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RARE EARTH ELEMENT CONTENT IN THE SZENTBÉKKÁLA SERIES OF PERIDOTITE INCLUSIONS

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ABSTRACT

The genetic relations of four nonfrequent xenolith inclusion groups (dunite, layered lherzolite, websterite and spinel-pyroxenite) to the hypothetical mantle source spinel-lherzolite (the most frequent inclusion) and to the host alkali basalts have been investigated. The concentrations of rare-earth elements (REE) in the basalts, in the peridotite inclusions and in the mineral separates of spinel-lherzolites and spinel-pyroxenites were determined by instrumental neutron activation analysis. The REE abundance patterns of peridotite inclusions show increasing REE concentrations in the order: dunite, spinel-lherzolite, layered lherzolite, websterite and spinel-pyroxenite. Except spinel-pyroxenite this series of inclusions represents a gradation from depleted (the former two groups) to enriched (the later two groups) remnants of source mantle material. The enrichment of REE in spinel-pyroxenites and alkali basalts are in accord with their 17 percent and 3 percent partial melting from a chondritic mantle source. On the basis of our REE concentration measurements on alkali basalts containing peridotite inclusions (Szigliget, Szentbékkálla, Kapolcs) we suggest the introduction of a new group, the peridotite inclusion containing basalt group into Gy. Pantó's classification of Hungarian basalts.

INTRODUCTION

Ultramafic inclusions keep on to be in the centre of interest as they are the carriers of many information about the constitution of upper mantle. They are the most ultramafic representatives of a differentiational series of which the varieties of basalts are the most frequent products on the surface of the Earth. From ultramafic mantle rocks to the basalts there are a lot of branching pathways during the differentiation. The stations of these pathways can be found in the form of rare, nonfrequent inclusions which have been enclosed and conveyed in small xenolithic ammounts mainly by alkali basalts penetrating the upper mantle and crust. With our measurements we intended to sketch some steps of processes which had formed the upper mantle and lower crust under the NW Balaton region and which can be deciphered from the xenolith inclusions after their arrangement along a hypothetical evolutionary chain.

Two previous works must be referred here. The olivine dominated inclusions of Hungarian alkali basalts were investigated comprehensively for the first time by Embey-Isztin, A. (1976), who identified their xenolithic nature, showed their mineral composition to have been a four phase spinel-lherzolitic one and proved their upper mantle origin. The other work is that of Pantó's one (1981), who has measured by

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mass-spectrometric method the REE abundances of different Hungarian volcanic rocks from the Cenozoic era. Among his measurements some results about the REE pattern of some basalts from this NW Balaton region occurred, although no those one which contain lherzolite xenolits.

The major purpose of the present paper is to report concentrations for rare earth elements in selected (frequent and mainly monfrequent) ultramafic inclusions, in their separated constituent minerals and in the host basalts, and to discuss briefly the genetic implications of these data. The REE determinations presented here were all made by instrumental neutron activation analysis (INAA) in the reactor of Budapest Technical University and the reactor of the Central Physical Institute of the Hungarian Academy of Sciences; the electron microsonda analyses were carried out on the JXA—50A type instrument of Department of Petrology and Geochemistry, Eötvös Loránd University.

SAMPLES

The source region of our samples is situated in a triangle bordered by the Balaton Lake from SE, by the Bakony Mountains from NE and by the Little Hungarian Plain from west *(Fig. 1)*. The NW Balaton basalt occurrences consist of tuff and lava type flecks (some kilometers in diamater) of alkali basalts forming an arc of a half-ring around the southern Little Plain. The rocks of this half-ring frequently contain

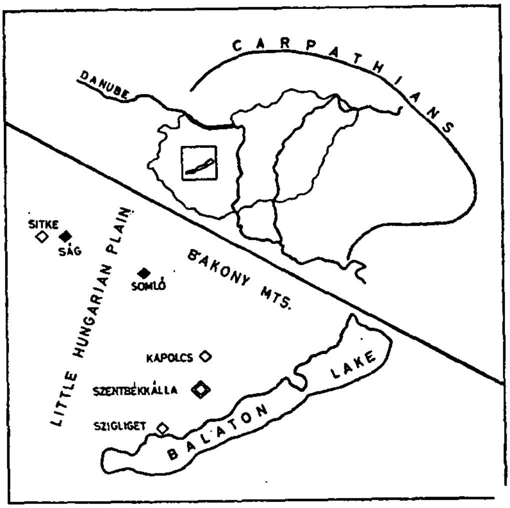

Fig. 1. Location of the NW Balaton region in Hungary, where the peridotite inclusions and host basalts were collected. (◇ — source of samples, ◈ — source of greatest part of samples, ◆ — sources of samples from literature (see Gy. Pantó, 1981/)

lherzolite inclusions as xenoliths in the rocks from other parts of the arc. The detailed petrological description of the occurrences has been given by Embey-Isztin, A. (1976).

The list of Table 1 shows the rock types investigated and the mesurements carried out on them. The series of nonfrequent ultramafic inclusions in from Szentbékkálla,

TABLE 1

The list of rock and xenolith types investigated and the measurements carried out on them

Name of rock	REE (INAA)	REE (INAA) on separated minerals	Electron microsonda analyses
Basalt (Szentbékkálla)	+		
(Kapolcs)	+		cpx-megacryst
(Szigliget)	+		
Lherzolite			
(Szentbékkálla)	+		
(Kapolcs)	+		
(Szigliget)	+		
(Sitke)	+		
THE SZENTBÉKKÁLLA SERIES			
Spinel-pyroxenite	+	+	+
Wehrlite	+		+
Layered lherzolite	+		
Average lherzolite		+	
Dunite	+		
Progran lherzolite		+	+

the most rich source region. Sample pairs of lherzolite and host basalt are from Szentbékkálla, Szigliget and Kapolcs, and only lherzolite sample is from Sitke. There are clinopyroxene megacrystalls from Szentbékkálla and Kapolcs.

REE ABUNDANCES IN ROCKS

The results of our neutron activation analyses are given in Table 2 for basalts and lherzolites, in Table 3 for the Szentbékkálla series of nonfrequent peridotite inclusions.

Alkali basalts

The total REE content is given by an estimation of $\frac{3}{2}$ times the sum of measured. lanthanide content, because we have results from about $\frac{3}{2}$ rd of all lanthanides only. This estimeted total REE content varies within a limited range between 240—340 ppm as compared to the 220—880 ppm (PANTÓ, GY., 1981) range of Hungarian basalts characteristical to the Southern Bakony and Balaton Highland group and the Mt. Ság in the Little Plain group in PANTÓ's classification. The chondrite normalized REE patterns of our three xenolith containing basalts are very similar to each other. *(Fig. 2.)* They exhibit a marked enrichment of light REE (LREE) and a moderate enrichment of heavy REE (HREE). The La/Lu ratio which roughly express the gradient of the slope is relatively high and varies between 160—220. These La/Lu ratio values are characteristical to the Little Plain group (PANTÓ, GY., 1981).

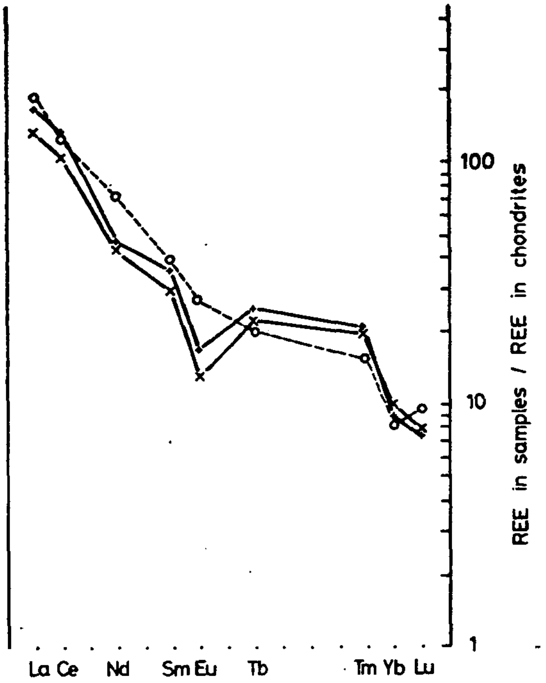

Fig. 2. Chondrite normalized REE abundances in three basalt samples (○—Szigliget, +—Kapolcs, ×—Szentbékkálla)

TABLE 2

REE content of rocks basalts and lherzolite inclusions (data in ppm)

	Basalts			Lherzolites				Average of 20 chondrites
	Szigliget	Kapolcs	Szent-békkálla	Sitke	Szig-liget	Kapolcs	Szent-békkálla	
La	56.6	50.9	39.7	0.6	0.4	1.4	1.2	0.30
Ce	107.0	110.8	87.8	3.1	1.5	4.0	2.7	0.84
Nd	42.0	25.6	25.4	1.2	0.5	1.3	<2.0	0.58
Sm	8.32	7.40	6.20	0.08	0.30	0.09	0.23	0.21
Eu	1.99	1.22	0.96	0.02	0.08	0.02	0.04	0.074
Tb	1.0	1.20	1.10	0.2	0.1	0.07	0.06	0.049
Tm	0.5	0.68	0.65	0.1	0.05	0.04	0.03	0.033
Yb	1.5	1.5	1.69	—	0.14	—	<0.5	0.17
Lu	0.30	0.24	0.24	0.05	0.06	0.05	<0.02	0.031
(Cr)	620						3200	
ΣLa-Lu	219.2	199.5	163.7	5.4	3.1	7.0	<6.0	2.3
$^3/_2\Sigma$La-Lu	328.8	299.3	245.6	8.0	4.7	10.5	<9.0	3.4
La/Lu	188.6	212.1	165.4					

Rare-earth element concentration was a good criteria to distinguish basalt groups. PANTÓ has performed this classification, and he has found that the REE patterns of rocks from a geographical region are similar to each other, therefore his groups were named after geographical regions. The locations of our basalt samples

TABLE 3

REE content of the series of inclusions from Szentbékkálla (data in ppm)

REE	Spinel-pyroxenite	Wehrlite	Layered lherzolite	Dunite
La	5.1	6.6	0.6	0.5
Ce	9.4	14.9	1.5	1.8
Nd	8.7	13.6	1.8	<0.5
Sm	2.76	3.25	0.56	0.08
Eu	0.81	1.17	0.19	0.03
Tb	0.45	1.0	0.14	0.04
Tm	0.2	0.5	0.06	0.02
Yb	0.9	1.5	0.2	<0.5
Lu	0.16	0.38	0.07	<0.02
(Cr)	50	9400	4400	1100
ΣLa-Lu	28.5	42.9	5.1	<3.5
$^{3}/_{2}\Sigma$La-Lu	42.7	64.4	7.6	<5.2

are near to his type-rocks, but do not match exactly with them. Although the place of occurrence of our three basalt samples fall onto his Southern Bakony Mountains and Balaton Highlands group's region (Szentbékkálla, Szigliget, Kapolcs), the REE abundance patterns of our samples (that of xenolith-containing basalts) show closer relation to the patterns of samples from the Little Plain group: Mt. Ság and Mt. Somló, on the basis of their steeper slopes with decreasing enrichment in LREE and marked Eu anomaly (except Szigliget). This contradiction forced us to suggest a completion of PANTÓ's classification with a transient new group of xenolith-containing basalts determined only on the basis of REE abundance pattern. This transient group should consist of those alkali basalts (and tuffs), which has

- — total REE content similar to that of rocks from the Southern Bakony and Balaton Highlands group,
- — La/Lu ratio similar to that of the basalts from the Little Plain group,
- — inclusion content from the upper mantle (lherzolite xenolith inclusions).

Lherzolites

The total REE content of lherzolites is very low. The $\frac{3}{2}$ times sum of La-Lu values varies between 4,7 and 10,5 ppm which range falls between the 1,5 to 3 times of chondritic sum. These low values are in accord with the petrological results (EMBEY-ISZTIN, A., 1975) on their upper mantle origin. The chondrite normalized REE patterns of samples from the four source regions are scattering in a range shown on *Fig. 3* and show considerable fluctuations. The patterns are characterized by marked Eu and sometimes Sm negative anomaly.

The Szentbékkálla series

There were five selected rare inclusions which had REE abundances transitional from lherzolitic to basaltic values. One of them which were named as Progran — because of its protogranular texture according to the classification of MERCIER and NICOLAS (1975) — has not been measured for REE content as a whole sample, but only in separated minerals. (In order to get real average from the mixture of component minerals we should have needed a greater piece of this xenolith, which has large mineral grains.) The four xenolith inclusions are: a dunite, a layered lherzolite, a

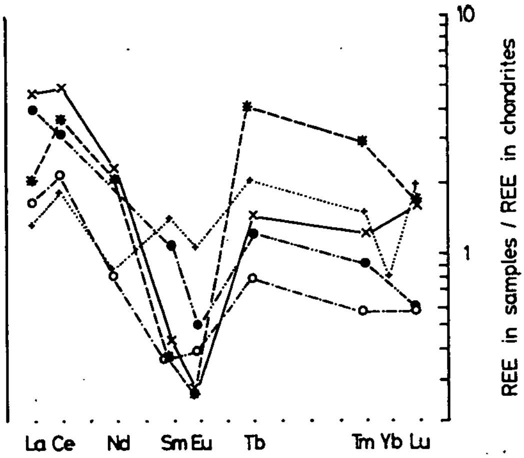

Fig. 3. Chondrite normalized REE abundances in Hungarian lherzolite xenolites, (× — Kapolcs, ● — Szentbékkálla /equigranular/, ∗ — Sitke, ○ — Szentbékkálla /dunite/, + — Szigliget).

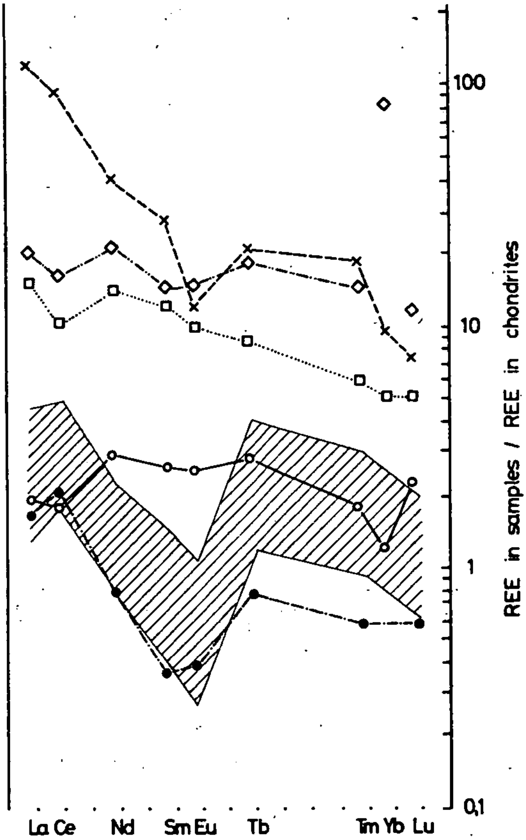

Fig. 4. Chondrite normalized REE abundances in the peridotite inclusions of the Szentbékkálla series and compared to the lherzolitic range, (×— Basalt, ◇ — Wehrlite, □ — Spinel-pyroxenite, ●— Dunite, ○— Layered lherzolite).

wehrlite and a spinel-pyroxenite. Their chondrite normalized REE patterns are given on *Fig. 4* and ordered according to their increasing REE content. (The REE abundances are listed in Table 3) They represent different evolutionary stages of parental rocks and melts as will be discussed later.

REE ABUNDANCES OF MINERAL SEPARATES OF THE PERIDOTITE INCLUSIONS OF THE SZENTBÉKKÁLLA SERIES

The four mineral phases of average lherzolite and three of the Progran sample (lacking the fourth phase in measurable amount) were separated by handpicking, the two phases of spinel-pyroxenites were separated by magnetic separator. Optical and X-ray diffractional identification also belonged to the sample preparations. The REE content of mineral separates of rocks referred in Table 1 are given in Table 4 for the two lherzolites and in Table 5 for spinelpyroxenites and basaltic megacrystalls.

TABLE 4

REE content of mineral fractions I (data in ppm)

	Average lherzolite				Progran sample		
	Olivine	Enstatite	Diopside	Spinel	Olivine	Enstatite	Diopside
La	0.14	0.12	1.10	3.0	0.3	0.2	1.5
Ce	0.34	0.28	3.8	42.2	0.7	0.6	4.6
Nd	0.5	0.07	2.8	23.1	—	—	3.0
Sm	0.03	0.05	1.65	0.33	0.06	0.06	0.7
Eu	0.01	0.004	0.31	0.42	0.02	0.02	0.18
Tb	<0.02	<0.02	0.33	0.4	0.06	0.1	0.3
Tm	<0.02	<0.02	0.16	2.0	0.02	0.05	0.2
Yb	0.04	0.14	0.56	0.7	—	—	0.50
Lu	0.14	0.03	0.09	0.17	0.01	0.02	0.13
(Cr)				16.2%			
ΣLa-Lu	0.6	0.6	10.8	72.3	1.2	1.0	11.0
$^3/_2$ΣLa-Lu	1.6	0.9	16.2	108.5	1.8	1.5	16.5

TABLE 5

REE content of mineral fractions II (data in ppm)

	Spinel pyroxenites (Szentbékkálla)				Megacryst from basalts	
REE	Spinel A	Cpx A	Spinel D	Cpx D	Szentbékkálla	Kapolcs
La	4.3	2.9	0.5	3.2	2.3	3.3
Ce	5.7	5.8	2.0	8.9	8.3	8.8
Nd	<5.0	7.0	<2.0	5.8	6.0	10.9
Sm	0.40	3.34	0.09	3.88	3.10	3.7
Eu	0.10	0.98	0.04	0.04	0.55	0.96
Tb	0.09	0.55	0.03	0.7	0.52	0.6
Tm	0.07	0.16	0.02	0.36	0.29	0.23
Yb	<0.5	<0.5	<0.5	<0.5	0.92	1.5
Lu	<0.05	0.17	<0.02	0.08	0.12	0.12
(Cr)	240	29	44	430		10
ΣLa-Lu	16.2	21.4	5.2	23.5	22.0	30.1
$^3/_2$ΣLa-Lu	24.3	32.1	7.8	35.2	33.0	45.1

The chondrite normalized REE abundance patterns of minerals in average lherzolite (Fig. 5a) clearly follows the order of partial melting determined from high pressure melting experiments (see. e.g. Mysen and Holloway, 1977, or Presnall *et al.*, 1978). The spinel component has the highest REE content; it is followed by that of clinopyroxene. During partial melting these two componets go into the melt firstly in the order: 1. spinel, 2. clinopyroxene (diopside). There are no considerable differencies between the REE patterns of average lherzolite and that of Progran sample *(Fig.5b)*. The very high point at Tm of spinel component is noteworthy. Mysen and Kushiro (1977) concluded from their high pressure melting experiments on peridotites that the role of garnets in the high pressure field is taken up by spinels (as the highest Al_2O_3 containing phase) in the lower pressure field after the garnet-peridotite ⇌ spinel-peridotite transformation. This outstanding Tm data point could be interpreted as the "remembering" of spinel to his "garnet past".

We can follow how partitional relations changes between the spinel and clinopy-

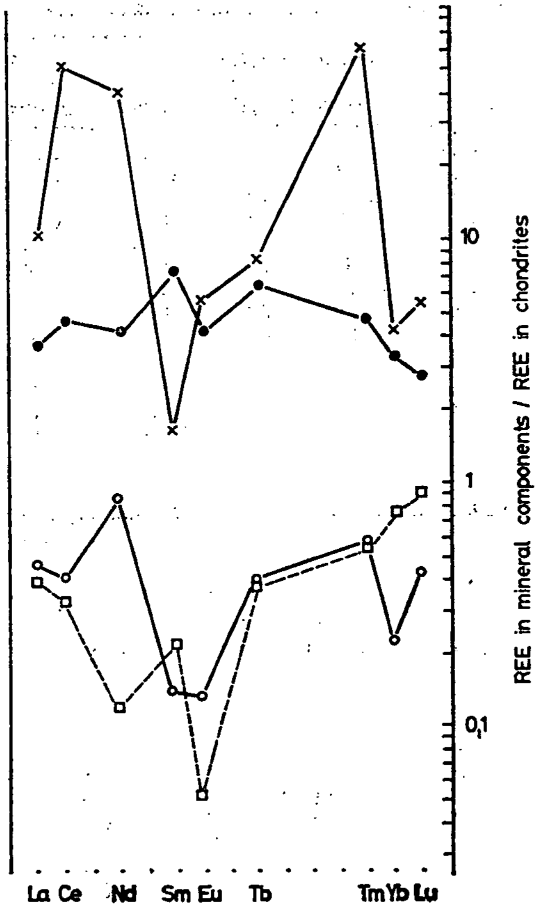

Fig. 5a: Chondrite normalized REE abundances in the mineral components of the average lherzolite, (× — Spinel. ● — Diopside, ○ — Olivine, □ — Enstatite).

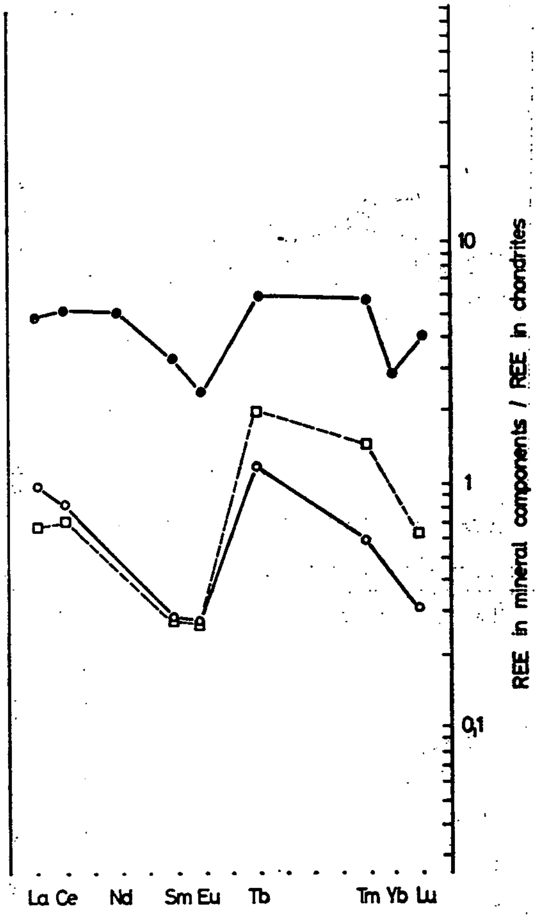

Fig. 5b. Chondrite normalized REE abundances in the mineral components of the Progran sample, (● — Diopside, ○ — Olivine, □ — Enstatite)

roxene components during partial melting when we compare the REE patterns of the spinel and clinopyroxene pair in the average lherzolite with that of in the spinel-pyroxenite. In lherzolitic mineral environment (and upper mantle pressures) spinel is the latest mineral component during crystallization and the first in partial melting: it is characterized with the highest REE content. After a higher degree of partial melting, when clinopyroxenes also went into the melt, and the melt withdrawed from the lherzolitic environment (pressure decreased) the roles between spinel and clinopyroxenite are inverted. *(Fig. 7)* Spinels are the first components during crystallization and clinopyroxenes has higher REE content.

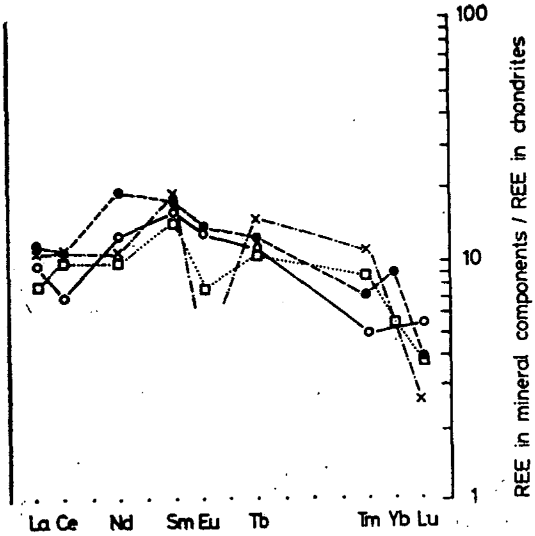

Fig. 6. Comparison of chondrite normalized REE abundances of cpx megacrystalls from basalt and cpx components of spinel-pyroxenite samples, (○ — cpx of spinel-pyroxenite A, □ — cpx megacryst. /Szentbékkálla/, ● — cpx megacryst. /Kapolcs/, × — cpx of spinel-pyroxenite D)

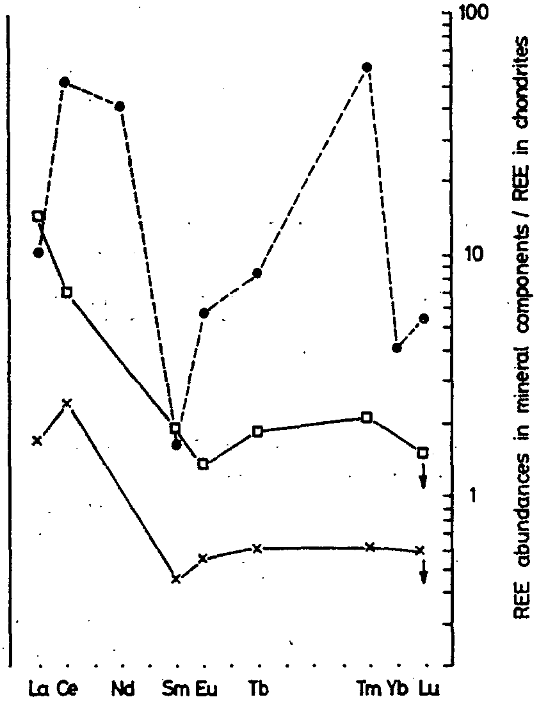

Fig. 7. Comparison of chondrite normalized RÉE abundances of spinel components of average lherzolite and of spinel-pyroxenites, (● — spinel of average lherzolite, □ — spinel of spinel pyroxenite A, × — spinel of spinel-pyroxenite D)

RESULTS FROM ELECTRON MICROSONDA ANALYSES

Electron microsonda analyses were carried out on some mineral components of Progran sample, of wehrlite, of spinel-pyroxenite and on clinopyroxene megacrysts of two basalts (Kapolcs and Szentbékkálla) in order to determine the tectonical settings of these samples. The data are given on Table 6.

TABLE 6

Results of electron microsonda analysis on mineral components of Progran lherzolite, wehrlite, spinel-pyroxenite and the clinopyroxene megacryst
(K. G. SOLYMOS and CS. SZABÓ)

	Progran lherzolite			Wehrlite		Spinel-pyroxenite A		Cpx megacryst (Kapolcs)
	olivine	enstatite	diopside	olivine	cpx	spinel	cpx	
SiO_2	38.58	54.00	52.20	38.31	50.10	—	49.22	48.84
TiO_2	—	—	0.07	—	0.47	0.49	1.17	0.97
Al_2O_3	—	2.26	3.25	0.07	3.36	61.98	7.87	7.63
FeO	8.24	6.23	2.97	13.90	4.51	16.50	6.24	5.82
MnO	0.10	0.15	0.10	0.27	0.16	0.06	0.18	0.10
MgO	51.94	36.48	17.68	47.12	17.29	21.41	15.10	16.12
CaO	0.08	0.93	20.98	0.05	22.66	—	18.64	18.94
Na_2O	—	—	0.48	—	0.16	—	1.24	1.17
Cr_2O_3	—	0.50	0.80	—	0.31	—	—	0.12
Sum	98.94	100.52	98.52	99.72	99.02	100.44	99.66	99.71
$\frac{100\ Mg}{Fe+Mg}$	91.8	91.3	91.4	85.8	87.2	69.8	81.2	83.2

Progran

The 100 Mg/Mg+Fe values of Progran sample showed the equilibrium character of this lherzolite. We have calculated the p-T conditions of its source region from the Ca and Al content of its diopside and enstatite (according to the method of MERCIER and CARTER, 1975) The mean temperature from the values from enstatite and diopside was 1150 °C (in the spinel-pyroxenite field). For the pressure region a range within 27—37 kbar (80—120 km) has been determined.

Taking into considerations of PRESNALL's attention to be cautious with using of the Al content of enstatite in determination of pressure in the spinel-lherzolite field we can conclude, that our sample, Progran falls onto the oceanic geotherm in the garnet-lherzolite field in MACGREGOR's diagram (MACGREGOR, 1974). As I know our Program sample is the only one from this zone in Hungary, investigated till now.

Wehrlite

The 100 Mg/Mg+Fe values of the components of wehrlite are more controversial. They are near equilibrium, but the values are a little bit lower than it should be necessary to their upper mantle origin. In the conclusion we point to its transitional character between lherzolitic samples with trapped melt (layered lherzolites) to products which were originated from crystallization of partial melts (but got stuck in deep). This latter type is represented by our spinel-pyroxenites.

Spinel-pyroxenite and clinopyroxene megacryst from basalt

The clinopyroxene of spinel-pyroxenite inclusion strongly resembles in composition, in REE content and pattern and 100 Mg/Mg+Fe value to the clinopyroxene megacryst from the basalt. But the two types represent two types of liquids. The estimated degree of partial melting of their source region as calculated from the ratios of their REE content to that of average lherzolitic one, was: 17 percent for spinel-pyroxenite and 3 percent for basalt. The spinel-pyroxenite originated in a zone, where all mafic liquid could have been crystallized, while clinopyroxene megacryst from basalt characterizes a liquid, where crystallization had begun only.

CONCLUSIONS

There are two important factors which have affected and formed the REE abundance characteristics of the ultramafic inclusions of the Szentbékkálla series investigated in this work. These two factors are partial melting and partial separation of melted liquids from the parental environment.

Rare-earth elements, as other incompatible elements, almost totally partition into the melt during partial melting processes. The high REE concentrations originated in this way are transported with the melt. If melt separates and crystallizes, it is easy to calculate the degree of partial melting, because the REE abundance is inversely related to the degree of partial melting (see e.g. the lunar series, Ringwood, 1975).

But the melt rarely separates totally from its parental environment. The arisen partial melt leaving the parental rocks in part only, its higher REE concentration is also retained partly with the residual melt. Changing p-T conditions may cause the recrystallization of this residual melt at the parental environment. This way the partial melting and partial retaining process can increase the concentration of REE on those places where the partial melt accumulated and decrease from where more melt had been withdrawed than had had been there earlier.

Our Szentbékkálla series of ultramafic inclusions can be arranged when we take into considerations these two mechanisms changing the REE concentrations. The highest REE abundances characterize those samples which had originated by separation of partial melt, i.e. the basalt and the spinel-pyroxenite samples. The second group of samples consists of rocks which retained more (e.g. layered lherzolites) or less (wehrlite) their lherzolitic character in spite of the fact that more partial melt had accumulated — and later crystallized — in them than originated from them. The third group consists of lherzolitic samples which in some degree has depleted in those components which had gone into the partial melt. The average lherzolite and the dunite sample with Progran sample belong to this group from our samples *(Fig. 8)*.

We can summarize our results in the following items:

1. Considering the lherzolites to be representative to the source region of basalts, the alkali basalts investigated by us were the products of 3 percent partial melting (average value).
2. During the partial melting of average lherzolite first spinel then clinopyroxene goes into the melt.
3. Spinel-pyroxenite inclusions represent a source region, where 15 percent partial melt of the lherzolitic source region was accumulated and solidified in deep.
4. In spinel-pyroxenite the partition of REE in spinel and clinopyroxene is inverted as compared to the lherzolitic case.

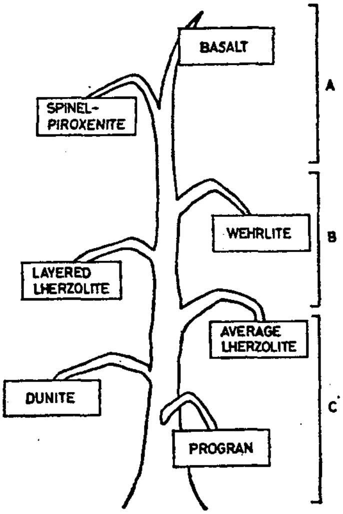

Fig. 8. Evolutionary model about the origin of different peridotite inclusions in the Szentbékkálla series. In this model the different degree of partial melting and the different degree of partial retainment of melted liquid determines the REE abundances of the members of the series. A — Great enrichment of REE. Partial melting separation of highest REE containing components and withdrawal of melt from the parental peridotitic environment. B — Enrichment of REE in the bulk sample (as compared to primary lherzolitic) mainly because of partial enrichment of the clinopyroxene component. C — Partial depletion of REE (as compared to primary lherzolitic) because of partial withdrawal of high REE containing mineral components, the spinel and clinopyroxene

5. Layered lherzolites and especially our wehrlite sample represent source regions enriched in high REE containing melt which then solidified in them.
6. In the Progran sample equilibrium of constituent minerals characteristic to the garnet-pyroxenite state has been preserved.

SUMMARY

Our REE measurements with INAA are, as we know, the first ones carried out on Hungarian peridotite inclusions. According to our model the series of ultramafic inclusions — with the supplementary host basalt — from Szentbékkálla represents different transitional or terminal stages of evolution of magma in the presence of parental mantle rocks. The results and the model discussed are in accord with earlier works on such types of inclusions from different parts of the world, and with the melting exporiments. It may have greater importance for the Carpathian Basin geology contributing to the understanding of processes which has origin in upper mantle regions.

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