Mineralia slov.
16 *(1984), 1, 29—37*

Global evolution of the mafic magmatism with special regard to the rare earth elements

CARL-DIETRICH WERNER

Bergakademie Freiberg, Sektion Goewissenschaften, Brennhausgasse 14,
9200 Freiberg, DDR

(9 figures and 1 table in the text)
Received October 12, 1983

Глобальное развитие мафического магматизма с особенным зрением на элементы редких земель.

Анализ глобального развития мафического магматизма основанного на, для этого пригодных картинах содержания элементов редких земель, позволяет различить его отношение к главным стадиям геодинамического режима в течении развития Земли. В результате понижения глобального теплотного течения и повышающегося разубаживания мантии о инкомпатибильные элементы являются основным изменением состава мафических магматитов. Особенно интенсивные магматические процессы протекали к концу архея. Для отдельных эпох являются характеристическими специфические магматические циклы.

Global evolution of the mafic magmatism with special regard to the rare earth elements

The analysis of the global evolution of the mafic magmatism basing on the therefore especially suitable REE patterns makes recognizable a distinct connection to the main stages of the geodynamic regime with the progress of the earth's history. With decreasing global heat flow and increasing impoverishment of the mantle for the incompatible elements substantial modifications of the mafic igneous rocks result. Obviously, the decisive event seems to be at the end of the Archaean. Within the individual stages distinctly marked cycles are evident.

Some years ago, at the final session of the field works 1980 in Prague, our colleague prof. N. L. Dobretsov has proposed a model for the global evolution of ophiolites (Dobretsov — Kepezhinscas, 1981). Continuing his ideas, it shall made an attempt for the global evolution of mafic magmatism in general on the basis of the rare earth elements. The 14 naturally existing REE (($_{57}La$ — $_{71}Lu$; $_{61}Pm$ does not occur because of its short half life period) are especially suitable for the substantial illustration of geologic events.

The variable distribution of the REE within the main mineral phases of the upper mantle (olivine, orthopyroxene, clinopyroxene and garnet) and whose different stability during partial anatexis in dependence of P and T enables to comprehend genetic events at the formation of mafic magmas in space and time. The secular diminuation of the thermal activity of the upper mantle with simultaneously decreasing on incompatible elements involve characteristic modifications of the mafic magmatites in the progress of the earth's history. They are especially marked during the Archaean.

Fig. 1 demonstrates the REE distribution between the primitive mantle (Mp) and the depleted mantle (Md) after the formal extraction of the present earth's crust (continental and oceanic; data from Wedepohl, 1981). The depleted mantle has a thickness of about 200 km, for strong incompatible elements considerably more (up to 900 km). The ratio LREE (La-Sm)/ /HREE (Eu-Lu) is distinctly higher in the crust and lower in the depleted mantle. The generation of mafic magmas should take place during the course of the earth's history from more and more depleted mantle areas apart from ranges with mantle metasomatism, mantle plumes, subduction and other disturbances.

In the following chapters all the rock types are demonstrated by their mean values, which enable a clearer comparison than by the range of scatter. The complete data will be published in a special paper (Werner, in press).

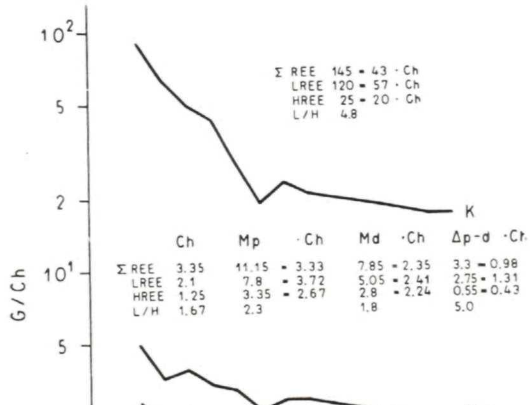

Fig. 1. Chondrite-normalized REE patterns for primitive (Mp) and depleted (Md) upper mantle and crust (K). REE data in ppm; Ch = average of the C1-C3 chondrites from the data of MASON (1979)

The Archaean komatiite-tholeiite sequence

From the first primitive basic to anorthositic crust of the earth, formed directly after the condensation of the earth's matter and the formation of the core, we don't know certain relics. As the oldest know mafic rocks the komatiitic-tholeiitic series of the greenstone belts appear, mainly evident on a sialic basement. Two main cycles may be distinguished:

3.5—3.3 b. y. (Barberton/RSA, Sargur/India, Pilbara/West Australia),

2.7—2.5 b. y. (Zimbabwe, Dharwar/India, Yilgarn/West Australia, Canada, Karelia/Finland-USSR).

A third cycle is known only relictic as enclaves in the 3.8 b. y. old Amitsoq gneisses from West Greenland. It may have an age of approximately 4 b. y.

The komatiites are predominantly effusive, partly explosive volcanics with mostly subaquatic emplacement and large thickness of the complexes. Generally, they contain olivine, orthopyroxene and plagioclase, but no clinopyroxene. The melting rate at the formation of the komatiitic magmas is very high: 40—70 % at high temperatures (more than 1650 °C) and low H_2O contents.

Fig. 2 demonstrates the REE patterns for some rock types of the three cycles. The oldest one (~ 4 b. y.) displays no big differences between peridotitic and basaltic komatiites. However, both the types are clearly enriched in face of the Mp. The second cycle (3.5—3.3 b. y.) is distinguished by a strong differentiation between PK and BK, and the PK patterns lie near by the Mp one. Within the third cycle, PK and BK are impoverished in LREE with lower contents of the hygromagmaphile REE (La-Pr) in the PK against Mp. Tholeiites and andesites on the other hand, which occur more frequently in the third cycle, possess considerably higher contents of LREE.

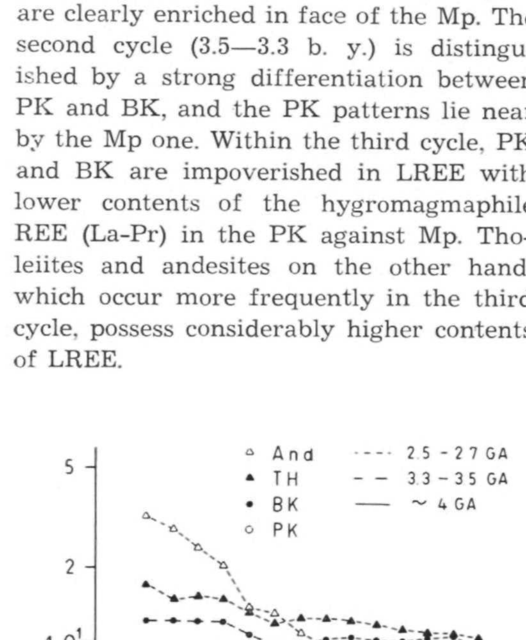

Fig. 2. Chondrite-normalized REE patterns for the Archaean komatiite-tholeiite association. PK — peridotitic komatiites, TH — tholeiites, BK — basaltic komatiites, AND — andesites

An explanation for the retrogression of the LREE contents in the youngest komatiites may lie in the progressive impoverishment on clinopyroxene in the upper mantle. This is made likely by the bulk chemistry of the komatiites, too, especially by the ratio CaO/Al_2O_3. These ratios change from 2—3 (1^{st} cycle) over 1—2 (2^{nd} cycle) to 0.6—1.2 (3^{rd} cycle).

Continental tholeiites

With the third cycle of the komatiitic-tholeiitic igneous event in the greenstone belts, at the border Archaean/Proterozoic, above all the thermal activity of the upper mantle seems to be exhausted widely. The magmatism is now of the type of the continental tholeiites. An old variant are the locally occurring cumulative complexes of the types Stillwater (2.7 b. y.), Great Dyke (2.5 b. y.) and Bushveld (2 b. y.).

A second cycle of the continental tholeiites we can find in the Late Precambrian, for instance in the Keweenawan and the Coppermine districts, North America (1.1 b. y.). At last, the plateau basalts of Mesozoic-Cenezoic age occur: Sibirian traps (250—220 m. y.), Karroo dolerites (200—165 m. y.), Paraná Basin (150—120 m. y.), Deccan traps and Thule Province (65—50 m. y.), and the Columbia River Province (15—10 m. y.). The main part of the Variscan initialites in Western and Central Europe belongs to this type, too (Werner, 1982). These two cycles are connected with intracontinental rift, resp. arcogene events, in parts joint with the separation of Gondwana, resp. the north drift of India.

Apart from the Keweenawan andesites and the Deccan traps with a certain alkaline tendency, the continental tholeiites (fig. 3) show relatively constant REE patterns over a time distance of more than

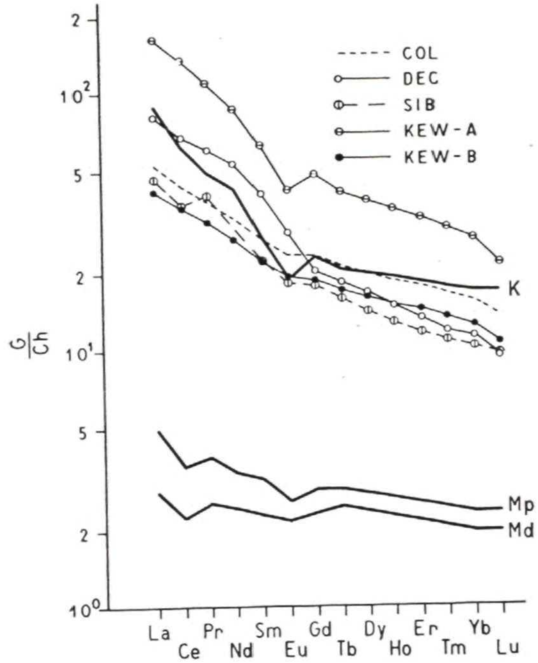

Fig. 3. Chondrite-normalized REE patterns for the continental plateau basalts. COL — Columbia River, Province, DEC — Deccan, SIB — Sibiria, KEW — Keweenawan, A — andesites, B — basalts

1 b. y. This may be the expression of comparable conditions of magma generation at 1200—1300 °C and 10—15 kbars in the presence of some water from a nearly homogeneous mantle composition. The somewhat elevated LREE contents could be the result of a supply of LREE enriched fluid phases from greater depths, possibly from the lower mantle. This can be derived from the Nd isotopes, too.

Oceanic tholeiites and ophiolites

The mass of the ophiolites is much larger than that of all post-Archeaen continental mafics together. The oldest known ophiolite complex is dated with 1.8—2 b. y. (Baykal-Muya Zone, Dobretsov — Kepezhinscas, 1981), however, ophiolites occur more and more from the Upper Proterozoic (Polar Urals, Central Europe) and the Cambrian (Northern Europe and Northern America), and reach their maximum during the Meso-Cenozoic with the formation of the recent oceans (about 2×10^9 km^3 basalts in 200 m. y.).

The oceanic tholeiites can be divided into three types, especially distinct at the REE: a primitive type (P), a 'normal' (N) and an enriched type (E). The prevailing N-type is mainly connected with the mid-ocean ridges. Elemental variations are depending from differing spreading rates, differing melting rates and the varying depth levels of the partial anatexis as well as from certain mantle inhomogeneities. The E-type is often connected with fractures zones and hot spot oder plume areas resp., combined with possibly anomalous mantle composition or fractionation in shallow-level magma chambers.

These three types are demonstrated in fig. 4. Gabbros and diabases can be divided into three types, too, but with distinctly lower enrichment of the LREE. This means originally primary differences between the intrusive and the extrusive melts. The positive Eu anomaly of the gabbros is involved by their higher plagioclase contents.

For the ultramafic members of the ophiolites there exist only few analyses. Due to their refractory or restitic character, they should be strongly impoverished in LREE. Actually, they show a more or less strong ascent of the LREE, very likely as the effect of the hydrothermal sub-sea floor serpentinization.

Oceanic island basalts

Within the oceanic lithosphere plates an igneous rock association with a completely

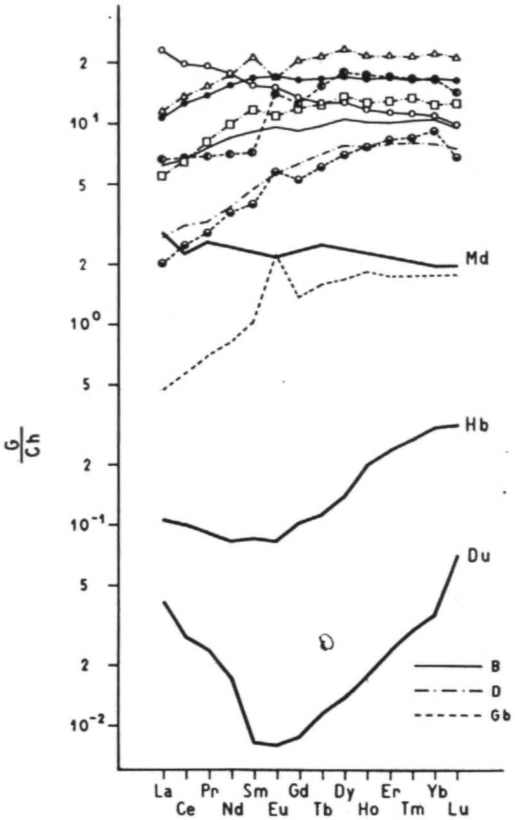

Fig 4. Chondrite-normalized REE patterns for the ophiolite association, B — basalts (tholeiites), Hb — harzburgites, D — dolerites ("diabases"), Du — dunites. Gb — gabbros

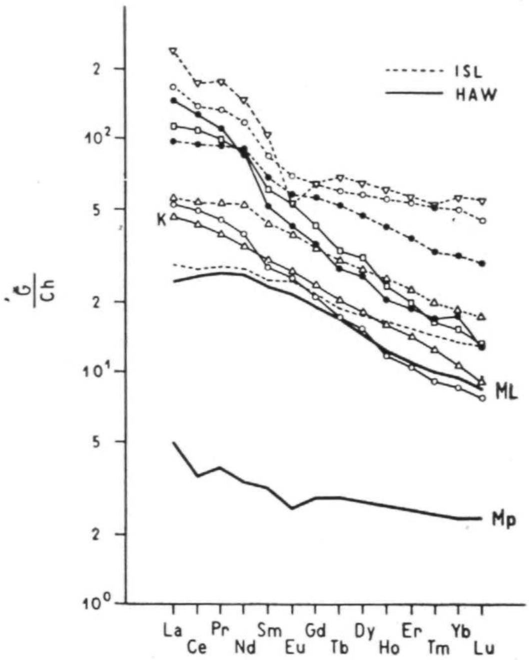

Fig. 5. Chondrite-normalized REE patterns for the oceanic island volcanic association. HAW — Hawaii, ML — Mauna Loa tholeiites, □ hawatites + mugearites, K — Kilauea tholeiites, ○ trachytes, △ alkali olivine basalts, ISL K Iceland (Tertiary) without signs — H-Mg tholeiites, △ — H-Fe tholeiites, ○ — icelandites, ● andesites, ▽ — rhyolites

differing petrochemical character occurs, but similar to continental within-plate mafic and alkaline rock series. It is connected with local hot spots in the mantle during the last 70 m. y., where the oceanic islands and seamounts were formed. Besides prevailing tholeiites, alkaline mafics and of minor importance felsic rocks, too, are evident.

Fig. 5. shows two examples, from Hawaii and from the Tertiary Iceland. The latter is conventionally looked as a part of the Thule Province, but on an oceanic basement. For each region a progressive increase in LREE is typical in the mafic to felsic sequence. The somewhat flatter ascent of the Iceland rocks may be the result of a less deep melting level. Because of the generally higher contents in incompatible elements compared with oceanic tholeiites, their parent melts must be originated in greater depths. From isotopic conditions the lower mantle is even thought by some authors.

Island arc igneous rocks association

Spreading within the oceanic lithosphere plates is necessarily connected with the subduction of oceanic crust on converging plate boundaries. In these regions the generation of characteristic igneous rock series takes place. They are of the Andean or of the island arc type. Only the latter may be regarded here. Three or four magmatite series can be divided: TH, CA, H-K, and SHO, and in each series we have basalts and andesites, apart from some other rock types.

Fig. 6 demonstrates clearly the increasing REE contents with increasing depth levels of the anatectic magma generation, and with the increasing K contents of the series. For comparison the mean values for the boninite/H-Mg andesite association are given.

Boninite/H-Mg andesite association

The first description of a boninite dates from 1890, but at first in the last five years these rocks have found a special interest. They are high-Mg (> 9 to more than 20 % MgO) plagioclase-free andesites with 56—58 % SiO_2, very poor in Ti, but considerably high in Ni and Cr. The boninites s. str. are tied to intra-oceanic island arcs (Bonin-Mariana arc), mainly as pillow lavas with olivine, chromite, clinoenstatite, H-Mg orthopyroxene, pigeonite, clinopyroxene and amphibole in a H_2O-rich glassy matrix. Other types are the H-Mg andesites from continental island arcs (Papua-New Guinea; Japan). All they are of late Mesozoic to Cenozoic age, older occurrences with a boninite tendency are known, for example, from the upper pillow lavas of the Troodos Massif, and within the ophiolites of Othris/Greece, Betts Cove/Newfoundland and Victoria/Australia. The boninites occur preponderantly in a fore-arc position with island arc tholeiites

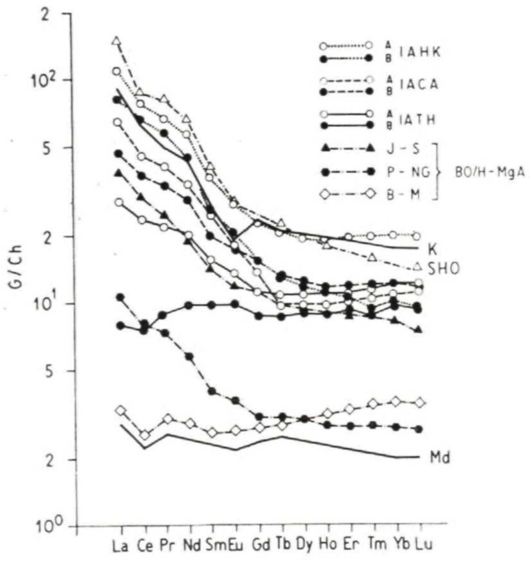

Fig. 6. Chondrite-normalized REE patterns for the island arc igneous rocks association. A — andesites, B — basalts, BO/H-MgA — boninite — H-Mg andesite series (mean values, explanation see fig. 7)

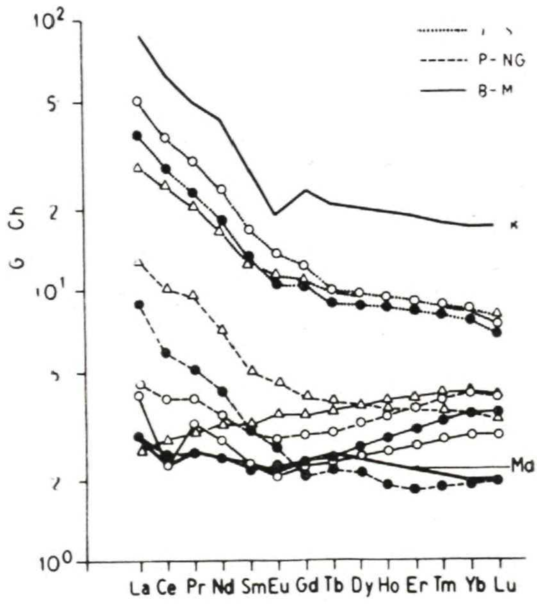

Fig. 7. Chondrite-normalized REE patterns for the boninite — H-Mg andesite series. J-S — Japan (Setouchi), B-M — Bonin-Mariana Arc, P-NG — Papua-New Guinea

as basement, and overlained by oceanic tholeiites.

Three sub-types of boninites are demonstrated in fig. 7. The most primitive REE pattern is in the rocks with the comparatively highest REE content. However, it is clearly lower than in normal island arc and oceanic tholeiites. Within the sub-type with the lowermost REE content, there is a typical V-shape pattern.

The H-Mg andesites from Cape Vogel (Papua-New Guinea) lie somewhat higher than the boninites, but in the main type with V-shape pattern, 'too. The Setouchi-H-Mg andesites from Japan possess no clinoenstatite, but orthopyroxene and olivine, and have clearly higher REE contents, somewhat differing from normal island arc volcanics, however.

Comparison of main types of mafic igneous rocks

If we compare the main types of mafic igneous rocks (fig. 8), clear differences with respect to the REE patterns are relevant. The poorest and youngest rocks are the boninites, generated from depleted mantle material with a relatively high melting rate. Then the oldest rocks (Archaean komatiites) succeed with very high melting rates in a ± primitive mantle. The striking similarity between basaltic komatiites and IATH gave rise to the models of Archaean subduction by some authors, but the rock association and the produced magma volumes are not comparable.

The highest REE enrichment show the oceanic and continental tholeiites, but with a different pattern. The first one were produced from a LREE depleted mantle, the second one from a possibly primitive mantle in a deep level or from a partially depleted, but somewhat metasomatized mantle. In table 1 some REE data for all main types are compiled.

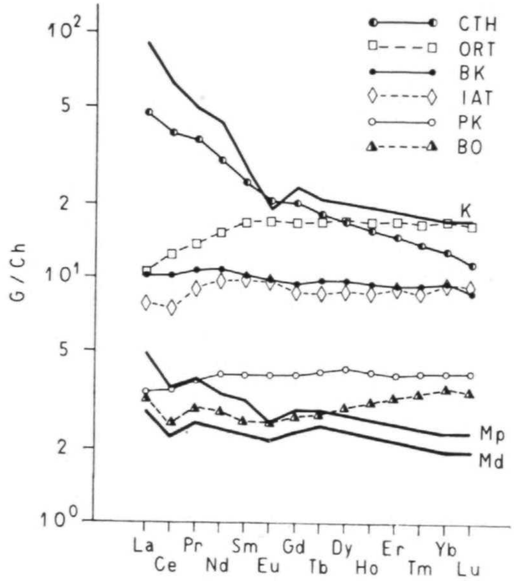

Fig. 8. Chondrite-normalized REE patterns for the main types of mafic igneous rocks. CTH — continental tholeiites, ORT — ocean ridge tholeiites, BK — basaltic komatiites, IAT — island arc tholeiites, PK — peridotitic komatiites, BO — boninites

Conclusions

In fig. 9 the occurrence of the main groups of mafic igneous rocks is time-scaled. After the condensation stage of the earth (A) with core formation, mainly degassing and a first primitive crust the stage of microplate tectonics (B, after Goodwin, 1981) follows with the komatiites during the Archaean. Here, the main formation of the earth's crust took place (Dobretsov, 1980; McLennan — Taylor, 1982). The three komatiitic cycles are clearly different. During the stage of the within-plate tectonics (C) in the Lower and Middle Proterozoic with only small crustal growth and intracontinental formation of troughs and protogeosynclines the continental tholeiites occur, which are generated in the next stage, too.

The final stage (D) started in the Late Precambrian with the ophiolites and the macroplate tectonics in more rigid plates, joint with ocean-floor spreading and subducion on Benioff zones. Connected with the ophiolites is the island arc magmatic activity. The within-plate alkaline igneous rocks belong to this stage, too, but their volume is very small, and to a certain extend they are 'exotic' rocks. The youngest formations are the boninite series, coupled with island arcs, but substantially and petrogenetically independant.

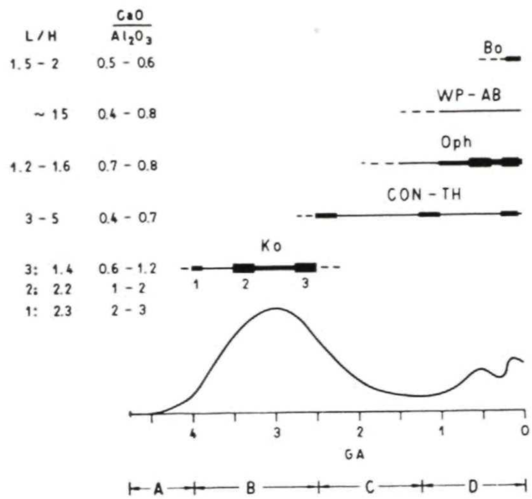

Fig. 9. Historical diagramm for the evolution of mafic magmatism compared with the crust formation (after Dobretsov, 1980) and the stages of the earth's evolution (after Goodwin, 1981). BO — boninites, WP-AB — within-plate alkali mafics, Oph — ophiolites, CON-TH — continental tholeiites, Ko — komatiites, A-D — evolution stages of the earth (see text)

REE mean values for the main types of mafic igneous rocks

Table 1

	CTH	ORT	BK	IAT	PK	BO
n	183	92	101	11	44	14
La	15.05	3.34	3.25	2.51	1.10	1.06
Ce	33.9	10.7	8.7	6.51	3.08	2.19
Pr	4.35	1.61	1.21	1.06	0.46	0.35
Nd	17.85	9.05	6.2	5.73	2.42	1.71
Sm	4.85	3.37	1.94	1.93	0.81	0.52
Eu	1.50	1.25	0.68	0.71	0.30	0.19
Gd	5.69	4.69	2.54	2.45	1.14	0.77
Tb	0.87	0.81	0.44	0.42	0.20	0.135
Dy	5.26	5.34	2.89	2.74	1.34	0.92
Ho	1.16	1.24	0.66	0.64	0.31	0.23
Er	3.05	3.55	1.81	1.88	0.85	0.68
Tm	0.44	0.53	0.28	0.28	0.13	0.11
Yb	2.46	3.27	1.71 1	1.82	0.80	0.69
Lu	0.37	0.54	0.28	0.30	0.14	0.115
Σ REE	96.8	49.3	32.6	29	13.1	9.7
LREE/HREE	3.65	1.32	1.89	1.58	1.51	1.52
La/Yb	6.12	1.02	1.90	1.38	1.38	1.54
$(La/Sm)_N$	1.94	0.62	1.05	0.81	0.85	1.27
$(La/Yb)_N$	3.69	0.62	1.15	0.83	0.83	0.93

We can perceive a congruency between the mafic magmatism and the crustal growth. The differing ratios of LREE/HREE and CaO/Al_2O_3 are the expression of an increasing depletion of clinopyroxene and incompatible elements within the upper mantle with more and more reduced melting rates. Especially clear is this tendency during the Archaean with three komatiitic cycles.

REFERENCES

Dobretsov, N. L. 1980: Introduction to Global Petrology (in Russian). *Novosibirsk.*

Dobretsov, N. L. — Kepezhinscas, V. V. 1981: Three types of ultrabasic magmas and their bearing on the problem of ophiolites. *Ofioliti, Bologna, 6, pp. 221—236.*

Goodwin, A. M. 1981: Precambrian Perspectives. *Science, Washington, 213, pp. 55—61.*

Mason, B. 1979: Meteorites. *U. S. Geol. Surv. Prof. Pap., Washington, 440-B-1.*

McLennan, S. M. — Taylor, S. R.: Geochemical constraints on the growth of the continental crust. *J. Geol., Chicago, 90, pp. 347—361.*

Wedepohl, K. H. 1981: Der primäre Erdmantel (Mp) und die durch Krustenbildung verarmte Mantelzusammensetzung (Md). *Fortschr. Min., Stuttgart, Beih. 59, 1, S. 203—205.*

Werner, C. D. 1982: Ophiolites and initialites — a comparing reflection. *Veröff. Zentralinst. Phys. d. Erde, Potsdam, 73, S. 55—64.*

Werner, C. D. in press.: Globale Entwicklung des basischen Magmatismus. *Z. geol. Wiss., Berlin.*