PS	PR	PC	M	PS	PR	PC
	N 32	N 44	N 46a	N 46b	N 46c	N 60	N 61a	N 61b	N 61c
La	6.8	3.6	6.2	4.1	4.8	5.5	6.6	7.2	6.3
Ce	17.2	10.4	17.4	13.0	13.2	15.0	16.8	18.5	16.4
Nd	15.4	9.7	17.5	12.8	11.3	17.6	16.5	15.1	16.3
Sm	4.82	3.03	4.66	3.42	3.48	4.19	4.69	4.45	4.17
Eu	1.50	0.93	1.50	1.28	1.21	1.48	1.50	1.54	1.43
Tb	0.96	0.72	0.88	0.71	0.71	0.85	0.89	0.88	0.86
Dy	5.9	5.6	5.7	6.0	4.6	4.3	5.9	6.0	6.1
Yb	3.77	2.54	3.51	2.96	2.86	3.29	3.43	3.43	3.10
Lu	0.56	0.34	0.51	0.40	0.40	0.54	0.58	0.48	0.50
Sc	42.7	15.8	42.9	27.9	28.2	40.0	45.6	41.4	40.0
Hf	3.3	1.9	3.1	2.3	2.3	2.6	3.2	2.9	2.8
Th	0.42	-	0.41	0.26	0.30	0.31	0.39	-	-

the data of Sc, La, and Lu. The contents of Ce, Nd, Eu, Tb, Yb, Hf, and Th were obtained with the planar Ge-detector 6–7 weeks after the end of the irradiation. Average errors of all determinations resulting from counting statistics can be seen from Fig. 2, where they have been plotted on the graphs of the samples N 12 and N 16. The accuracy of the determinations has been checked with the contents of the U.S.G.S. standard rocks BCR-1 and G-2 (Flanagan 1973), which were simultaneously analysed. More detailed information about the techniques used is given in the publications by Schock (1973, 1977).

The rare earth element contents

The contents of the determined elements can be seen from Table 1. In Fig. 2 the values of the

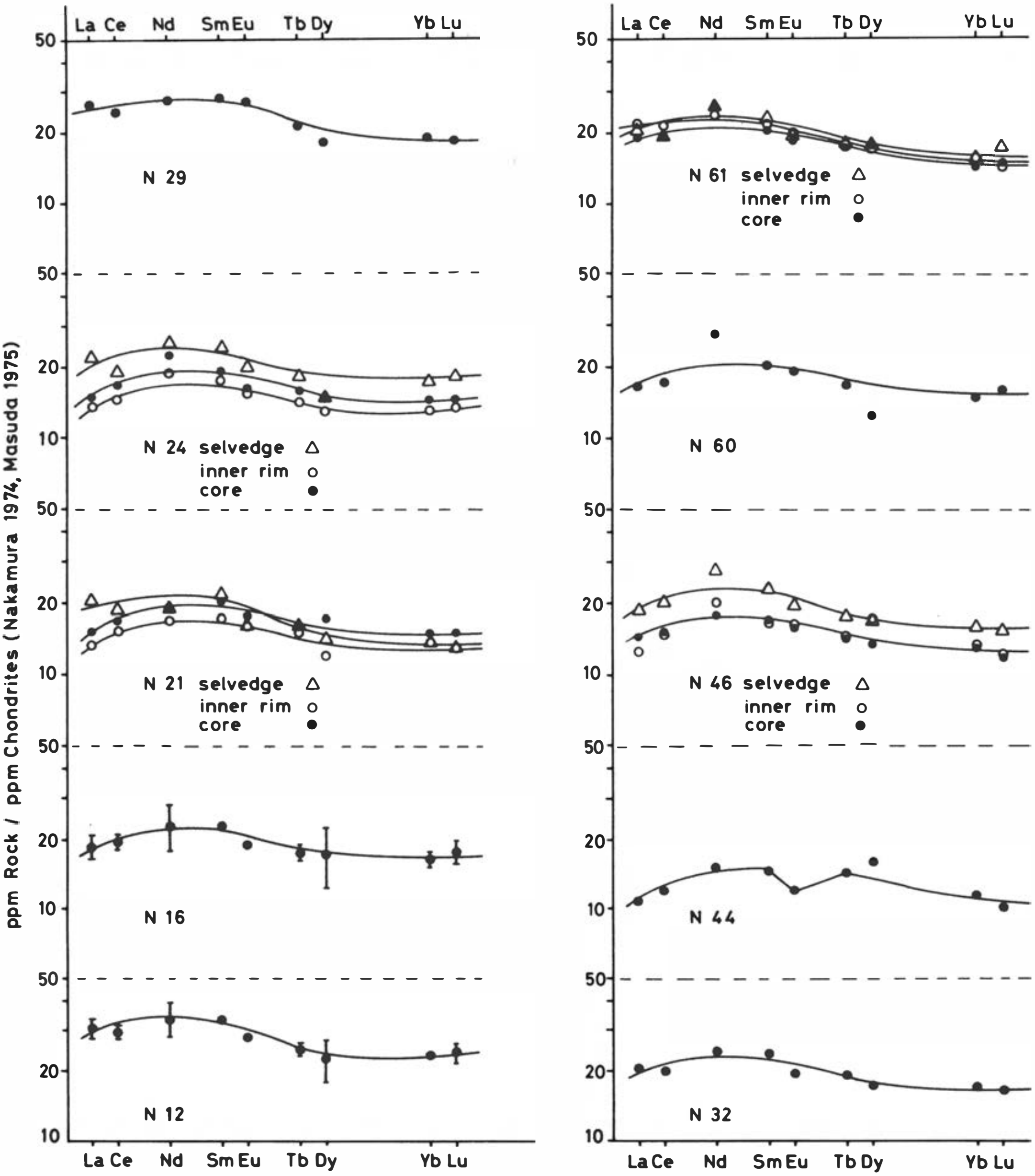

Fig. 2. Rare earth element distribution pattern of 18 Støren greenstones of the Norwegian Caledonides south of Trondheim. N 21, N 24, N 46, N 61 = Pillows. N 12, N 16, N 32, N 60 = Massive lava parts of the interior of thicker pillow lava flows. N 29, N 44 = Matrix between pillows. Analyst: H. H. Schock. All rock values are normalized to a chondritic average (Nakamura 1974, Masuda 1975).

individual elements are divided by the respective values of chondrites (Nakamura 1974, Masuda 1975) and plotted as a function of the atomic number of the elements. From Fig. 2 it is thus apparent that the Støren greenstones are enriched in REE between 10 and 30 times as compared to chondrites. The distribution curve shows a smooth curvature because Nd and Sm are in many cases relatively enriched and La and Ce relatively depleted. Analyses of individual pillows, where the core, the inner rim, and the outer selvedge of one pillow have been separately analysed (N 21, N 24, N 46, N61), show that the selvedges are enriched in REE with respect to the pillow cores and inner rims. There are no systematic differences between the REE contents of pillow cores and inner rims. In two cases (N 24, N46) the distribution curves run parallel to each other, in two other cases (N 21, N61) nearly parallel to each other. A similar near-parallel behaviour of the REE patterns in metamorphosed basic lavas was also observed by Hellmann et al. (1977 b) in Ordovician spilites of New South Wales (Smith 1968). The REE behaved remarkably coherently during the mineralogical adjustment of the Støren greenstones. Apparently no differentiation took place between light and heavy REE in the Norwegian Støren greenstones.

The enrichment of the REE in the pillow selvedges which is particularly obvious in the samples N 24 and N 46 is difficult to explain. A primary origin of this distribution pattern is improbable. The pillow selvedges represent the quenched outer glassy crust of the pillows which originally had the same chemical composition as the melt. The pillow cores had a much slower cooling rate than the pillow selvedges. Therefore crystals could form in the pillow cores, and the surrounding residual melt in the pillow cores was enriched in REE since incompatible elements such as the REE become enriched in the residual melt during fractional crystallization. These primary differences in the REE distribution within the pillow cores could not be detected with the method used, since we made a whole-rock analysis of the cores. The REE contents of the selvedge and the whole core of an individual pillow were probably therefore originally the same.

A secondary origin of the REE enrichment in the pillow selvedges is much more probable. The originally glassy selvedges of the pillows are most strongly altered and consist of chlorite, actinolite, and leucoxene, whereas the inner rims consist of many varioles with epidote and feldspar. The cores show a fine-grained intergrowth of actinolite, epidote, feldspar, quartz, carbonate, and leucoxene with some phenocysts which are pseudomorphs of carbonate, chlorite, epidote (and quartz) after pyroxene (or feldspar). The pillow lavas must have taken up water after the consolidation and during submarine weathering and metamorphism to form the secondary mineral assemblage just mentioned. The REE distribution may be the result of these secondary alterations. Since the crystals of the core are much more resistant to alteration processes than the glassy parts, a redistribution of the REE took place first in the glassy parts during submarine weathering and metamorphism. A transport of REE within the glassy parts from the core to the selvedge of the pillows may be responsible for the REE enrichment in the selvedges because the glassy parts of the core originally had a higher REE content than the crystals of the core, and the selvedges had an average REE content corresponding to the REE content of the melt. This transport and homogenization within the glassy parts means a depletion of REE in the core and an enrichment of REE in the selvedge for the whole-rock analysis. Thus the REE are probably mobile during submarine weathering and metamorphism, a suggestion which has also been proposed by Wood et al. (1976), Floyd (1977), Hellmann et al. (1977 a, b), and Menzies et al. (1977). According to Menzies et al. (1977:1425), light REE are more vulnerable to change during metamorphism than heavy REE. In most samples of the Norwegian greenstones a slight negative Ce anomaly can be seen which may be due to interaction with sea water (Hellmann et al. 1977 b: 157).

The samples N 12, N 16, N 32, and N 60 are unpillowed massive lava parts which occur in the interior of thicker pillow lava flows. These massive parts are less sensitive to secondary alterations than individual pillows because they are more coarse-grained, originally contained less glass than the pillows, and have less cooling joints along which water could circulate and cause secondary alterations. The REE distribution curves of these samples should therefore approximately reflect the primary REE distribution pattern of the Støren greenstones. From Fig. 2 it can be seen that the samples N 12, N 16, N 32, and N 60 are 20 to 30 times enriched in REE compared to the average chondrites. The differences in the REE contents between pillowed and unpillowed magmatic bodies of the Støren greenstones are not very pronounced and the secondary alterations observed in the pillows are only of minor importance.

The samples N 29 and N 44 represent the matrix between the pillows which is the alteration product of originally glass-rich hyaloclastite fragments. N 29 has a similar REE content as the pillows and the massive lava parts. In contrast to N 29, N 44 has a low REE content. This sample could be interpreted as part of a primitive un-

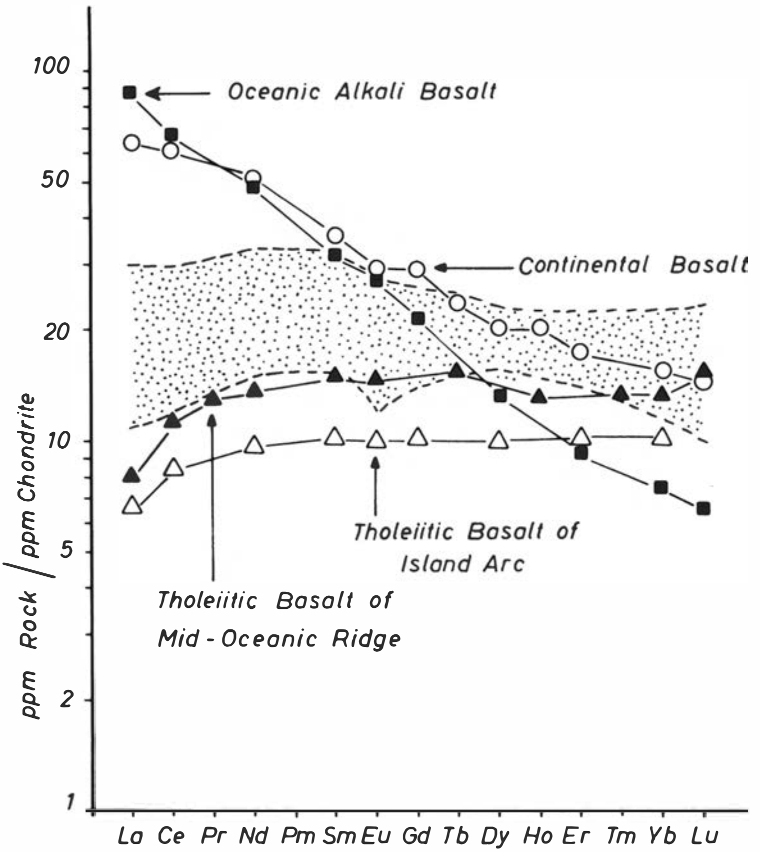

Fig. 3. Distribution of the rare earth elements in oceanic alkali basalts (Hawaii; Kay et al. 1973), continental basalts (Steens Mountain/Oregon; Helmke et al. 1973), tholeiitic basalts of mid-oceanic ridges (Schilling 1971) and island arc tholeiites (Scotia Arc; Hawkesworth et al. 1977). The dotted area comprises the field of the analysed Støren greenstones south of Trondheim, Norway. All rock values are normalized to a chondritic average (Nakamura 1974, Masuda 1975).

modified melt. But this interpretation is misleading because N 44 consists mainly of chlorite and is the most strongly altered sample. It contains 37.7% SiO_2, 19.4% Fe_2O_3 (total), 13.6% MgO, and 8.6% H_2O (Loeschke 1976 b) and shows corundum in the CIPW-norm which is a definite proof of secondary alteration effects. The low REE content of N 44 is therefore of secondary origin. A secondary phase such as chlorite can affect the uptake of trace elements (Hellmann et al. 1977 b). The near parallel behaviour of the REE distribution curves of Fig. 2 is not a result of fractional crystallization, but is due to secondary alterations, because these can mimic to some degree natural crystallization patterns – a fact which has been studied in detail by Hellmann et al. (1977 b). N 44 is the only sample which shows a negative Eu anomaly.

Geotectonic implications

With the exception of Ti, Zr, Y, P, and Nb, the REE are the elements which are least affected by secondary alterations. Other major and trace elements, particularly Si, Mg, Ca, Na, K, Rb, Sr, are more sensitive to secondary alterations. This is due to the different ionic potentials of the elements and their different behaviour in an aqueous medium (Mason 1966: 163). To our knowledge, there are no elements which are completely insensitive to secondary alterations. In the previous chapter the influence of secondary processes such as weathering and metamorphism on the REE has been explained. The secondary alterations of the REE in individual pillows have been found to be of minor importance and the REE contents of the massive

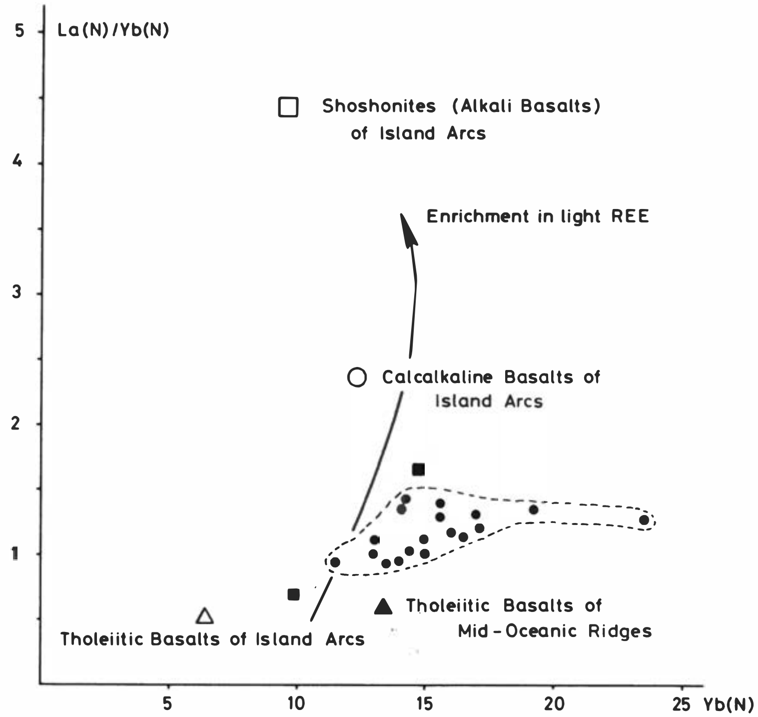

Fig. 4. La(N)/Yb(N) ratios of island arc basalts (Jakes et al. 1972) and tholeiitic basalts of mid-oceanic ridges (Schilling 1971). N denotes chondrite-normalized values (Nakamura 1974, Masuda 1975). Black dots: 18 analysed Støren greenstones south of Trondheim, Norway. Black squares: 2 Støren greenstones south of Trondheim, analysed by Dypvik et al. (1976).

unpillowed parts of thicker pillow lava flows are thought to reflect approximately the primary REE contents of the Støren greenstones. Therefore it is reasonable to use the REE contents as a guide to the identification of the original magma type of the Støren greenstones and their former geotectonic position which is an essential question for any reconstruction of the eugeosynclinal environment of the Støren greenstones.

Comparisons between eugeosynclinal volcanic rocks and young volcanic rocks of different geotectonic positions are most important (Carmichael et al. 1974: 558). Recent volcanism is mostly connected with divergent or convergent plate boundaries and the principal connections between geodynamic and magmatic processes are mainly accepted also for Palaeozoic and Late Precambrian times (Gorshkov 1972: 123, Green 1972: 64, Le Pichon 1973: 274, Miyashiro 1975: 250, Ringwood 1975: 312).

The REE of young basaltic rocks show a distribution pattern which makes it possible to distinguish between basalts of oceanic islands, continental plateaus, island arcs, and mid-oceanic ridges (Fig. 3). In Fig. 3 the REE distribution curves of various basalts have been plotted to display the different fractionation trends of light and heavy REE in different basalt types. The dotted area indicates the field of the analysed Støren greenstones. Though it is difficult to interpret the data of the REE of the Støren greenstones because they show a considerable spread around an average value, it may tentatively be concluded from Fig. 3 that the average value of the Støren greenstones plots in a field which is transitional between mid-oceanic ridge basalts and island arc tholeiites on the one side and continental basalts and oceanic alkali basalts on the other side. The most likely field of the Støren greenstones would be the field in which the REE contents of the unpillowed massive lava parts plot which show an enrichment of 20 to 30 times compared to the average chondrites (see Fig. 2, sample N 12, N 16, N 32, N 60). This field corresponds to the field of basalts of more evolved island arcs since 'the overall abundance levels of incompatible elements tend to be relatively low in rock series following the tholeiitic trend and high in rock series following the calc-alkaline trend' (Ringwood 1975: 240).

To show this more instructively, Fig. 4 has been drawn where different basalts of island arcs and their La(N)/Yb(N) ratios have been plotted. The data are from Jakeš et al. (1972) and reveal that calc-alkaline basalts of island arcs are enriched in light REE compared to tholeiitic basalts of island arcs. Tholeiitic basalts are typical for young immature island arcs (i.e. Tonga, Kermadec) and calc-alkaline basalts are typical for more evolved island arcs with a greater crustal thickness (i.e. Japan) (Miyashiro 1974). In Fig. 4 the Støren greenstones plot in a field which is transitional between tholeiitic basalts of immature island arcs and mid-oceanic ridges, and calc-alkaline basalts of more evolved island arcs. Therefore, the REE content of the Støren greenstones gives evidence to support the opinion that the volcanic rocks of the Caledonian geosyncline south of Trondheim were formed in an Ordovician island arc which was slightly more evolved than the first immature stages. This is also the conclusion from the geological and stratigraphic development and the major element geochemistry of the whole Ordovician section of the Caledonian geosyncline south of Trondheim (Loeschke 1976 b).

REE investigations can therefore give additional information to the results of geological field work if the secondary effects of the post-crystallization elemental redistribution can be evaluated.

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