DISTRIBUTION PATTERNS OF RARE EARTH ELEMENTS IN MINERALS

By

HENRICH NEUMANN, BRENDA B. JENSEN, and ARILD O. BRUNFELT

(Mineralogical-Geological Museum,
University of Oslo, Sars gate 1, Oslo 5)

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Abstract. Replotting of a large number of the rare earth element analyses of minerals available in the literature has shown that rare earth element fractionation in minerals follows relatively simple trends. In particular, the take-up of rare earths in many rock-forming minerals is strongly selective and follows a pattern which is predictable in terms of the ionic radii of the major elements involved. The rocks of a number of differentiation series show common REE fractionation trends which can be explained in terms of crystal fractionation of the rock-forming minerals.

Introduction

A new method of plotting abundance data of rare earth elements (REE)[1] was proposed in a previous paper (JENSEN and BRUNFELT 1965). It was used to replot a large number of the available analyses of REE in *rocks* (for the elements La to Tb only). The result was a series of relatively smooth curves showing maxima either at La or Tb.

It is to be expected that plots of *mineral* data, by the same system, will give similar smooth curves, and the present paper: 1) shows the results of our attempts to check this by plotting much of the mineral data available in the literature by the same system, and 2) uses these and other plots of the same type as a basis for some conclusions concerning selective take-up of REE in certain minerals during crystallization.

Method of plotting

The new method of plotting was suggested after it had been demonstrated that: 1) a number of basalts (continental and oceanic) show very similar REE distributions and are the only crustal rocks to show such a grouping, and 2) fractionation of the REE in igneous rocks is minimal for elements in the centre of the series.

It was therefore proposed that primary differences in total abundance of REE should be eliminated by ratioing every analysis, element by element, with a terrestrial reference distribution (obtained by averaging the REE analyses of three basaltic rocks). Differences in total REE content should then be eliminated by normalizing all analyses to an element in the range Eu, Gd, Tb, or, where possible, to an average value for all three elements in an attempt to minimize effects due to analytical error.[2]

The resultant ratios, when plotted against atomic number, should then give curves which represent only the degree of REE fractionation in the sample relative to the reference distribution.

[1] La to Lu inclusive.

[2] In the present paper, Gd has been used as the normalizing element, since the majority of data have been obtained by X-ray spectrographic analysis, which frequently does not yield data for Eu and Tb.

A general discussion of other plotting methods and a full account of the method of calculating the reference distribution are given in JENSEN and BRUNFELT (1965).

Comparability of results

A major problem when plotting data from the literature is the question of comparability of results obtained by different workers. In the case of *rocks*, the majority of analyses have been obtained by neutron activation methods by SCHMITT, HASKIN, GOLDBERG, and co-workers or by X-ray spectrographic analysis at the Vernadskii Institute (Moscow) (for References, see JENSEN and BRUNFELT 1965). When ratioed to a common reference analysis, all of these data gave smooth curves and were assumed to be comparable.

In the case of *minerals*, analyses have been carried out largely by X-ray spectrographic methods, and a great percentage of the available data comes from either the Vernadskii Institute (VI) or the Institute of Mineralogy, Geochemistry, and Crystal Chemistry of Rare Elements, Moscow (IMG). Plots of these data, calculated as before, give again smooth curves for virtually all data obtained at the VI, but much more irregular results for the data of IMG. This is presumably due, in part at least, to differences in analytical technique, since:

1. Minerals of the same species (but from different localities) have frequently been analysed by both institutes. The data of the VI, when calculated by this method, consistently give smooth curves, while those of the IMG are smooth in some cases and highly irregular in others. An example of this is the data for allanites (Figs. 1 and 2).

2. In two cases it would appear (although not specifically stated) that portions of the same mineral specimen have been analysed by both institutes and again greater irregularity is seen in the data of the IMG (Fig. 3).

3. Of all the *rock* analyses plotted by this method, the only markedly irregular curves were two based on data obtained at the IMG (JENSEN and BRUNFELT 1965, Fig. 6a).

This is not only a matter of differing standards, since the use of an IMG standard as reference distribution still fails to give smooth curves.

These results are both amazing and highly disturbing, and the

matter clearly requires a much more detailed and very careful examination, but, for the present at least, we feel constrained to exclude the data of the IMG from our considerations and to base our conclusions primarily on the results of VAINSHTEIN *et al.* (1956), MURATA *et al.* (1957), GAVRILOVA and TURANSKAYA (1958), BALASHOV *et al.* (1960, 1961, 1965), and TOWELL *et al.* (1965 B).

Comments based on mineral plots (Figs. 2-11)

Table 1 lists the mineral analyses which have been taken from the literature and recalculated to give data for the Figures in this paper. It at once becomes clear that there is a great need for more data:

a. for all minerals from rocks other than granites and pegmatites;
b. for a number of REE-rich minerals (e.g. sphene, pyrochlore, zircon, fluorite, etc.);
c. for minerals with low REE content for which very little data are at present available (e.g. felspars, biotites, pyroxenes, etc.).

It is, nevertheless, possible to draw the following tentative conclusions from the mineral plots:

1. Both for the rock-forming minerals (where the take-up of REE is relatively small and assumed to be due to substitution in the lattice) and for the REE minerals proper, smooth curves are characteristic. In addition to the full analyses plotted in these Figures, a number of partial analyses have been recalculated and found to show the same smooth curves. Table 2 summarizes these results, but the curves have not been included.
2. Many minerals show a wide range of possible REE distributions (which is greater in the case of such minerals as monazite and allanite than that shown by igneous rocks).
3. Data for Ce fall on the curve for minerals (as they did in the majority of cases for igneous rocks). It is therefore concluded that Ce seldom, if ever, exists in the Ce^{+4} oxidation state under the conditions obtaining during the crystallization of igneous rocks.[1]

[1] In the case of the minerals of the S. California batholith, where anomalous Ce is reported, it has been stated that the analytical method used does not give high accuracy for this element.

A recent analysis of the alteration products of eudialyte (BALASHOV *et al.* 1965), however, shows that anomalies in the Ce figure *may* be introduced during weathering (Fig. 11). It remains to be seen whether this is a special case or a common occurrence.

Crystallochemical considerations

Having established that the REE distributions in minerals, as well as in rocks, commonly give smooth curves when plotted according to this method and that the range of REE distributions observed for one mineral is sometimes greater than that observed for all igneous rocks, it would appear highly probable that REE fractionation in igneous rocks is primarily crystallochemical (fractionation according to ionic radius).

In order to study selective take-up of REE during crystallization of a melt, it is necessary to consider more closely just what is represented in our plots.

When a particular mineral specimen is ratioed to the basaltic reference distribution, the resultant curve can be thought of as a composite of two main factors: 1) the state of REE fractionation in the melt relative to the reference distribution at the time the mineral crystallized, and 2) the degree of REE fractionation produced by the mineral due to preferential take-up from the melt. It is not possible to separate 1 and 2, unless it can be assumed that the REE distribution of the rock in which the mineral occurs is the same as that of the melt prior to crystallization (i.e. to assume that crystallization has taken place in a 'closed system'). If this is a valid assumption, then, provided one knows: 1) the REE composition of the total rock, 2) the REE composition of all the component minerals, 3) the mode, and 4) the order of crystallization, these two factors can be separated. Such a complete analysis clearly involves a great deal of work, but some suitable data are available and are plotted in Figs. 12–20. In these plots, the total rock analysis is used as the reference distribution when plotting mineral data, and, where possible, each plot covers the whole series from La to Lu.

Before commenting on these curves, it is advisable to discuss the theoretical considerations more fully and to attempt to predict the type of REE substitution to be expected in specific cases.

Substitution of REE for a particular element in a lattice will be controlled by: 1) chemical considerations such as the availability of these and other elements of similar ionic radius in the melt, and 2) structural considerations such as bonding forces, charge, and optimum ionic radius for the given lattice position. Of these, ionic radius is likely to be the factor mainly responsible for *fractionation* within the REE series.

It seems reasonable to assume that, in the majority of cases, the ionic radius of the element, which commonly occupies a given lattice position, is close to the optimum value for that position. The effective ionic radius of an element increases, of course, with increasing co-ordination number, but, as a first approximation, the question has been considered in terms of the ionic radii of elements in 6 co-ordination.

Elements which are important constituents of rock-forming minerals and which have ionic radii such that they provide suitable sites for substitution of REE fall into three main groups:

a) those having ionic radii smaller than Lu (e.g. Mg, Fe, Zr, Ti, and Sc),
b) those having ionic radii greater than La (e.g. K, Ba, and Sr),
c) those having ionic radii between those of La and Lu (e.g. Ca and Na).

Substitution for group a) elements can be expected to result in preferential concentration of the smaller (heavier) REE, while substitution for group b) elements will result in preferential concentration of the large (lighter) REE. Calcium and sodium have ionic radii approximately equal to Eu and Gd, respectively, (according to the ionic radii of AHRENS 1952 and revised by GREEN 1959). Substitution can, therefore, be expected to concentrate members in the middle of the series. The curve away from the optimum position will presumably be exponential in every case.

The increase in effective ionic radius with co-ordination number is commonly assumed to be of similar magnitude for all crystalline material (GREEN 1959). KHOMYAKOV (1963), however, suggests that the magnitude varies considerably according to position in the periodic table and that, as a result, the pattern of REE fractionation due to substitution for a given element will vary according to the co-ordi-

nation number of the structure involved. He calculated, for example, that for a structure of co-ordination number 12, the effective ionic radius of Ca is equal to that of Pr.

Plots of a rock and the minerals which it contains (Figs. 12-20)

Data from four papers have been recalculated to give these figures: *A*. TOWELL *et al.* (1965 B); *B*. GAVRILOVA and TURANSKAYA (1958); *C*. FIN'KO (1964); and *D*. VAINSHTEIN *et al.* (1956).

Certain difficulties were encountered in plotting this data:

1) The San Marcos gabbro analysed by TOWELL *et al.* (1965 A) shows a distribution below that of the basaltic average. Plots of the data for the dolerite W–1 obtained by TOWELL *et al.*, however, show a very similar distribution, which indicates that this is a difference in standards used rather than a true difference in distribution. All the data of TOWELL *et al.* have therefore been ratioed to an average of their own results for basaltic rock (San Marcos gabbro and W–1). The resultant curves are relatively smooth if anomalous Ce and Eu are ignored. In the case of Ce, anomalies are probably due to analytical error, since it is stated that the method gives poor accuracy for this element. In the case of Eu, high analytical accuracy is indicated, and so the possibility of anomalous fractionation of Eu due to its existence in the Eu^{+2} state has to be considered.

2) The data of GAVRILOVA and TURANSKAYA for the Kirovograd granite (Figs. 16 and 17) are normalized, not to their published figure for Gd, but to an 'adjusted' value which makes allowance for the undetermined quantity of Gd in the felspar.

A. The batholith of Southern California (Towell et al. 1965 B)

This batholith consists of five phases of injection: gabbro, tonalite, granodiorite, quartz monzonite, and pegmatite. TAYLOR and ESPTEIN (1962) state that 'because the chemical analyses of the rocks fall near smooth variation curves, and because the mineral percentages also range systematically from the gabbros to the granites, the dominant process that brought about the variations must have been both systematic and relatively simple'. LARSEN (1948) suggested that all

these rock types were produced by differentiation of primary gabbroic magma at depth. TAYLOR and EPSTEIN have shown that the series also shows a steady increase in the O^{18}/O^{16} ratio and conclude that: 'Whereas the oxygen isotopic evidence is compatible with the mechanism of fractional crystallization of a primary gabbroic magma at depth, this mechanism cannot be proved by the available evidence.'

Four of the rock types have been analysed for REE abundances: gabbro, tonalite, granodiorite, and leucogranite. Plots of these whole rock analyses (Fig. 12) show a progressive enrichment of the larger REE of the same type as that shown by the Sandyk massif (Fig. 6e, JENSEN and BRUNFELT 1965), which further supports the suggestion that these rocks are the result of differentiation of a primary gabbroic magma.

Plots of the minerals have been ratioed to the whole rock analyses on the assumption that no further differentiation took place after injection of each of the phases. In the case of the gabbro (Fig. 13), it can be seen that:

1. The ferro-magnesian minerals hornblende and augite concentrate the smaller REE preferentially as was predicted. The falling off towards La is not a uniform trend as there is a marked increase in fractionation over the range Sm to La.

2. Apatite and calcic plagioclase are considerably enriched in the larger REE relative to the total rock. If substitution in both cases is for Ca, then the type of fractionation is contrary to that which was suggested from our earlier considerations of ionic radii (p. 146). Two possible explanations occur to us: a) the effective ionic radius of the Ca position in these structures is considerably larger than the ionic radius of Ca in 6 co-ordination, or b) the composition of the REE in the total rock is very different from that of the melt at the time of crystallization of these minerals (due, for example, to preferential extraction of smaller REE by early-formed ferro-magnesian minerals). Since there are indications in two other cases that plagioclase commonly shows an REE distribution very close to that of the melt from which it crystallizes, the data for apatite were replotted on the assumption that both minerals crystallized late from a melt showing REE distribution similar to that of the plagioclase. The result is a curve for apatite of the type predicted for Ca substitution (Fig. 13A) with a maximum in the range Tb–Dy. Unfortunately, the suggestion

that ferro-magnesian minerals formed first is not substantiated by the work of TAYLOR and EPSTEIN (1962), who made a study of oxygen isotope ratios in these rocks and gave calcic plagioclase as one of the first minerals to start crystallizing. The same distribution would be observed, however, if these minerals crystallized over a long period with a very appreciable increase in the take-up of REE towards the end of the crystallization.

Plots of the apatite of the tonalite, ratioed to the whole rock, show a maximum in the centre of the series, if anomalous Tb is ignored (Fig. 14).

Plots of the minerals of the leucogranite ratioed to the whole rock (Fig. 15) show no strong fractionation:

1) Plagioclase shows an REE distribution very close to that of the total rock.

2) Biotite has taken up REE virtually without fractionation.

3) Potash felspar shows slight preference (as might be expected) for the larger end of the series.

B. Kirovograd granite (GAVRILOVA and TURANSKAYA 1958)

Two REE analyses of the whole rock are available (GAVRILOVA and TURANSKAYA 1958, and BALASHOV 1963). The data, plotted to the average basalt reference analysis, are shown in Fig. 16. These analyses are in fairly good agreement and show the rock to be moderately enriched in the larger REE relative to the reference basalt.

In addition, GAVRILOVA and TURANSKAYA have analysed a number of minerals from this rock. The data are only complete for elements in the range La to Gd, but plots of these values, normalized to the whole rock (Fig. 17), show that:

1. Plagioclase and biotite take up REE with very little fractionation (as in the case of the Rubidoux granite).

2. Apatite shows strong fractionation over the range La–Gd, with a maximum at the Gd end.

3. Garnet fractionates REE even more strongly than apatite, with maximum again at the Gd end. (The composition of this garnet is not given.)

4. Monazite is only slightly enriched in larger REE relative to the whole rock.

C. Pumice of rhyolitic composition (FIN'KO 1964)

This rock has a high total REE content. It consists of a glass with 2 to 3% phenocrysts. Sanidine, sodic plagioclase, magnetite, and aegerine-augite are the predominant phenocrysts, with lesser amounts of ilmenite, olivine, zircon, chevkinite, and apatite.

The whole rock data, ratioed to the basaltic average, give a smooth curve which shows moderate fractionation (Fig. 18). The glass, ratioed to the whole rock, shows slight increase in the larger REE, while chevkinite phenocrysts, ratioed to the whole rock, show very strong fractionation with preferential take-up of the larger REE (Fig. 19).

D. Granitoids of the Ukrainian Shield (VAINSHTEIN *et al.* 1956)

In this case, four granitic rocks have been analysed together with one or two of the REE bearing minerals which they contain (Figs. 20a to d). The data are incomplete and have been normalized to Sm = 1.00 or Nd = 1.00, but the following deductions can be made.

1. Monazite and allanite show only moderate enrichment in the larger REE relative to the total rock.

2. Sphene shows strong fractionation with a maximum at the smaller end (Sm). (It is much to be regretted that so little REE data are available for this mineral. REE fractionation due to take-up during crystallization of sphene could be a major factor in REE fractionation in igneous rocks.)

It would appear from these four studies that take-up of REE in rock-forming minerals is frequently of the type which can be predicted from knowledge of the substitutions involved—thus, ferro-magnesian minerals show a preference for small REE elements; K felspars show a preference for large REE elements; apatite (in one case at least) shows a preference for elements in the middle of the series.

A number of different distributions, however, are observed (e.g. in the case of apatite, biotite, and plagioclase).

Explanations of some of these distributions have been suggested in the preceding discussion, but two additional points should perhaps be stressed at this stage. 1) Owing to the very low total abundance of REE in rock-forming minerals, the incorporation of very small amounts of accessory REE minerals in the analysis sample could radically

alter the fractionation pattern observed. 2) All assessment of the REE in minerals relative to the whole rock distribution must be based on the assumption that the rock has crystallized as a closed system, an assumption which may very well be incorrect for the majority of granitic and pegmatitic rocks.

It might well be expected that take-up of the REE minerals proper would cause very strong REE fractionation, but for all available analyses of a whole rock and its constituent monazite, only very slight fractionation is observed, which means either that the monazite tends to crystallize without fractionation from a melt rich in larger REE, or that each of these granites has 'lost' a late liquid fraction greatly enriched in smaller REE. In this connection, it is also of interest to restate the REE distributions found by MURATA *et al.* (1957) in monazites from a quartz monzonite at Toluca, North Carolina (Fig. 6, Nos. MN 7, MN 8, MN 9, and MN 10). The main body of the quartz monzonite contains monazite showing strong enrichment in the larger REE (relative to the basaltic average). This enrichment is even greater in monazites from a nearby quartz monzonite dike. In pegmatitic segregations of the dike, however, the monazite shows very strong relative depletion of the larger REE. It would seem quite clear that the crystallization of monazite is not the primary cause of REE fractionation in this case, but reflects a trend controlled by some other factor or factors.

The only evidence which we have for strong fractionation by REE minerals proper is the preferential take-up of large REE by the chevkinite of the alkali rhyolite of FIN'KO. This is one case where we can feel relatively secure in assuming a 'closed system' of crystallization.

Take-up of REE in minerals related to igneous differentiation

JENSEN and BRUNFELT (1965) reached the conclusion that: 'The observed variations in REE distribution (*in igneous rocks*) can be explained in terms of two trends of REE fractionation. Ultrabasic, basic, and intermediate rocks can be regarded as the products of differentiation according to the main trend of steady enrichment of the melt in the lighter REE, while pegmatitic and metasomatic rocks are the products of the reverse trend. The change in trend takes place when a melt is granitic or syenitic in composition. . . .'

Such trends can be traced in a number of differentiation series. They are here represented diagrammatically by plotting the ratio of just two elements in the range La to Tb against rock type (Fig. 21)[1] In the S. California and Sandyk massifs only the main trend is observed, but at Susamyr the reverse trend is also present.

The main trend can be readily explained in terms of the take-up of REE by substitution in the lattice of rock-forming minerals. All such minerals take up REE, but our plots suggest that the strongest fractionation within the REE series occurs when substitution is for certain elements of small ionic radius (e.g. Fe, Mg, and Ca). Steady enrichment of the residual melt in the larger REE can therefore be expected so long as minerals of this type are crystallizing.

The reverse trend (observed over the range La to Tb when aplitic and pegmatitic rocks are forming) was previously attributed (JENSEN and BRUNFELT 1965) to: 1) crystal fractionation involving K felspar, or 2) formation of complexes under the somewhat specialized conditions existing in such a melt. The present data indicate that 1) is not likely to be a major factor (since the REE of K felspar and biotite in both the Rubidoux granite and the Kirovograd granite show very little fractionation), but suggest a third factor 3) strong fractionation by certain REE minerals proper (e.g. chevkinite).

The fact that the main trend is not observed among the smaller REE (Dy–Lu) can be explained again in terms of substitution for Fe, Mg, and Ca. Fig. 22 shows observed fractionation in ferro-magnesian minerals (hornblende and augite) and calcian minerals (apatites). Such fractionation, if dominant, will clearly give simple trends in the region La–Tb, but variable trends over the remainder of the series dependent upon the type of crystallization taking place.

Conclusions

1. Many minerals give relatively smooth curves when plotted by the new method, i.e. degree of fractionation varies directly with atomic number for elements in the range La to Tb.

[1] La and Sm have been chosen for these plots since relatively rapid determination of these elements in rocks is possible by instrumental neutron activation analysis (BRUNFELT and STEINNES).

2. Some minerals show a wider range of REE distributions than igneous rocks, e.g. monazites and allanites.

3. Selective take-up of REE in many rock-forming minerals follows a pattern which is predictable in terms of the ionic radii of the elements involved.

4. Strong fractionation is observed in a number of cases where REE are substituting for Fe, Mg, og Ca.

5. The trend of steady enrichment of the residual melt in the larger REE, which has been repeatedly observed as the 'normal' trend during differentiation of a basic magma, can readily be explained in terms of selective take-up of REE in the rock-forming minerals.

6. A reverse trend involving strong fractionation takes place when the melt is rich in volatiles, alkalis, and REE, when REE minerals proper begin forming. Such a melt is clearly unlikely to crystallize as a closed system, and it is therefore much more difficult to determine the degree of REE fractionation and the factors controlling it. Fractionation by REE minerals proper, and complexing in the melt, however, are two possibilities.

7. It seems highly probable that with more data it will be possible to establish a set of relatively simple laws governing the behaviour of REE during crystallization, which could be of the utmost importance as a tool in the interpretation of the petrological and genetical history of a rock series.

Acknowledgements

The work was carried out while two of the authors (B. B. J. and A. O. B.) held research fellowships granted by the Royal Norwegian Council for Scientific and Industrial Research and the Norwegian Research Council for Science and the Humanities.

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Accepted for publication December 1965
Printed June 1966

Table 1. *Data from which the Figures have been constructed*

No.	Mineral, source rock, and locality	Author and year	Author's No.	Fig.
	ALLANITE			
AL 1	Pegmatite, Crabtree Creek, N. Carolina	Murata *et al.* 1957	25	2
AL 2	Aplite pegmatite, Jamestown, Colerado	" "	26	"
AL 3	Carbonate vein, Mtn. Pass, California	" "	27	"
AL 4	Pegmatite, Ytterby, Sweden	Vainshtein *et al.* 1956	3	"
AL 5	" Falun, Sweden	" "	4	"
AL 6	" Vaarala, Finland	" "	6	"
AL 7	" Hitterö, Norway	" "	8	"
AL 8	" Tedino, Karelia	" "	9	"
AL 9	" Impidakhti, Karelia	" "	10	"
AL 10	Contact hydrothermal, Zabaikalye	" "	18	"
AL 11	Granite, Ukraine	" "	20	"
AL 12	" "	" "	21	"
AL 13	" "	" "	22	"
AL 14	Rapakivi granite, Ukraine	" "	25	"
AL 15	Pegmatitic stringers in gneiss, Ukraine	" "	27	"
AL 16	Pegmatite, N. W. Karelia	Kalita 1959	2	3
AL 17	" vein, Topornaya Varaka	Zhirov *et al.* 1961	1	"
AL 18	" " " "	" "	2	"
AL 19	" " Tedino (cf. 8)	" "	3	"
AL 20	" " "	" "	4	"
AL 21	" Kindomys	" "	6	"
AL 22	" Kamennaya Taibola, Karelia	Semenov and Barinskii 1958	90	"
AL 23	" Chkalov vein, N. Karelia	Mineyev *et al.* 1962	1	"
AL 24	" Panfilova Varaka, Karelia	" "	3	"
AL 25	Granite, El'dzhurtinskii, N. Caucasus	Lyakhovich and Barinskii 1961	35	"
AL 26	Pegmatite, Kheta-Lambino	Rudovskaya 1964	12	"
AL 27	" Kuru-Vaara	" "	8	"
AL 28	" Zhil'naya	" "	11	"
	LOMBAARDITE			
L 1	Pegmatite, Åskagen, Sweden	Neumann and Nilssen 1962	—	2
	GADOLINITE			
GD 1	Granite pegmatite, Ytterby, Sweden	Vainshtein *et al.* 1958	51372	4a
GD 2	" " "	" "	3	"
GD 3	" Falun, Sweden	" "	51374	"
GD 4	" Hitterö, Norway	" "	51366	"
GD 5	" Indysh R., N. Caucasus	" "	—	"

Table 1. (cont.)

No.	Mineral, source rock, and locality	Author and year	Author's No.	Fig.
	GADOLINITE (cont.)			
GD 6	Coarse grained Alaskites, no locality	Vainshtein *et al.* 1960	—	+
GD 7	" "	" "	—	4a
GD 8	" "	" "	—	"
GD 9	Granite pegmatites, no locality	" "	—	"
GD 10	" "	" "	—	"
GD 11	" "	" "	—	"
GD 12	" "	" "	—	"
GD 13	" "	" "	—	+
GD 14	" N. Caucasus	Semenov and Barinskii 1958	97	3
	EUDIALYTE			
E 1	Pegmatite, locality unknown	Vainshtein *et al.* 1956	460	4b
E 2	Eudialytite, Lovozero	Balashov and Turanskaya	2665	"
E 3	Eudialyte lujavrite, Lovozero	" " 1961	731	"
E 4	" " "	" " "	2336	"
E 5	Foyaite "	" " 1960	65	"
E 6	" "	" " "	11	"
E 7	" "	" " "	320	"
E 8	Lujavrite "	" " "	26a	"
E 9	Foyaite "	" " "	45a	"
E 10	" "	" " "	970	"
E 11	Lujavrite "	" " "	991	"
E 12	Pegmatite "	" " "	1390	"
E 13	" "	" " "	1458	"
E 14	" "	" " "	1132	"
	LOVOZERITE			
LO 1	Pegmatite, Lovozero	Balashov and Turanskaya 1961	93/4	5
	MURMANITE			
MR 1	Porphyritic lujavrite, Lovozero	Balashov and Turanskaya 1961	XXI	5
	SPHENE			
SP 1	Allanitic granite, Priazovi	Vainshtein *et al.* 1956	1280	5
SP 2	Amphibole ijolite, Lovozero	Balashov and Turanskaya 1961	2254	"
	CHEVKINITE			
CH 1	Alkali syenite pegmatite, Kola pen.	Semenov and Barinskii 1958	—	5

Table 1. (cont.)

No.	Mineral, source rock, and locality	Author and year	Author's No.	Fig.
	CHEVKINITE (cont.)			
CH 2	Pegmatite, Dugdin massif	Pavlenko *et al.* 1959	DG126	5
CH 3	Rhyolitic pumice, no locality	Fin'ko 1964	—	5, 19
	RINKOLITE			
RN 1	Pegmatite, Khibina massif	Vainshtein *et al.* 1956	—	5
	LOVCHORRITE			
LV 1	Pegmatite, Khibina massif	Vainshtein *et al.* 1956	—	5
	VUDJAVRITE			
V 1	Pegmatite, after rinkolite, Khibina	Vainshtein *et al.* 1956	—	5
	Nb LABUNTSOVITE			
LB 1	Pegmatite, Lovozero	Balashov and Turanskaya 1960	—	5
	GARNET			
1/17	Granite, Kirovograd	Gavrilova and Turanskaya 1958	1052/5	17
	MONAZITE			
MN 1	Pegmatite, Hitterö, Norway	Murata *et al.* 1957	13a	6
MN 2	" Yucca valley, California	" "	14	"
MN 3	Biotite schist, Shelby District, N. Carolina	" "	15	"
MN 4	Granite, Chesterfield county, Virginia	" "	16	"
MN 5	Beach sand, Byron Bay N. S. W. Aust.	" "	17	"
MN 6	Sillimanite schist, Shelby District, N. Carolina	" "	18	
MN 7	Quartz monzonite, N. Carolina District	" "	19	"
MN 8	" " pegmatite " "	" "	20	"
MN 9	" " dike " "	" "	21	"
MN 10	" " pegmatite " "	" "	22	"
MN 11	Biotite gneiss, " "	" "	23	"
MN 12	Granite, Kirovograd, Ukraine	Gavrilova and Turanskaya 1958	1052/5	"
MN 13	Pegmatite, Brazil	Vainshtein *et al.* 1956	1	"
MN 14	Granite, "	" "	2	"
MN 15	Pegmatite, Madagascar	" "	3	"
MN 16	" Mozambique	" "	4	"
MN 17	" Korea	" "	5	"

Table 1. (cont.)

No.	Mineral, source rock, and locality	Author and year	Author's No.	Fig.
	MONAZITE (cont.)			
MN 18	Unknown, Fukushima, Japan	Vainshtein *et al.* 1956	6	6
MN 19	Pegmatite, Hitterö, Norway	" "	7	"
MN 20	" " "	" "	8	"
MN 21	" Arendal, Norway	" "	9	"
MN 22	" " "	" "	10	"
MN 23	" Chernaya Salma, Karelia	" "	11	"
MN 24	" Tedino, Karelia	" "	12	"
MN 25	Granite, Borshchevochny mtns. Zabaikalie	" "	13	"
MN 26	Pegmatite " "	" "	14	"
MN 27	Granite, Zacontiiskoe, E. Siberia	" "	17	"
MN 28	Alaskite, Milzei, E. Tuva	Pavlenko *et al.* 1959	24	"
MN 29	Pegmatite dike, Uzuntaiga, E. Tuva	" "	26	"
	BRITHOLITE			
BR 1	Pegmatite, Dugdin massif	Pavlenko *et al.* 1959	16	7
	RHABDOPHANE			
RH 1	Sediments, Ukraine	Vainshtein *et al.* 1956	12	3/7
RH 2	" "	Semenov and Barinskii 1958	25	3
	GORCEIXITE			
GR 1	Diamond placers, Minas Gerais, Brazil	Semenov and Barinskii 1958	37	7
GR 2	Marl, Bashi, Alabama	Murata *et al.* 1957	40	"
	APATITE			
AP 1	Granite, Kirovograd, Ukraine	Gavrilova and Turanskaya 1958	1052/5	7/17
AP 2	Urtite, Lovozero	Balashov and Turanskaya 1960	—	7
AP 3	Ijolite-urtite, Lovozero	" "	—	"
3/13	Gabbro, San Marcos, S. California	Towell *et al.* 1965	—	13
1/14	Tonalite, Bonsall, S. California	" "	—	13
	CALCITE			
CA 1	Carbonatite, E. Sayan mtns.	Vainshtein *et al.* 1961	CK4–20	8
	BASTNÆSITE			
BS 1	Mountain Pass, California	Semenov and Barinskii 1958	2	8
BS 2	Sulphide Queen ore, Mtn. Pass, California	Murata *et al.* 1957	31	"

Table 1. (cont.)

No.	Mineral, source rock, and locality	Author and year	Author's No.	Fig.
	BASTNÆSITE (cont.)			
BS 3	Karonge mine, Ruanda Urundi, Africa	Murata *et al.* 1957	32	8
BS 4	Pegmatite, Pikes Peak, Colorado	" "	33	"
BS 5	Carbonate vein, Mtn. Pass, California	" "	34	"
BS 6	" " "	" "	35	"
BS 7	Hydrothermal vein, Gallinas mtn., New Mexico	" "	36	"
	CALKINSITE			
CL 1	Carbonate vein, Bearpaw Mtns., Montana	Murata *et al.* 1957	44	8
	BURBANKITE			
BU 1	Carbonate vein, Bearpaw Mtns., Montana	Murata *et al.* 1957	41	8
	SAHAMALITE			
SH 1	Ore body, Mtn. Pass, California	Murata *et al.* 1957	43	8
	PARISITE			
PA 1	Ore body, Mtn. Pass, California	Murata *et al.* 1957	42	8
	CORDYLITE			
CO 1	Alkali syenite pegmatite, S. Greenland	Semenov and Barinskii 1958	19	9
	DAVIDITE			
D 1	Pegmatite, Tuftan, Norway	Neumann and Sverdrup 1960	—	9
	LOPARITE			
LP 1	Average of 9 rocks from Lovozero	Balashov and Turanskaya 1960	—	9
	ÆSCHYNITE			
AE 1	Pegmatite, Balyktyghem massif	Pavlenko *et al.* 1959	8/1	10
	PYROCHLORE			
PY 1	Pegmatite, Dugdin massif	Pavlenko *et al.* 1959	DG126	10
	FERGUSONITE			
F 1	Pegmatite, Dugdin massif	Pavlenko *et al.* 1959	296	10
F 2	Syenite, Agash massif	" "	AG 46	"
F 3	" "	" "	AG154	"

Table 1. (cont.)

No.	Mineral, source rock, and locality	Author and year	Author's No.	Fig.
	ZIRFESITE			
Z 1	Lovozero massif	Balashov *et al.* 1965	—	11
Z 2	Khibina massif	" "	—	"
	AUGITE			
1/13	Gabbro, San Marcos, S. California	Towell *et al.* 1965	—	13
	HORNBLENDE			
2/13	Gabbro, San Marcos, S. California	Towell *et al.* 1965	—	13
	BIOTITE			
2/15	Leucogranite, Rubidoux Mtns. S. California	Towell *et al.* 1965	—	15
3/17	Granite, Kirovograd, Ukraine	Gavrilova and Turanskaya 1958	1052/5	17
	FELSPAR			
4/13	Plagioclase, gabbro, San Marcos, S. California	Towell *et al.* 1965	—	13
3/15	K-felspar, leucogranite, Rubidoux Mtns. S. California	" "	—	15
1/15	Plagioclase, leucogranite, Rubidoux Mtns. S. California	" "	—	"
4/17	Felspar, granite, Kirovograd, Ukraine	Gavrilova and Turanskaya 1958	1052/5	17

+ Not included in the plots.

Table 2. *Additional minerals for which partial data have been calculated*

Mineral	Elements determined	Author and year	Author's No.
Chevkinite	La, Ce, Pr, Nd, Sm	Pavlenko *et al.* 1959	TKL32
"	La, Ce, Pr, Nd, Sm, Gd	" "	DG126
Thorite	Nd, Sm, Gd	" "	UT52/2
Pyrochlore	La, Ce, Pr. Nd	" "	4 samples
Catapleite	La, Ce, Nd	Vainshtein *et al.* 1956	11
Lamprophyllite	La, Ce, Pr, Nd	Balashov and Turanskaya 1960	1289
Nordite	La, Ce, Pr, Nd	" " "	—
Belovite	La, Ce, Pr, Nd, Sm	" " "	—
Innelite	La, Ce, Nd	" " "	—
Lomonosovite	La, Ce, Pr, Nd, Sm	" " 1961	1289

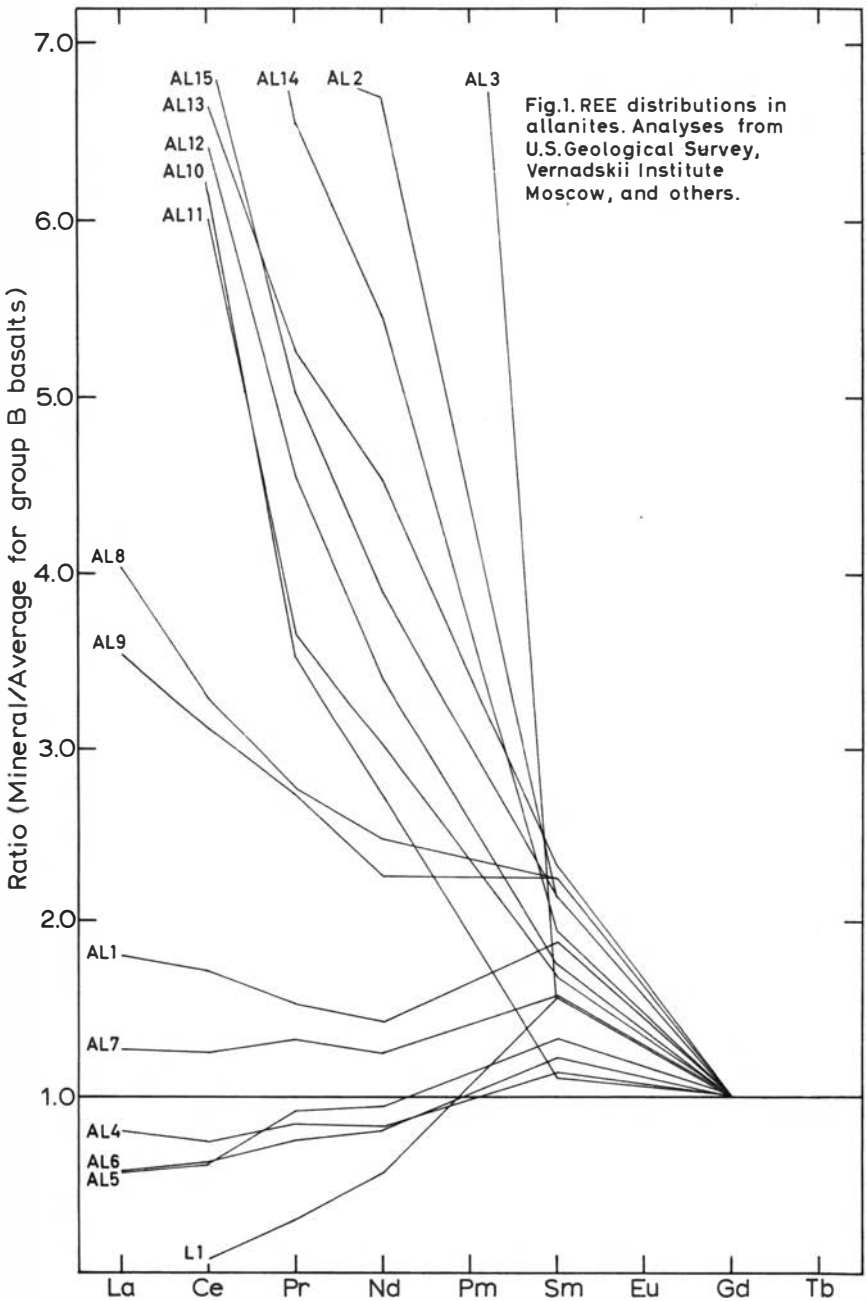


Fig. 1. REE distributions in allanites. Analyses from U.S. Geological Survey, Vernadskii Institute Moscow, and others.

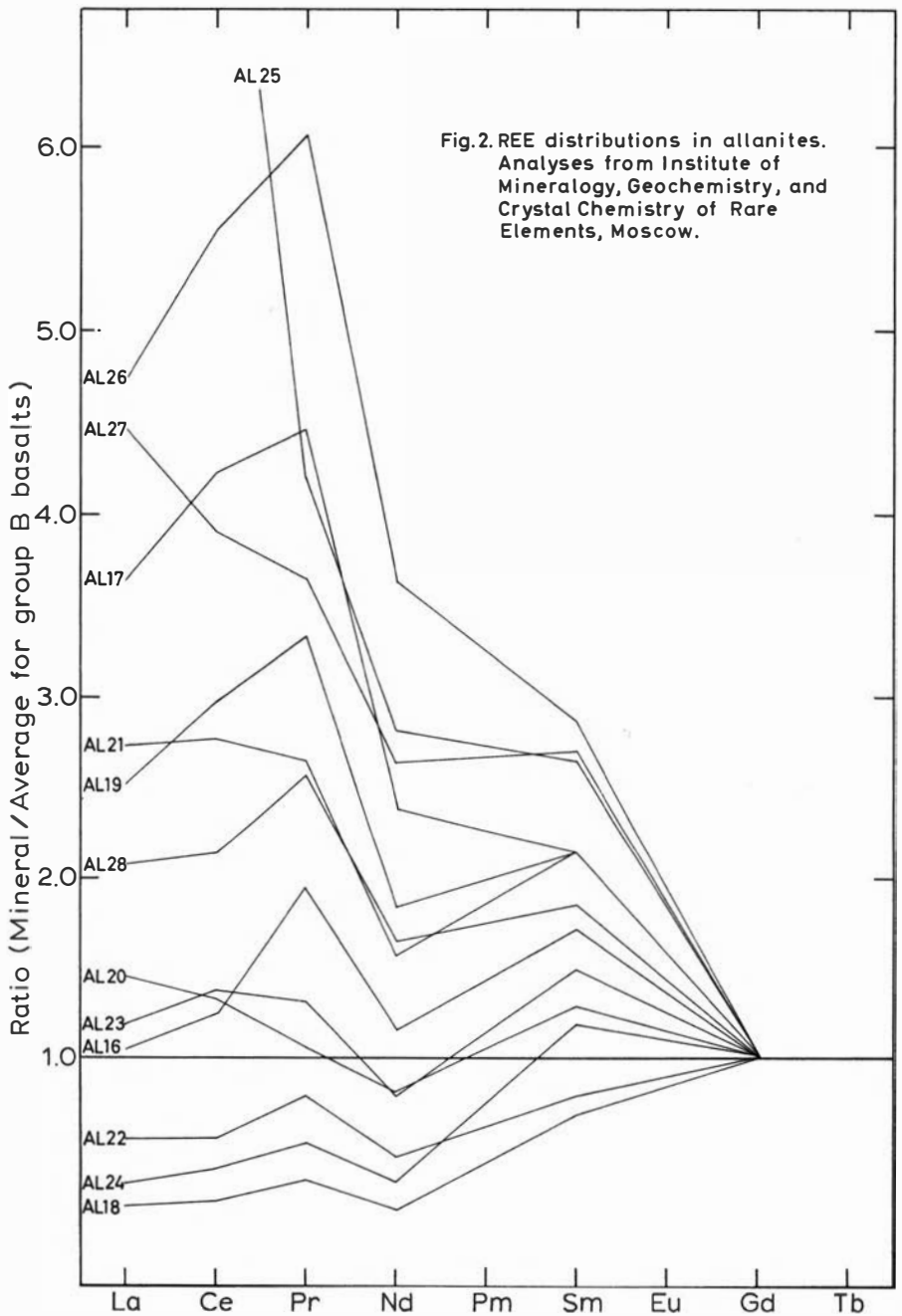


Fig. 2. REE distributions in allanites. Analyses from Institute of Mineralogy, Geochemistry, and Crystal Chemistry of Rare Elements, Moscow.

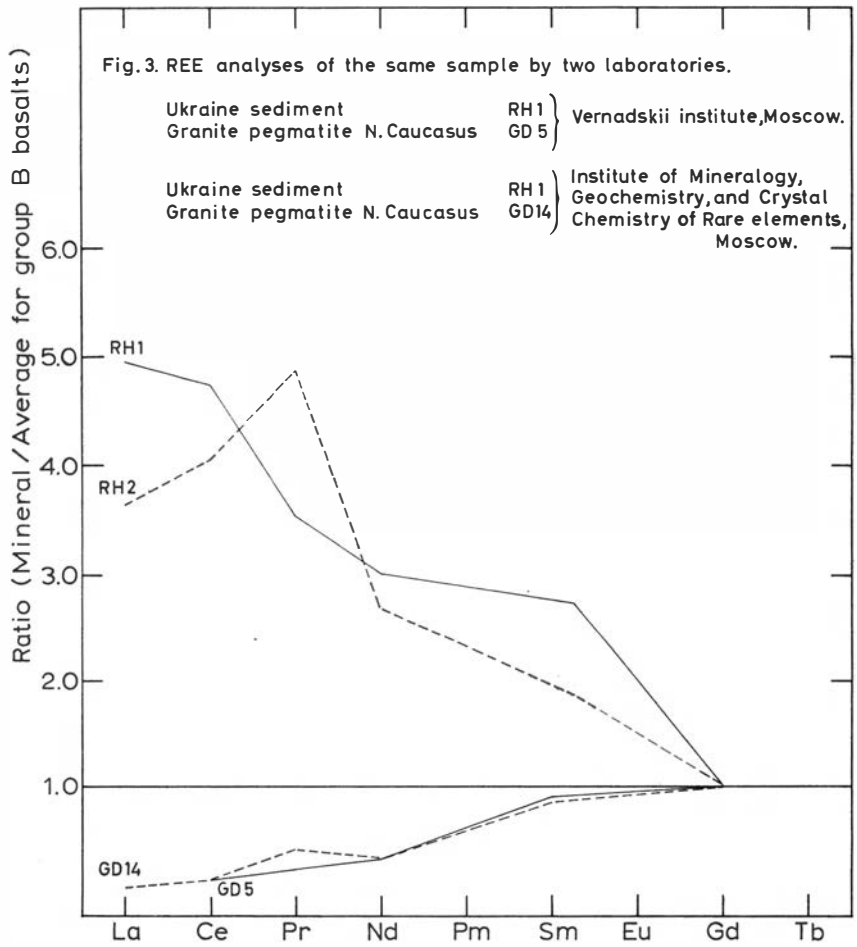


Fig. 3. REE analyses of the same sample by two laboratories.

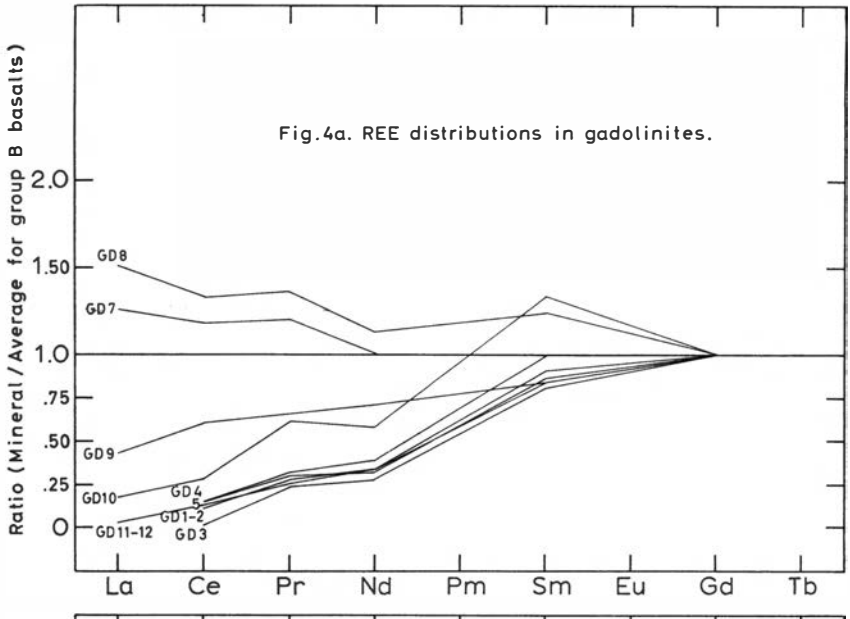


Fig.4a. REE distributions in gadolinites.
Ratio (Mineral / Average for group B basalts)
2.0
1.50
1.0
.75
.50
.25
0
GD8
GD7
GD9
GD10
GD11-12
GD4
5
GD1-2
GD3
La
Ce
Pr
Nd
Pm
Sm
Eu
Gd
Tb

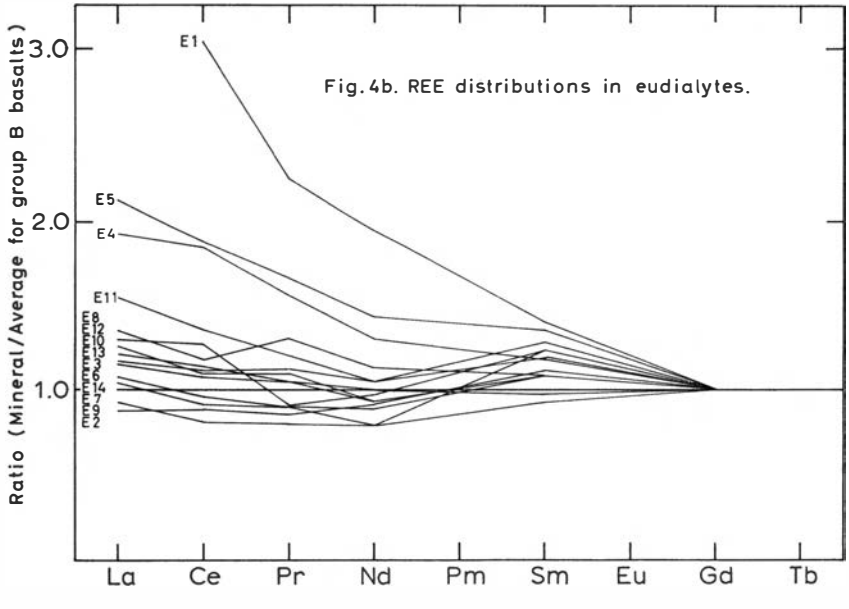


Fig.4b. REE distributions in eudialytes.
Ratio (Mineral/Average for group B basalts)
3.0
2.0
1.0
E1
E5
E4
E11
E8
E12
E10
E13
E3
E6
E14
E7
E9
E2
La
Ce
Pr
Nd
Pm
Sm
Eu
Gd
Tb

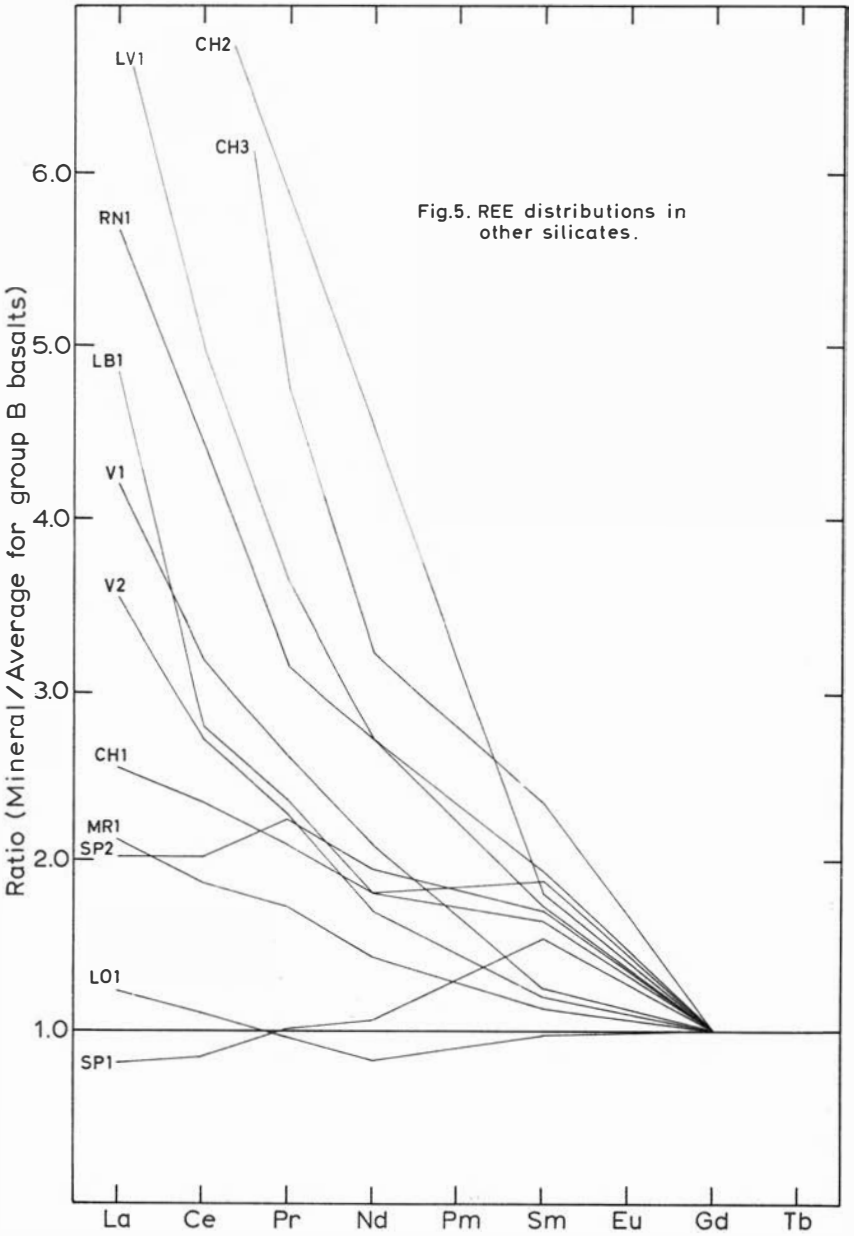


Fig.5. REE distributions in other silicates.

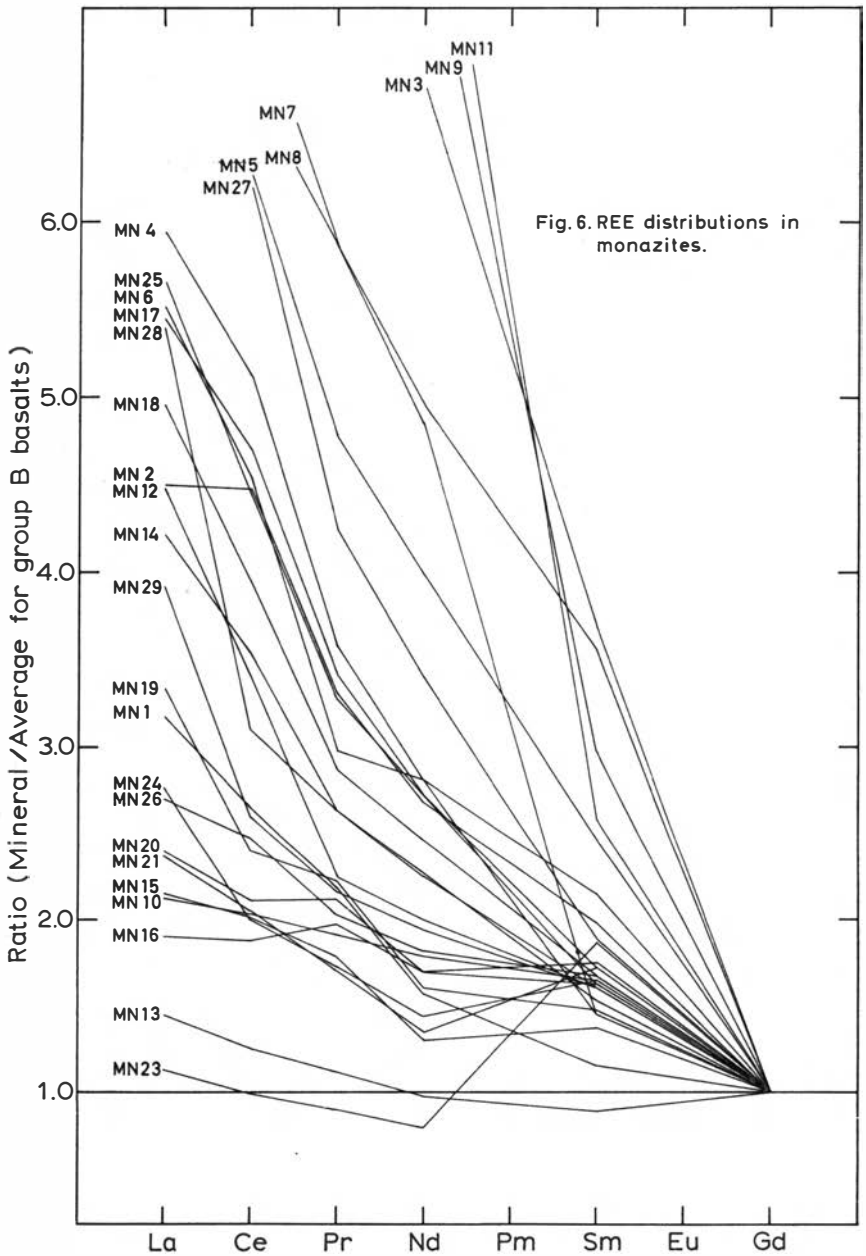


Fig. 6. REE distributions in monazites.

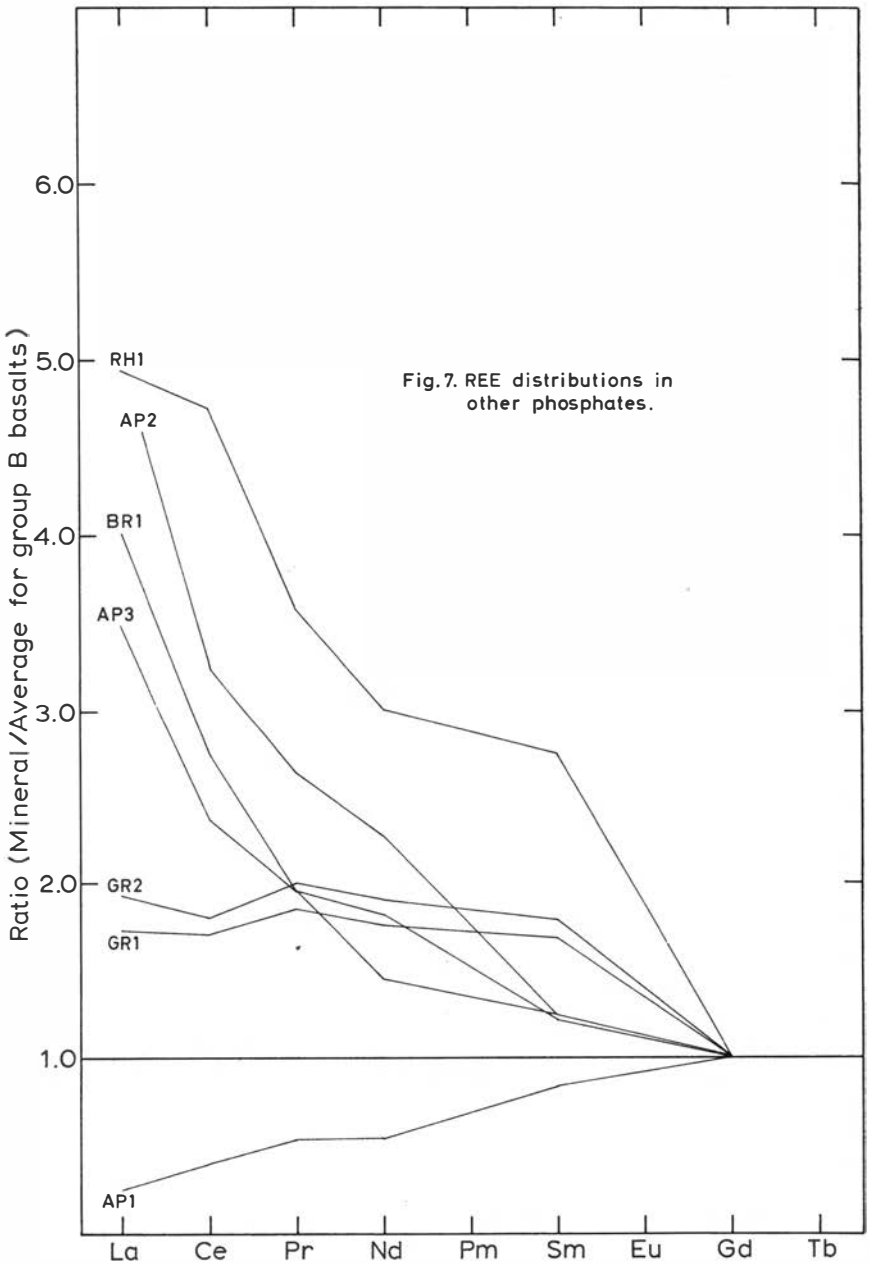


Fig. 7. REE distributions in other phosphates.

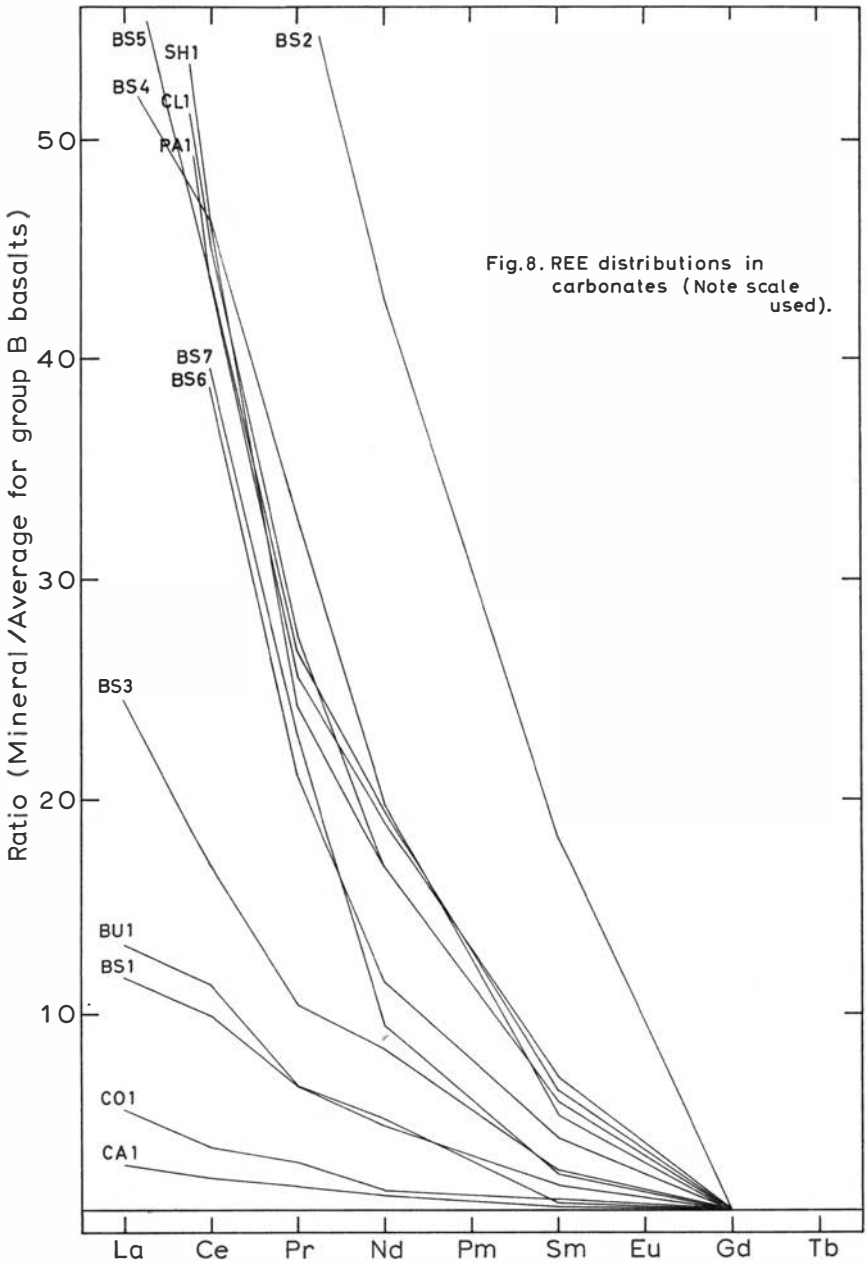


Fig.8. REE distributions in carbonates (Note scale used).

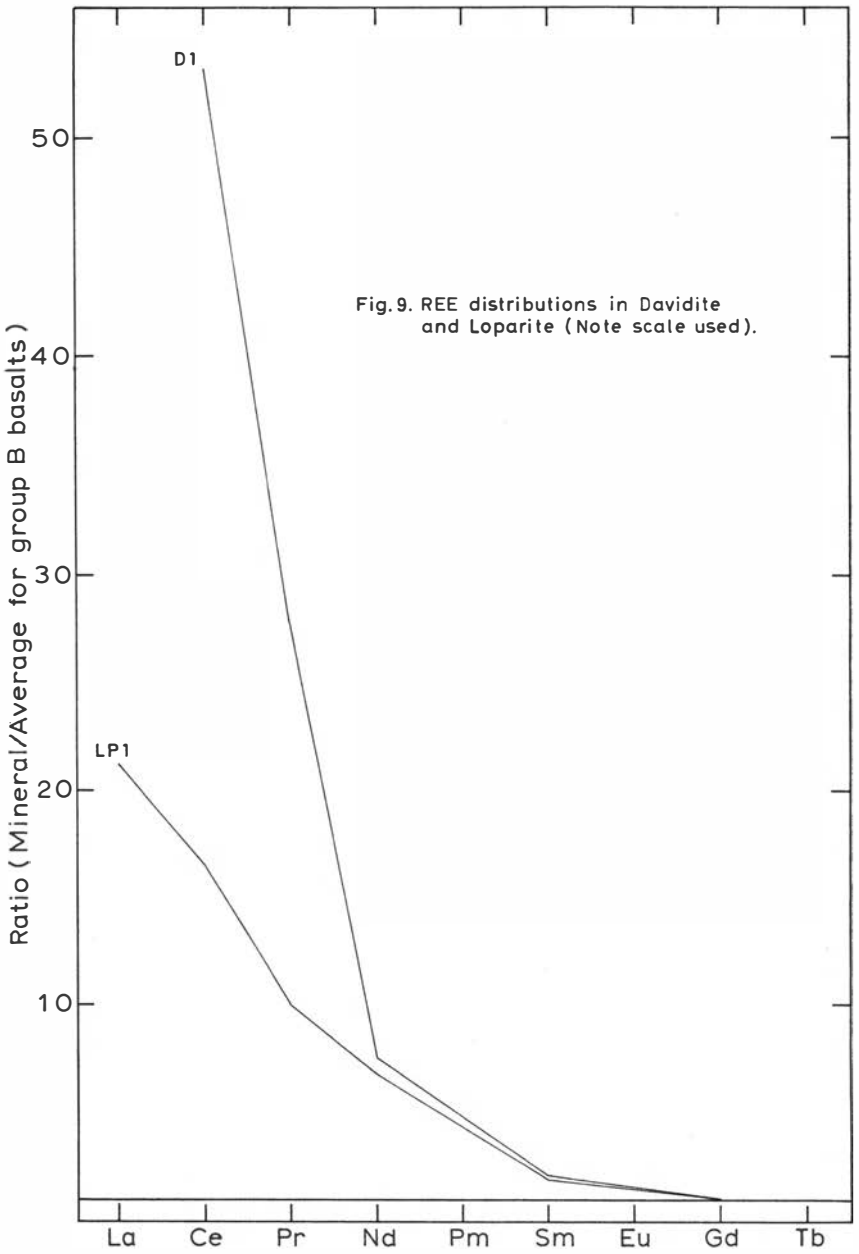


Fig. 9. REE distributions in Davidite and Loparite (Note scale used).

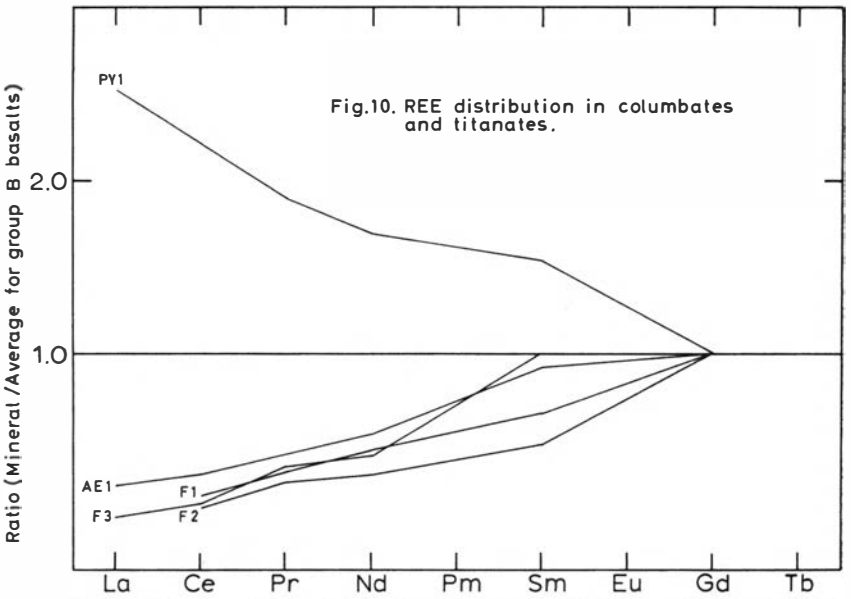


Fig.10. REE distribution in columbates and titanates.

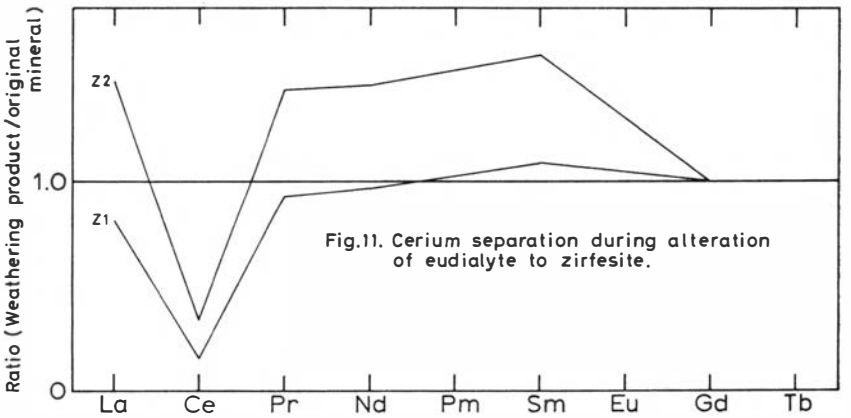


Fig.11. Cerium separation during alteration of eudialyte to zirfesite.

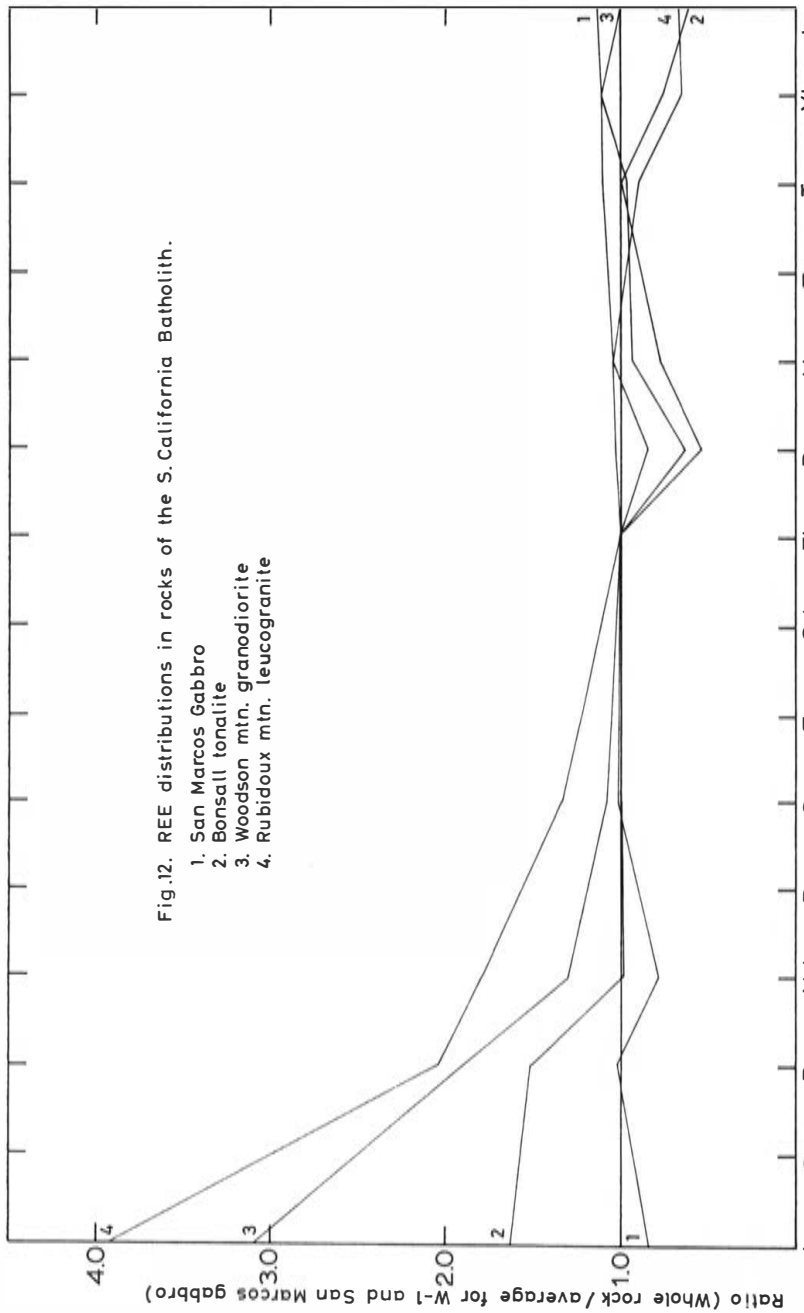
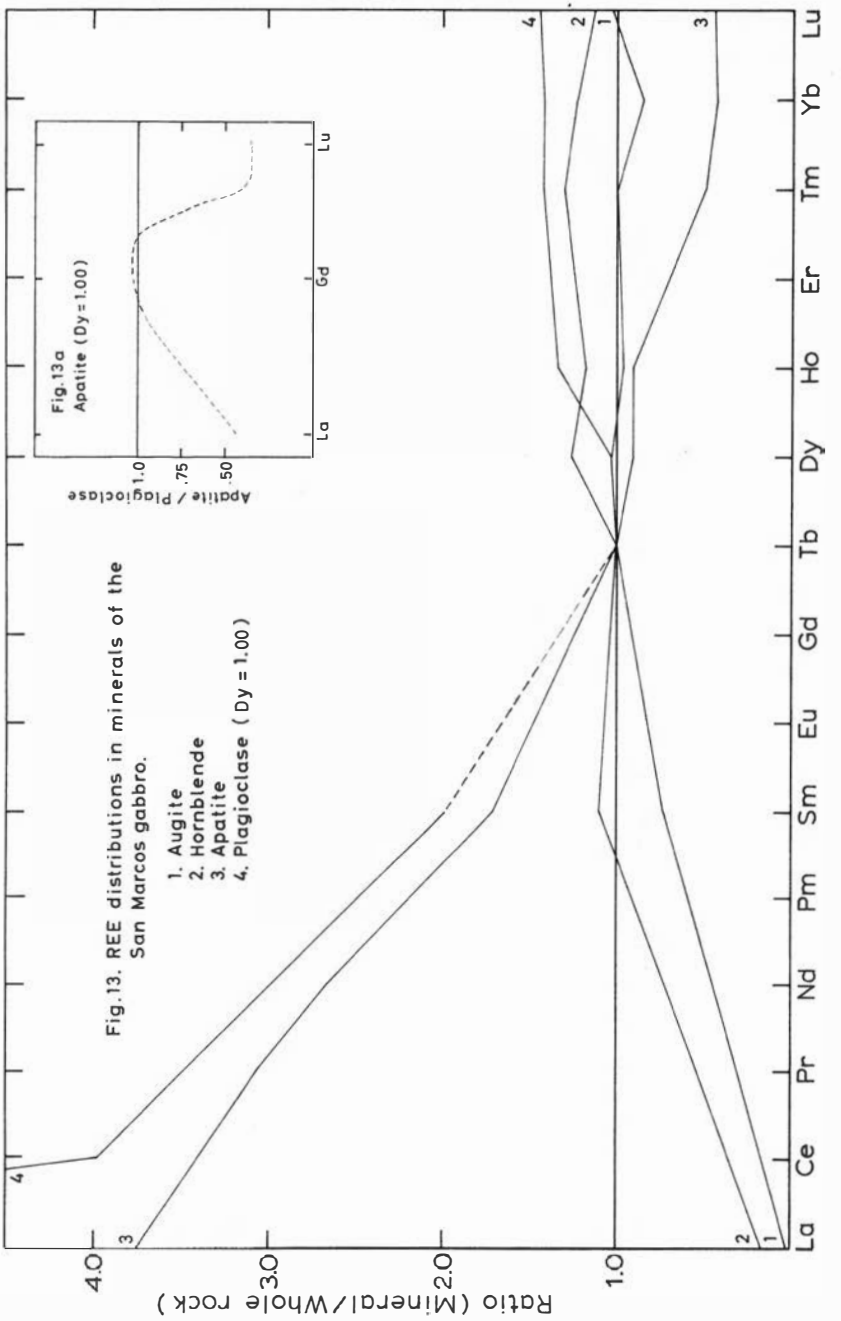


Fig.12. REE distributions in rocks of the S. California Batholith.
1. San Marcos Gabbro
2. Bonsall tonalite
3. Woodson mtn. granodiorite
4. Rubidoux mtn. leucogranite


Ratio (Mineral/Whole rock)
4.0
3.0
2.0
1.0
La Ce Pr Nd Pm Sm Eu Gd Tb Dy Ho Er Tm Yb Lu
1. Augite
2. Hornblende
3. Apatite
4. Plagioclase (Dy = 1.00)
Fig.13. REE distributions in minerals of the San Marcos gabbro.
Fig.13a
Apatite (Dy=1.00)
Apatite / Plagioclase
1.0
.75
.50
La
Gd
Lu

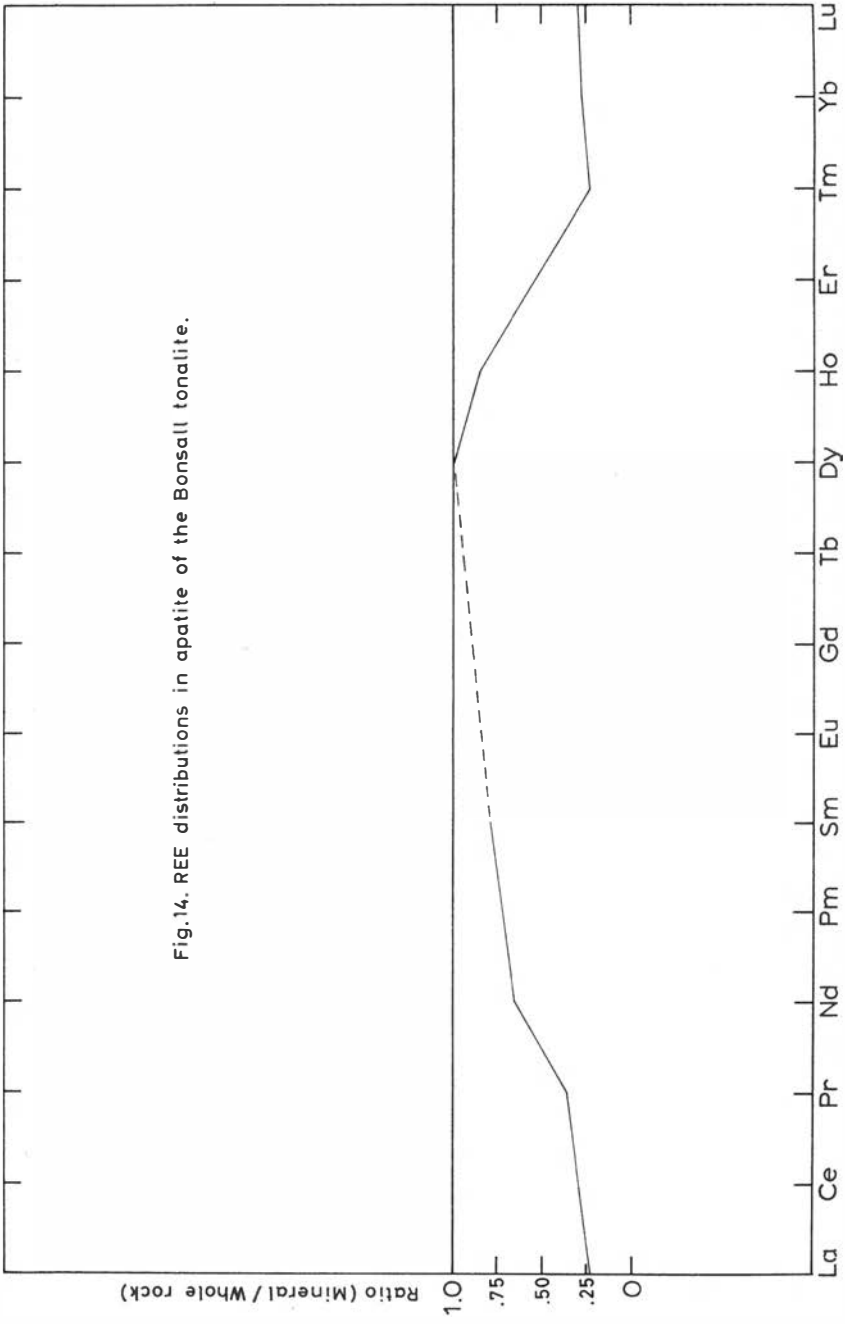


Fig.14. REE distributions in apatite of the Bonsall tonalite.

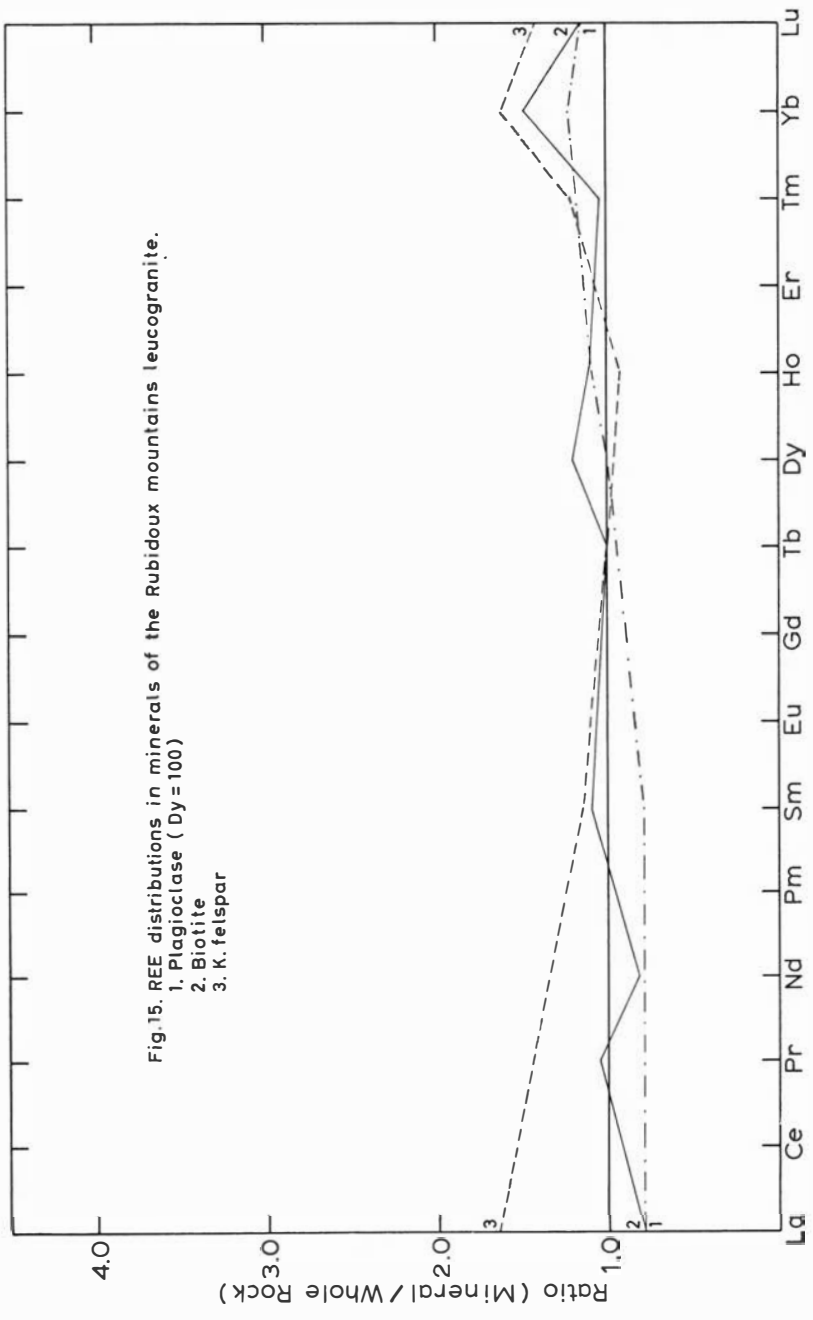


Fig.15. REE distributions in minerals of the Rubidoux mountains leucogranite.
1. Plagioclase (Dy = 100)
2. Biotite
3. K. felspar

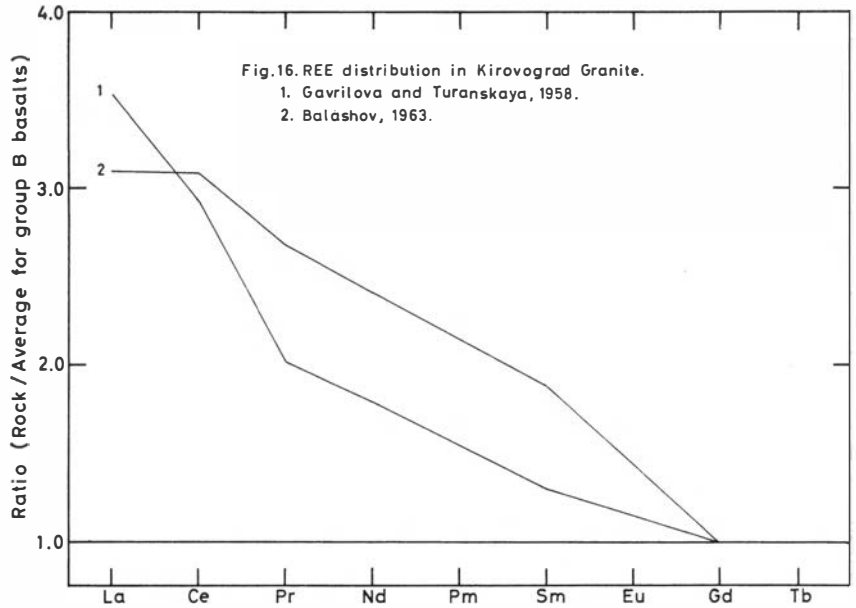


Fig. 16. REE distribution in Kirovograd Granite.
1. Gavrilova and Turanskaya, 1958.
2. Balashov, 1963.
Ratio (Rock / Average for group B basalts)
4.0
3.0
2.0
1.0
1
2
La
Ce
Pr
Nd
Pm
Sm
Eu
Gd
Tb

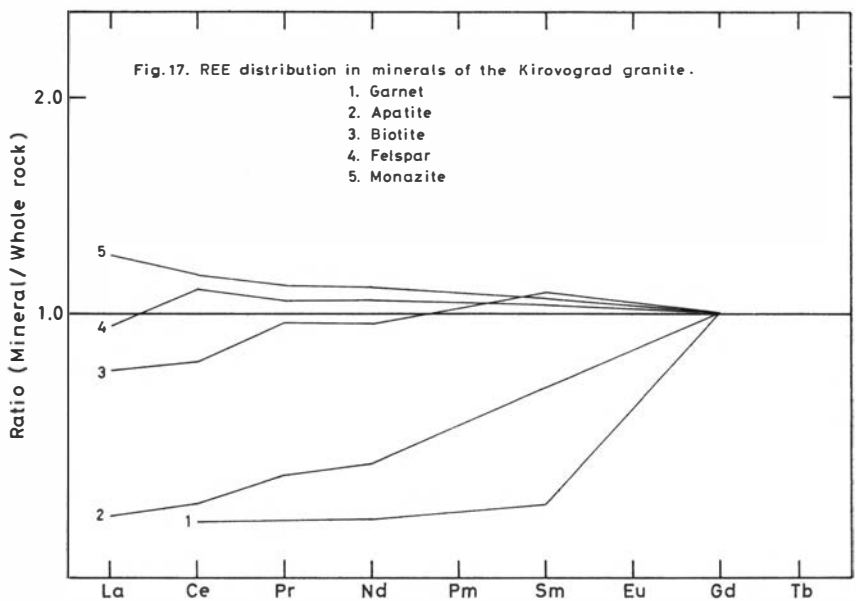


Fig. 17. REE distribution in minerals of the Kirovograd granite.
1. Garnet
2. Apatite
3. Biotite
4. Felspar
5. Monazite
Ratio (Mineral / Whole rock)
2.0
1.0
5
4
3
2
1
La
Ce
Pr
Nd
Pm
Sm
Eu
Gd
Tb

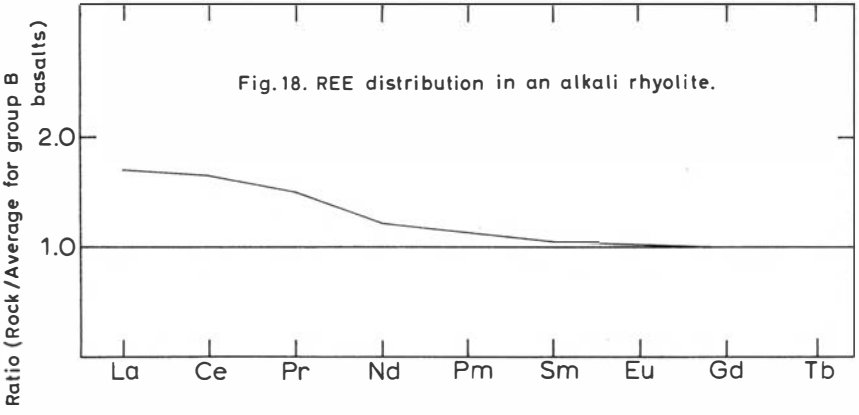


Fig. 18. REE distribution in an alkali rhyolite.

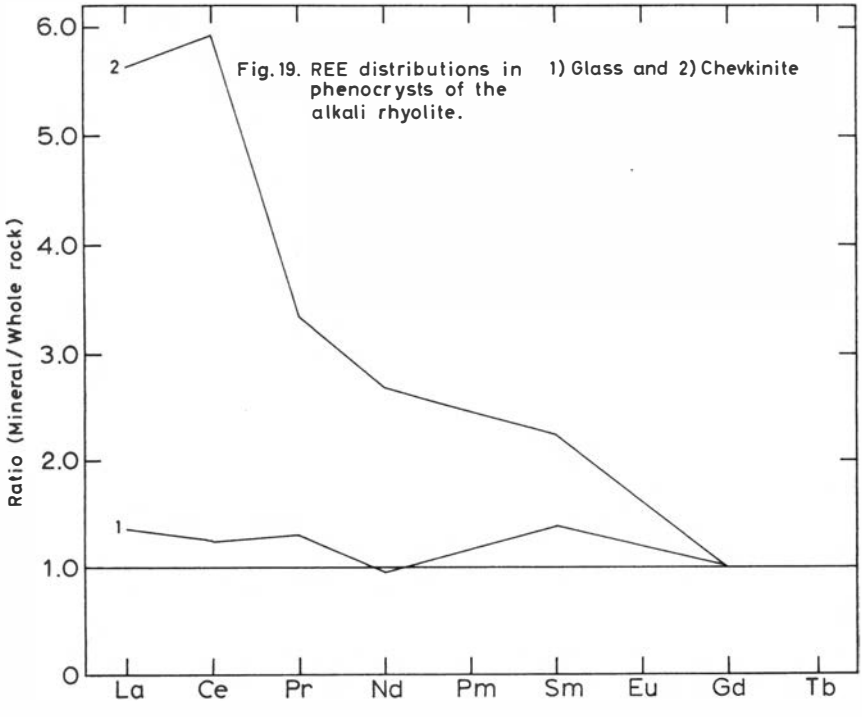


Fig. 19. REE distributions in phenocrysts of the alkali rhyolite. 1) Glass and 2) Chevkinite

Fig. 20. REE distribution in the minerals of granitic rocks.

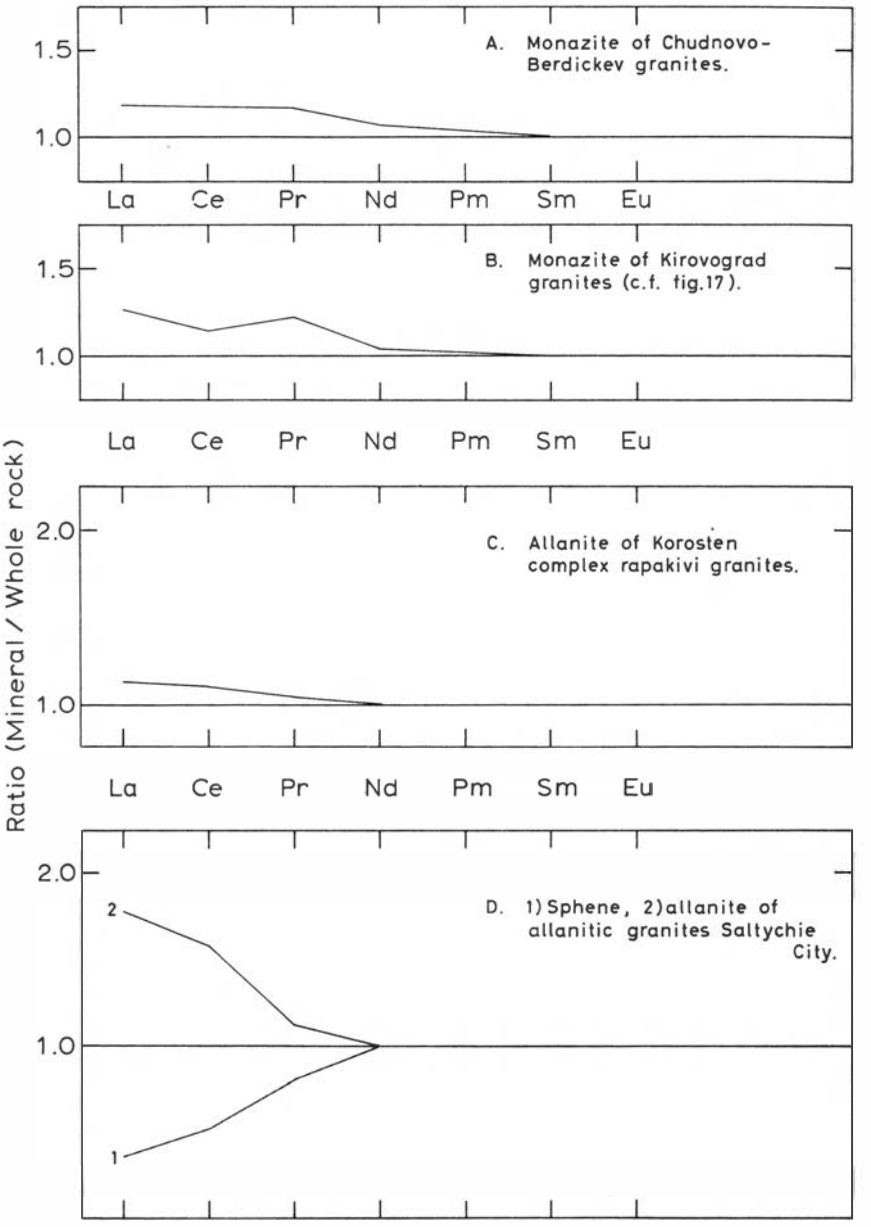


Fig. 21. $^{La}/_{Sm}$ ratios as indicators of REE fractionation trends.

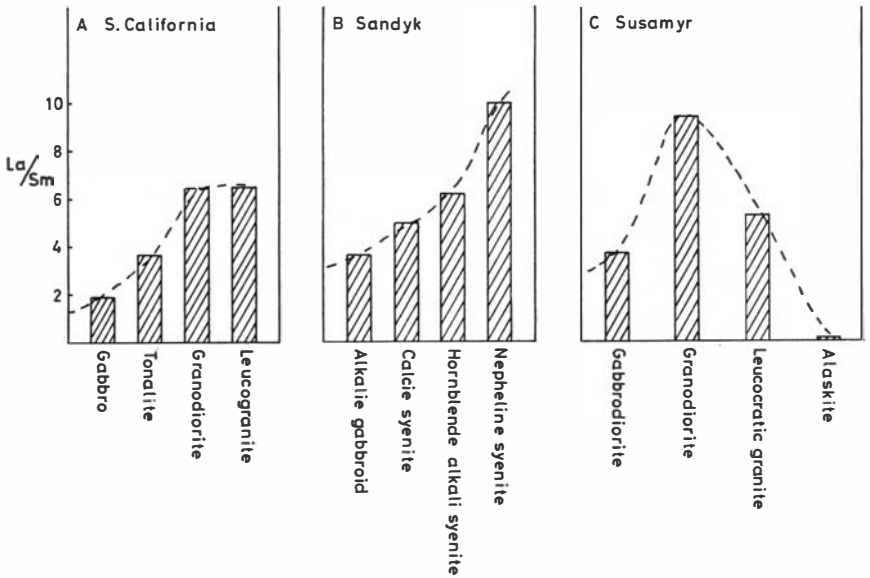
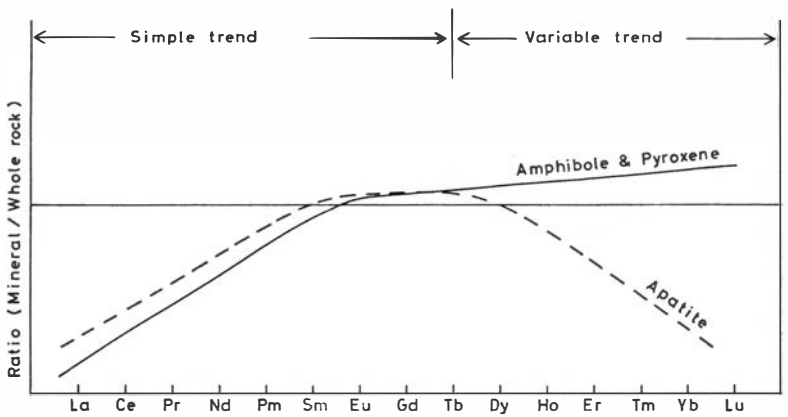



Fig. 22. REE substitution for Fe, Mg and Ca.