



Genesis of Japanese Geosynclinal Basalts in view of
Rare Earth Features *

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running title

Rare Earths in Japanese Geosynclinal Basalts

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Abstract. Rare earth elements (REE), Ba, Sr as well as major elements in 47 pre-Cenozoic geosynclinal volcanics in Japan are determined. The types of chondrite-normalized REE patterns can be classified into two large groups viz. solid-type (La-depleted type) and liquid-type (La-enriched type). It is observed that each type thus classified are also closely related to major element features. While there is little difference in SiO_2 and total Fe contents between the solid-type rocks and the liquid-type rocks, the former tends to be richer in MgO and CaO and poorer in TiO_2 , Na_2O , K_2O , P_2O_5 , Sr and Ba than the latter.

The geographical distribution of two types of the geosynclinal volcanics is different from ^(that) of the Cenozoic volcanics in Japan.

In southwest Japan, solid-type rocks occur mostly in the axial zone (Mikabu zone) of the Paleozoic terrain, whereas liquid-type rocks occur in the flank zones of the Paleozoic geosynclinal terrain. Two types of REE fractionation are observed in the volcanics. For rocks from the axial zone, REE increase uniformly without mutual fractionation in residual magmas (Tomisuyama type), whereas REE contents in the rocks from the flanks increase with smooth, mutually differential fractionation as the solidification proceeds (Nakaoku type). The difference may depend upon the depth of magma chamber; Nakaoku type differentiation probably occurs in a deeper place than does the Tomisuyama type. The REE pattern of volcanics in the axial zone bears considerable similarity to that of the abyssal tholeiite, and the Ba content relative to La content is akin to the nature

of the abyssal tholeiite than that of the island-arc ones. Some solid-type patterns with slight inflection can be interpreted as suggesting the oscillating melting and crystallization, which may occur in a dynamic environment like rifting. There are some variations of REE patterns within the two large groups. Large variations among these rocks can be attributed to the magmatic differentiation or partial melting: The magma of solid-type rocks in the axial zone was produced by extensive partial melting of the mantle which has probably solid-type pattern. On the other hand, the basalt of the liquid-type in the flanks was probably a product of partial or zone melting of the same mantle. However there remains some possibility of an alternative mechanism such as source effect. The petrochemical features of basaltics from northeast Japan can be distinguished from those of southwest Japan. It implies that the mantle composition and/or the condition of crustal development was not the same between the two areas until the late Cretaceous after the late Paleozoic.

By analogy with the current knowledge concerning a close relation between the tectonic settings and the geochemical features of the present-day volcanics, the geosynclinal basalts in question are inferred to have been formed during a tensional tectonic movement and have erupted along a local rift zone like the marginal seas and inter-arc basins in the Western Pacific Ocean or along part of a global rift system such as the Red Sea Trough.

Introduction

Pre-Cenozoic basic rocks in orogenic zones have recently been studied in relation to the ophiolite problem and tectonisms of the geosyncline. Especially, in the past few years rare earth element (REE) distributions in the volcanic rocks has provided a valuable contribution to the distinguishing of the various types of the ancient volcanic rocks and understanding the genetical condition of them (Herrmann and Wedepohl, 1970; White et al., 1971; Montigny et al., 1973; Herrmann et al., 1974; Jahn et al., 1974; Arth and Hanson, 1975).

On the other hand, it has been widely accepted that the Cenozoic volcanic rocks in the Japanese Islands laterally and continuously change their petrological features (Kuno, 1960). Such a variation is genetically documented in the island arcs and it is considered that the physico-chemical processes responsible for the magma genesis should also laterally change (Sugimura, 1960, 1968; Kuno, 1966). Rare earth elements as well as major elements in Cenozoic volcanic rocks are also found to show a lateral variation in the Japanese Islands (Masuda, 1966).

Nevertheless, it is dubious whether the upper mantle and tectonic processes leading to the volcanisms could maintain constancy through geological time in evolution of the Japanese Islands. It is, therefore, of prime significance to examine the long history of evolution of volcanisms on the Islands since the Paleozoic. Geochemical data pertaining to an early stage of late Paleozoic geosyncline in the Islands have recently been accumulated. From the geochemical

properties of geosynclinal basalts in the Japanese Islands, Sugisaki and Tanaka (1971) concluded that magma types of pre-Cenozoic geosynclinal volcanics and their distributions were entirely different from those of Cenozoic ones. Furthermore, the inferred tectonism prevailing in the Paleozoic, based on the petrochemical evidence, was also assumed to be not identical with the Cenozoic ones (Sugisaki et al., 1971, 1972).

In the present work, the geosynclinal basalts are examined mainly from the viewpoint of REE and Ba abundances. The features of these elements as well as the major elements in the geosynclinal volcanics were inspected in comparison with the Cenozoic volcanics on the earth in order to clarify the genesis and evolution of geosynclinal basalt magma and the Japanese Island.

Samples

Samples of the volcanics were collected from the various areas in Japan (Fig. 1). These samples are mostly products of submarine volcanisms generated in Paleozoic geosynclinal basin. These volcanogenic rocks are intercalated in the sedimentary formations such as greywacke, shale, limestone or chert.

In southwest Japan, at present, the Paleozoic group is distributed in an outer (Pacific side) terrain and in an inner (continental side) one, the basaltic volcanics being commonly found in both of them. The volcanic activities responsible for these rocks are mainly recognized in the Middle Carboniferous to Middle Permian in various districts (Kanmera, 1971). In Fig. 1, the sampling areas of E, H and

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I are included in the outer terrain and F and G are in the inner one. Thick basic complexes, which are considered as the products of the Permian submarine volcanisms, saliently occur in a narrow strip along the northern boundary of the outer Paleozoic terrain and they are collectively called basic rocks of the Mikabu type.

Samples of almost 550 rocks were collected and analysed for major elements and some minor elements such as first row transition metals and Sr. Part of these analyses have already been published (Tanaka, 1970, 1974; Suzuki et al., 1971; Shiida et al., 1971; Tanaka and Sugisaki, 1973; Kawabe, 1974). and the rest will be published in the future. Samples for the present investigation were chosen from this collection. The location and rock name for each of the samples studied here are shown in Fig. 1 and Table 2.

Analytical method and procedure

The REE and Ba were determined by the mass spectrometric stable isotope dilution method. Composite spike solution was added to about 0.3g of rock powder. The sample was decomposed using hydrofluoric acid and perchloric acid, and trace elements were separated by cation exchange resin. The details of the procedures for ion exchange and mass spectrometry are similar to those used by Masuda et al. (1972) for lunar samples.

P The major element compositions of these rocks were determined by a wet-chemical method modified by Sugisaki and

Tanaka (1971 a). The contents of water and carbon dioxide were carefully determined because of existence of carbonate and hydrate minerals in the samples.

The duplicate determinations of REE and Ba have been made for each of the standard rocks JB-1 and BCR-1, and their results are listed in Table 1 in comparison with other workers' data. The data for BCR-1 in this work are in agreement, within difference of 2 percent for most REE, with those obtained by Gast et al. (1970), Philpotts and Schnetzler (1970), Haskin et al. (1970) and Nakamura (1974). Although the Lu abundance in this work is lower than those of above authors except for Nakamura (1974), the reliability of the lower values was discussed by Nakamura (1974).

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The contamination derived from the impurities of the reagents used here does not exceed 0.1 percent of the obtained values. The precisions and accuracies for most REE and Ba are considered better than 1.5 percent. The accuracies of the starred data in Table 2 might be a little inferior to those of the rests, because of some difference in procedure between the two series of the data. Nevertheless, the accuracies of the starred ones are estimated to be better than 3 percent.

The analytical error is expected to be within 10 percent in the determination of Sr contents (Hattori et al., 1972).

Analytical data for major element compositions of standard rocks (JB-1 and JG-1) are reported by Sugisaki and Tanaka (1971 a). The values are within the range of values recommended by Ando et al. (1971).

P For strict examination of the structure of the REE pattern in the Masuda-Coryell plotting (Masuda, 1962; Coryell et al., 1963), REE abundances not only in the terrestrial materials but also in chondrites as reference need to be precise. Masuda et al. (1973 a) concluded, on the basis of the nine chondrite analyses, that the normalization by the Leedey chondrite REE abundance is the most advisable for such a purpose. Hence, the REE abundances in the Leedey chondrite are used here as normalizing values (Table 1).

Examination of possibilities of contamination and alteration

It can be concluded that the considerable variation of REE patterns observed in the rocks is not explained by a process of alteration or contamination but ascribed to fractionation, as previously suggested in the discussion of the Nakaoku geosynclinal basalt body (Tanaka and Sugisaki, 1973).

For the Nakaoku basaltic samples, the order of the concentration of the REE is H 27 (highest), H 43, H 26, H 22, H 18, H 12 and H 15 (lowest) as seen in Fig 2-c. This order is complete reversal of the stratigraphical order of the samples; H 27 is the lowest and H 15 the highest. Relative positions of the patterns of tuffaceous rocks in Fig. 2-c are also parallel with the stratigraphical situations in this volcanic body. This fact suggests that ^(the) REE abundances in tuffaceous rocks which are probably liable to alteration are not changed in effect.

Eu, which can be divalent and are chemically inclined to behave together with Ca^{2+} and/or Sr^{2+} in plagioclase, is not anomalous in the REE patterns (Figs. 2) except for gabbros in Shikoku. As a corollary of this, it is very likely that Ca^{2+} and Sr^{2+} in rocks was neither selectively removed nor replaced by Na^+ by such a process as spilitization. Moreover, as discussed in following section, some of the major elements are obviously correlated to the REE pattern. As the REE pattern is judged to have been hardly modified by the alteration, the major element compositions of these geosynclinal volcanics cannot have been much changed.

Analytical results

Chemical compositions of the samples are given in Table 2 (trace elements) and in Appendix (major elements and CIPW norms). Almost all these samples contain some amounts of carbonate which could be ascribed to contamination from foreign sources (Tanaka, 1970). The author recalculated each bulk chemical composition to 100 percent on a carbonate- and water-free basis. The recalculated figures are used in the following discussions.

Leedey chondrite-normalized REE patterns of the samples are exhibited in Figs. 2.

Thirty-four basic rocks newly analyzed and 13 basic rocks previously discussed (Tanaka and Sugisaki, 1973; Tanaka, 1974) can be classified grossly into three groups according to their chondrite-normalized REE patterns: (1) Geosynclinal volcanics

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with logarithmically linear or nearly linear REE patterns form one group; A 4, B 36, C 18, C 58, C 86, C 104, E 4, E 21, F 39, F 81, G 10, H 22, H 26, H 27, H 40, H 43, I 66 and I 86. (2) REE patterns of C 92, D 3, E 53, F 3, H 2, H 76, H 92, I 55, I 108, I 113, I 115, I 118, I 121, I 127, I 129, I 136, I 145 and IB 9 show a striking contrast to those of the above group. They show convex or inflectional curves. The curvature is relatively great for the span for lighter members of lanthanides, and enrichment factor, relative to chondrite, of La is smaller than that of Sm. (3) Pattern of E 20, G 29, H 12, H 13, H 15, H 18, I 19, I 23 and I 143 are situated mostly between the above two groups and they are slightly convex. Their enrichment factors of La, however, are greater than that of Sm.

The inclinations of the linear patterns of group (1), especially from southwest Japan (i.e. G 10, F 39 and I 66), resemble each other although the samples differ in their absolute REE concentrations. The inclinations of the patterns are much steeper than those of Japanese Cenozoic high-alumina basalts (Masuda, 1966) and Deccan Plateau tholeiites (Nakamura and Masuda, 1971), and slighter than those of alkali basalts (Nagasawa, 1973; Kay and Gast, 1973). On the other hand, the convex pattern of group (2) has a considerable similarity to that of the mid-oceanic ridge basalts (Schilling, 1971).

Masuda (1962) found a regular variation of the REE abundances with their atomic numbers, on the earth. On the assumption that the primary material constituting the terrestrial earth had the chondritic REE abundances, Masuda and Matsui (1966) extended their discussion to the evolution of the earth and further to the formation of crust and mantle. Their mathematical treatment of the solidification process of molten chondritic material shows that, if the equilibrium between the solidifying material and residual melt is maintained and the relative magnitudes of partition coefficients of REE are constant through a solidification process, it is possible to distinguish the REE pattern of the liquid phase from that of the solid phase. Masuda (1966) named them liquid-type and solid-type, respectively. Up to now it has been thought that most terrestrial material can be classified into the two types, together with derivative types produced from the two primary types. The first group of the Japanese geosynclinal basalt (1) as mentioned above is substantially equivalent to the liquid-type designated by Masuda (1966) and the last two group (2) and (3) to the solid-type. In this paper, the second group will be hereafter designated "primary solid-type" (S_1) and the third one "modified solid-type" (S_2). The average REE contents and the chondrite-normalized patterns of these three groups are shown in Table 3 and Fig. 3, respectively.

Table. 3 and Fig. 3 near here

Discussion

Correlation of REE pattern with major elements compositions

Forty samples of lava and holocrystalline basaltic rocks were used in the following discussion. Frequency distributions of major and trace elements are shown in Fig. 4, according to the above classification. Between both types, solid and liquid, there is a marked difference in nearly all elements except for SiO_2 and total Fe. Solid-type rocks tend to be richer in MgO, CaO and poorer in TiO_2 , Na_2O , K_2O , P_2O_5 , Sr and Ba than liquid-type ones.

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The difference between both types can be recognized more clearly on the $(\text{La})_{\text{EF}}/(\text{Sm})_{\text{EF}} - (0.9\text{Fe}_2\text{O}_3 + \text{FeO})/\text{MgO}$ diagram, Fig. 5, where, e.g., La with the subscript EF denotes the enrichment factor (i.e., concentration ratio) of La relative to Leedey chondrite.

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Lateral distribution of geosynclinal basalts of different types

A spatial distribution of the geosynclinal basalts clearly emerges from a plot of REE pattern on a Japanese map (Fig. 6B), as described below.

(1) Northeast Japan

In the southern Kitakami area ("C" in Fig. 1), abundant volcanic rocks and their pyroclastics are intercalated in the Paleozoic formations, from the Silurian to the Permian. Kanisawa (1971) and Sugisaki and Tanaka (1971 b), from the major element compositions and their characteristics, concluded that the magma types of volcanics from that area were different

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from those from the southwest Japan. As shown in Fig. 2-a the three patterns of C 58, C 86 and C 104 are log-linear, whereas C 18 shows a log-linear REE pattern with slight inflection near Er. Of the samples from the Kitakami area, C 92 is the only one with a primary solid-type pattern. Both of C 92 of solid-type and C 104 of liquid-type were collected from the Motai group of the Devonian, the Kitakami area, but differ in their REE patterns. The relation of the volcano stratigraphy of these two samples is ambiguous.

D 3 is a metamorphic rock collected from near the boundary between two metamorphic zones, A and B, designated by Miyashiro (1958) in Abukuma plateau. The REE pattern of D 3 is inherently solid-type, although it is hard to tell the original kind of the volcanics for this sample. The occurrence of the solid-type volcanics in both the west part of the Motai group and the east part of Abukuma plateau is intriguing in view of tectonic condition of the magma genesis. It is worth noting that tectonically tensional settings during the early Paleozoic on the east part of Abukuma and the west part of Kitakami, where solid-type rocks are observed, were suggested on the basis of the microfabrics in rocks (Hara et al., 1972).

All the rocks from the stratigraphic horizon above the early Paleozoic in the Kitakami area, B 36, C 18, C 58 and C 86 are not of solid-type but of liquid-type. Volcanism responsible for these liquid-type volcanic rocks seem to have been active from the Carboniferous to the Cretaceous in the area.

(2) Southwest Japan

Masuda (1966), in Japanese Cenozoic basalts, found the three distinct types of REE patterns, namely, primary solid-type, primary liquid-type and secondary liquid-type, which correspond to tholeiites, high-alumina basalts and alkali olivine basalts, respectively. The present author discriminated REE patterns of Japanese Cenozoic basalts published by several authors and classified them into four groups. Their geographical distribution is shown in Fig. 6A. Two lines of A-B and C-D in the figure represent the boundaries drawn by Kuno (1966), which divide the areas of three basaltic rock series.

Solid-type rocks and primary liquid-type rocks occur on the Pacific side of the Japanese Islands, whereas on the Japan Sea side secondary liquid-type rocks occur. This lateral distribution of REE pattern types exhibits a striking contrast to that of the pre-Cenozoic ones (compare Fig. 6A and 6B).

Solid-type basalts occur mostly in the narrow Mikabu zone of the Paleozoic geosynclinal area, whereas, on both flanks of the Mikabu strip, liquid-type rocks occur exclusively (Fig. 6B). None of secondary liquid-type rocks is observed in the pre-Cenozoic.

On the other hand, in a Mesozoic terrain called Shimanto group, solid-type basalts (H 76 and H 92) are observed in southwest Japan, whereas, in the Kitakami area, liquid-type Mesozoic basalts (B 36 and C 18) are found. After the late Paleozoic, solid-type and liquid-type are found to occur in southwest Japan, while in northeast Japan, only liquid-type

occurs. These aspects of the distribution of the REE patterns would lead one to the presumption that there existed a critical difference of mantle source and/or crustal development between the southwest Japan and the northeast Japan at least until the Upper Cretaceous after the late Paleozoic.

A relationship between Ba and REE

The solid-type REE pattern observed in the geosynclinal basalt is closely similar to that of the tholeiite from island arcs (Masuda 1966, 1968; Philpotts et al., 1971) as well as ^{the} abyssal tholeiite (Schilling, 1971) or tholeiite from the marginal sea or inter-arc basins (Hart et al., 1972; Ridley et al., 1974).

Nevertheless, Ba on the chondrite-normalized pattern shows distinctly higher concentration relative to La in the island arc tholeiites (Philpotts et al., 1971), while in the abyssal tholeiites, Ba on the pattern is situated lower than La. As to the Japanese Paleozoic geosynclinal basalts, Ba enrichment relative to La on the pattern is not so strong as that observed in the island arc tholeiite (see Fig. 3). No affinities between the Paleozoic geosynclinal basalts in southwest Japan and the island arc tholeiite were also recognized about the transition metal features (Kawabe, 1974).

Genesis of the REE pattern with inflection

Three rocks of F 3, I 23 and I 34090503, classified as solid-type appear to be composed of two linear segments with an inflectional point. This peculiarity may be interpreted in two ways as follows.

(1) Five REE patterns of Mid-Atlantic Ridge gabbros are quite different from those of abyssal tholeiite, and the estimated partition coefficient functions pertaining to those gabbros have an inflection at Tb: This feature represents the continental nature (Masuda and Jibiki, 1973). For example, mixing of 3% of the averaged liquid-type material in the Paleozoic geosyncline (av. L in Fig. 3) with 97% of Mid-Atlantic Ridge gabbro (G in Fig 7) can give rise to REE pattern with an inflection (W in Fig. 7). The REE pattern resulting from this mixing is similar to the patterns for the above geosynclinal basalts with inflection point, although the position of the inflection for the former is not perfectly identical with that for the latter.

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(2) Another interpretation about REE pattern with inflection was mathematically proposed by Masuda et al. (1971). It is schematically shown with a modification in Fig. 8. Suppose that a solidification is proceeding as a whole, and that the temperature of a melt decreases in an oscillating fashion. According to such a temperature change, the formation of crystals takes place for the most of time, but melting occurs for a short time possibly at regular intervals. In addition,

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suppose [1] that a little amount of melt is removed from the system when the formation of crystals takes place, and a fraction of the formed crystals remelts after this removal and is incorporated to the total melt, [2] that the process like this is repeated many times, and [3] that the bulk REE partition coefficient function with inflection works through the processes. Then one can obtain a REE pattern such as W in Fig. 7 with an upward inflection for the resultant residual melt. Such an oscillating melting and crystallization may occur in a dynamic environment as magma chamber is ascending intermittently, in keeping with the solidus temperature and pressure.

In either of the above processes, chondrite-normalized REE pattern like W in Fig. 7 with an inflection comes into being. This pattern resembles that of I 34090503.

Furthermore, by dividing W in Fig. 7 by the bulk partition coefficient function estimated by Masuda and Matsui (1966), we can obtain R (Fig. 7) which is composed of two concave curves. The pattern R in Fig.7 resembles H 15 regarding its shape. Hence, it is conceivable that the geosynclinal basalt such as H 15 is produced by partial melting of source material like I 34090503 (wehrlite).

Different kinds of REE fractionation in geosynclinal basalts

Two kinds of the REE fractionation, namely, the Nakaoku type and the Tomisuyama type, were observed in the geosynclinal basalts as shown in Fig. 9.

The Nakaoku type REE fractionation described by Tanaka and Sugisaki (1973) in a Paleozoic basalt body is apparently the same as the one observed in Hawaii (Schilling and Winchester, 1969), and rare earth elements are smoothly and differentially fractionated relative to chondrite; the lighter REE are considerably enriched, whereas concentrations of the heaviest REE remain approximately constant. In this case, basaltic rocks change their magma types from tholeiite to alkali basalt during the solidifying process. This type of REE fractionation had occurred on both flanks of the Japanese geosynclinal belt, where tholeiite and alkali basalt coexisted spatially as pointed out by Sugisaki and Tanaka (1971 b).

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The Tomisuyama type REE fractionation described by Tanaka (1974) in a Paleozoic gabbroic body resembles those of Skaergaard intrusion (Haskin and Haskin, 1968) and Pindos ophiolite suite (Montigny et al., 1973). In this case, the concentration of REE appears to have uniformly increased in residual magmas as the solidification proceeds, with little change in the shape of REE pattern, and also the magma type remains unchanged.

There has been no satisfactory explanation for these two contrasting fractionation types. The difference between both types might be attributed to the difference of the crystallizing mineral species and/or the amount of liquid trapped among the crystallizing minerals.

The explanation based on the difference in the pressure having prevailed at the magmatism is more plausible. According to experiments carried out by Tanaka et al. (1974), bulk REE partition coefficients between the basaltic liquid (glass) and crystals continuously vary with atomic number of the element under pressure of 20 Kb, whereas under the pressure of one atmosphere, the coefficients show little variation with atomic number. Similarly, the results of experiments using synthesized diopside showed the atomic number dependence of the coefficients under 20 Kb (Masuda and Kushiro, 1970) and little dependence under one atmosphere (Masuda et al., 1973 b). The experimental results quoted above led the writer to the conclusion that Nakaoku type differentiation occurs in a great depth as suggested by Tanaka and Sugisaki (1973), while Tomisuyama type fractionation occurs at a shallower depth than that of Nakaoku, under a condition of nearly one atmosphere. This inference does not conflict with geological evidence: Nakaoku basaltics are the eruptive rocks (Shiida, 1962), probably reflecting the varying stages of magmatic differentiation which arose at depth, while Tomisuyama basic rocks are the intrusive rocks and the product of differentiation in the shallow place (Suzuki et al., 1971). These geological environments of two igneous bodies resemble the Hawaiian volcanoes and the Skaergaard intrusion, respectively.

Source of the geosynclinal basalts

It is of geological and geochemical importance to explore the source materials for the basaltic magmas with different REE patterns. There arise two possibilities pertaining to the origin of the basalt magma sources; one posits a single source material and the other a dual source.

(1) The first hypothesis of the single source assumes that the primary solid-type materials (S_1) is the original source and the liquid-type and modified solid-type (S_2) rocks are derived from the primary solid-type material by partial melting and/or fractional crystallization. When the primary solid-type material undergoes partial melting and/or a zone melting, it can bring about a modified solid-type magma, depending on the geological settings. When the degree of partial melting is very small or the passed volume of zone melting is very large, it gives birth to liquid-type magma. Mathematical examinations of partial melting, zone melting or fractional crystallization of materials with primary solid-type REE patterns by using a set of bulk REE partition coefficients estimated by Masuda and Matsui (1966) are shown in Fig. 10. The log-linearity of actual geosynclinal basalts which are collectively exhibited in the lower part of Fig. 10 is remarkable. The linearity can theoretically result either from the limited extent (say, one percent or less) of the partial melting of primary solid-type materials or from the zone melting passing through at least 30 times

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the melting volume. The fractional crystallization which should take place during magmatic processes cannot cause such a discrete change as from solid-type to liquid-type regarding the REE pattern.

(2) The second hypothesis assumes, as the magma source, the fractionated mantle with more than two types of materials with respect to the REE pattern. This possibility was discussed by Masuda (1966) and his many articles. The liquid-type material corresponds to the remnant liquid (melt) which was produced through the fractional crystallization of chondritic initial melt, namely, through the successive removal of solid (crystal) formed from the melt. The solid-type material corresponds to the aggregate of solids (crystals) removed from the liquid-type melt. So far, it has been considered that most terrestrial materials can originate from either the liquid-type materials or solid-type ones with no or some modifications. In this case, the liquid-type geosynclinal basalt magma is derived from the mantle of liquid-type materials by nearly total melting and, usually, some extent of subsequent fractional crystallization. The solid-type geosynclinal basalts (S_1 and S_2) are derived from the solid-type mantle by nearly total or relatively large extent of partial melting.

The choice between the two as above is far from feasible at present, but particularly when seeing that the log-linearity observed in some geosynclinal basalts, for example, C 86, E 4 and I 66, is remarkable, it seems quite natural to consider

that the latter process (2) is responsible for the genesis of these liquid-type rocks.

However, the possibility that some rocks regarded as liquid-type (e.g. B 36, H 40 and I 86) were derived by a few percent partial melting of the solid-type mantle is also considerably sound, because the log-linearity of these samples seems not so perfect as the rest, although it is not always facile to classify a particular sample into either of the two groups, even with the current high accuracies of analyses. For more strict discussion, more precise determinations are needed.

Genesis of the geosynclinal basalt viewed from tectonics

Japanese pre-Cenozoic geosynclinal basalts were discussed from a petrochemical point of view in the previous sections. However, REE pattern has lately attracted considerable attention on account of a close association with global tectonics (Schilling, 1971, 1973).

Recently, it has become increasingly clear from considerable evidence of earth sciences that the early stage of tectonism of the pre-Cenozoic geosynclinal belt in Japan was under a tensional condition rather than a compressional one. Sugisaki et al. (1971, 1972), from geochemical properties and the distribution of the geosynclinal basalts in the Japanese Islands, drew a conclusion that rifting occurred in the Japanese late Paleozoic geosyncline. Based on the deformation of the metamorphic rocks in several areas of Japan,

Hara et al. (1972) suggested tension tectonics in the Paleozoic in advance of the compression one.

The various types of REE patterns of the Japanese pre-Cenozoic geosynclinal basalts and their lateral distribution should be noted. Solid-type patterns are found mostly in the basic rocks of the axial zone, and liquid-type ones occur in the Paleozoic group of both of the flanks (Fig. 6B). The REE pattern in rocks of the axial zone bears considerable similarity to that of the mid-oceanic ridge basalt (Schilling, 1971) which is generated under a tensional condition. The marginal sea or the inter-arc basin such as the Lau basin and the Parace Vela basin is another significant example as a tensional environment. In these areas, rocks with solid-type and modified solid-type were reported (Hart et al., 1972; Ridley et al., 1974).

It is of much interest that the regional distribution map of REE pattern of the Japanese pre-Cenozoic geosynclinal basalts (Fig. 6B) is akin to that of the Red Sea. Basaltic rocks of the solid-type were reported for the samples from the axial part of the Red Sea Rift, whereas that of the liquid-type was found at Jebel Teir Island located at the southern end of Red Sea Trough (Schilling, 1969). Higher ratio of enrichment factor of La to that of Sm (La_{EF}/Sm_{EF}) for Jebel Teir tholeiite probably reflects continental nature, because the continental tholeiite is considered to have higher La_{EF}/Sm_{EF} (Herrmann and Jung, 1970; Nakamura and Masuda, 1971).

In the Japanese Islands, the Paleozoic solid-type rocks are mainly found in the axial zone. On the analogy of the Red Sea, a rift structure is assumed to have been formed in the Paleozoic geosyncline of Japan. A main conduit within the rift may have been narrow and long, but deep enough to trigger off remelting of the upper mantle materials of the solid-type. In the flank part of the geosyncline, where the upper mantle was suppressed by fractured crust, modified solid-type and liquid-type effusives had occurred, and they were products of partial and/or zone melting followed by a fractional crystallization. Since the different fractional crystallization types, i.e., Nakaoku type and Tomisuyama type described above, can be attributed to pressure effect, magmatic differentiation of the axial Mikabu zone is inferred to have occurred at a relatively shallower depth, while that of the flank zones at a greater depth.

The concept of a tension tectonics seems to be plausible based on REE pattern analysis, too. If we consider that the oscillating melting and crystallization described in the previous section resulted from an oscillating pressure release and ascent of magma chamber, such a dynamic environment indicates a tensional condition.

Successive eruptions of basalt magma are observed in the Nakaoku area, where the most fractionated magma erupted at the earliest stage and finally the most primitive magma. Such a sequence of eruption from a magma chamber may be easily derived from a vertically elongated magma chamber with some

narrow parts. The magmatic process working in the magma chamber of this kind may be more or less similar to that in a zoned magma chamber (Smith and Barly, 1966) or a mechanism which gives rise to a composite lava flows (Kennedy, 1931) or something like that along a vertical fissure.

The tectonically tensional condition forms a striking contrast to the compressional one prevailing in the island-arc volcanism. As discussed in the above section, the Ba content relative to the La content as well as zonal distribution of the two types of REE pattern do not support the possibility of island-arc origin of the geosynclinal basalts. Thus the geosynclinal basalts are concluded to have been formed during tensional tectonic movement and have erupted along a local rift zone like the marginal seas and inter-arc basins in the Western Pacific Ocean or along a part of a global rift system such as the Red Sea Trough.

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Captions for Figures

Fig. 1

Sketch map showing the Paleozoic and Mesozoic in Japan. The letters (A-I) in the map show the local areas studied in the text. The figure in the parentheses shows the number of rock samples analysed.

Fig. 2

Chondrite-normalized REE patterns of geosynclinal basaltic rocks. Fig. 2-a: Hokkaido (A), northern Kitakami (B), southern Kitakami (C) and Abukuma (D) areas. Fig. 2-b: Kanto (E), Mino (F) and Tamba (G) areas. Fig. 2-c: Kii (I) area. Fig. 2-d: Shikoku (I) area.

Fig. 3

Chondrite-normalized REE patterns averaged for each group of geosynclinal basalts in the Japanese Islands (cf. Table 3).

Fig. 4

Comparison of the frequency distribution of major and minor elements for the different REE pattern groups. Tuffaceous rocks were not included in this diagram.

Fig. 5

Diagram showing the relation between $(La)_{EF}/(Sm)_{EF}$ and $(0.9 Fe_2O_3+FeO)/MgO$, where, e.g. La with the subscript EF denotes the enrichment factor (i.e. concentration ratio) of La relative to chondrite.

Fig. 6

A spatial distribution of the Cenozoic (mostly the Quaternary) basaltic rocks (Fig. 6A) and pre-Cenozoic (mostly the Paleozoic) geosynclinal basaltic rocks (Fig. 6B) in Japan. Data on Cenozoic basalts are from Masuda (1966, 1968, 1969), Onuma et al. (1968), Philpotts et al. (1971), Ando et al. (1971), Yajima et al. (1972), Nagasawa (1973) and Nishimura and Masuda (1974). The lines, A-B, C-D and E-F were quoted from Kuno (1966), dividing the petrographic provinces in the Quaternary. The lines A-B and C-D are boundaries between the tholeiite and high-alumina basalt zones and line E-F is that between the high-alumina basalt and alkali olivine basalt zones.

Fig. 7

Chondrite-normalized REE pattern. W; Mathematically obtained pattern with inflection. B; An example of smoothly curved pattern (H 76). G; Mid-Atlantic Ridge gabbro (RD20-AM30) after Masuda and Jibiki (1973); REE pattern R which resembles H 15 is theoretically obtained by assuming an equilibrium with W under an operation of the partition coefficient estimated by Masuda and Matsui (1966).

Fig. 8

Schematic diagram showing a process which makes REE pattern with inflection. A, B, C, etc. in the diagram indicate proceeding of magmatic process.

Fig. 9

Comparison of two distinct types of REE fractionation in the geosynclinal basalts. REE fractionation patterns of Nakaoku, Tomisuyama, Hawaii and Skaergaard intrusion are from Tanaka and Sugisaki (1973), Tanaka (1974) Haskin and Haskin (1968) and Schilling and Winchester (1969), respectively.

Fig. 10

Diagram showing a linearity of the liquid-type REE patterns observed in this study and theoretical variation of REE pattern during zone melting and partial melting. Numerals (10, 20, 30 and ∞) attached to the patterns of zone melting and numerals (5, 2, 1 and 0) to those of partial melting represent the travel distance expressed in the unit of a zone length and the percent fraction of liquid phase, respectively.

Table 1. Analytical results of the standard rocks JB-1 and BCR-1 with the data obtained by other workers (ppm)

	JB-1 *		BCR-1				Leedeey
	This work	This work	Gast et al.	Philpotts and	Haskin et al.	Nakamura	Chondrite***
	(I.D.)	(I.D.)	(1970) (I.D.)	Schnetzler (1970) (I.D.)	(1970) (N.A.)	(1974) (I.D.)	
La	37.0 ± 0.3	25.1 ± 0.1	26.1 ± 0.1	—	25.2 ± 1.0	24.4 ± 0.2	0.378
Ce	67.5 ± 0.4	53.6 ± 0.3	54.9 ± 0.0	53.9 ± 0.7	54.2 ± 1.2	54.2 ± 0.4	0.976
Nd	26.8 ± 0.2	28.9 ± 0.2	28.8 ± 0.0	28.6** ± 0.6	30.5 ± 4.3	28.8 ± 0.2	0.716
Sm	5.13 ± 0.03	6.70 ± 0.05	6.74 ± 0.0	6.62** ± 0.06	7.23 ± 0.37	6.72 ± 0.04	0.230
Eu	1.55 ± 0.01	2.00 ± 0.01	1.97 ± 0.02	1.942 ± 0.008	1.97 ± 0.04	1.98 ± 0.0	0.0866
Gd	4.82 ± 0.02	6.76 ± 0.02	—	6.47 —	8.02 ± 1.29	6.67 ± 0.02	0.311
Dy	4.19 ± 0.06	6.37 ± 0.04	6.20 ± 0.02	6.36 ± 0.02	6.55 ± 1.41	6.36 ± 0.02	0.390
Er	2.28 ± 0.02	3.68 ± 0.0	3.71 ± 0.02	3.58 ± 0.03	3.51 ± 0.88	3.70 ± 0.02	0.255
Yb	2.14 ± 0.01	3.36 ± 0.01	3.68 ± 0.06	3.38 ± 0.02	3.48 ± 0.12	3.40 ± 0.03	0.249
Lu	0.308 ± 0.002	0.500 ± 0.006	0.59 ± 0.05	0.536 ± 0.004	0.526 ± 0.15	0.503 ± 0.004	0.0387
Ba	511 —	684 ± 2	699 ± 14	646 ± 1	656 ± 4	696 ± 2	4.21

± values of this work indicate deviations from the mean of duplicate analyses.

* Recalculated values on a water-free basis.

** The values were lowered by 11 percent (Gast et al., 1970).

*** Masuda et al., 1973

Table 2,-1

Table 2. REE, Ba and Sr abundances (ppm) in the Japanese pre-Cenozoic geosynclinal volcanic rocks ***

Sample	A 4*	B 36*	C 18*	C 58*	C 86*	C 92*	C 104*	D 3*	E 4	E 20*	E 21*	E 53
La	39.2	25.1	32.7	—	24.1	1.80	23.2	1.38	36.7	9.38	27.3	4.54
Ce	67.3	57.4	69.9	19.3	53.7	4.54	49.2	3.36	80.6	23.3	52.9	12.9
Nd	33.8	33.3	34.6	13.7	30.0	5.23	28.2	2.90	43.4	18.2	26.1	12.0
Sm	7.86	7.78	7.21	4.27	7.54	2.02	6.73	1.19	9.78	5.29	5.74	3.73
Eu	2.64	2.54	2.12	1.61	1.99	0.694	2.24	0.518	2.88	1.92	1.71	1.33
Gd	5.82	7.97	6.51	5.48	7.81	3.11	6.85	2.01	9.59	6.19	5.75	4.34
Dy	5.75	6.85	4.75	6.53	7.57	4.06	6.24	2.65	8.39	5.73	4.52	3.91
Er	2.33	3.06	2.29	3.63	3.60	2.44	2.96	1.71	3.83	2.71	1.72	1.93
Yb	—	1.93	2.05	—	—	2.23	2.36	1.90	2.86	—	—	1.43
Lu	0.248	0.239	0.298	0.526	0.444	0.370	—	0.203	0.364	0.303	0.172	0.178
Ba	895	145	257	19.2	317	23.1	81.7	60.0	407	58.0	12.9	7.91
Sr**	854	339	906	117	478	275	411	180	276	2030	—	24

* See the text

** Analyzed by H. Hattori

*** Recalculated values on a carbonate- and water-free basis

Table 2,-2

Table 2 (Continued)***

Sample	F 3*	F 39	F 81	G 10	G 29*	H 2*	H 12	H 13	H 15	H 18	H 22	H 26
La	3.66	15.6	7.97	16.8	7.18	2.28	7.76	4.31	6.04	8.95	12.0	14.2
Ce	9.37	33.6	19.0	38.3	17.2	6.29	16.6	10.2	13.5	20.7	25.8	32.3
Nd	8.16	18.6	12.1	21.5	13.3	6.32	9.99	7.17	9.07	12.7	14.9	17.7
Sm	2.76	4.49	3.34	5.11	4.27	2.90	2.97	2.23	2.85	3.44	3.94	4.45
Eu	1.07	1.61	1.09	1.73	1.42	1.18	1.20	0.849	1.14	1.21	1.45	1.55
Gd	3.78	4.77	—	5.16	5.43	4.53	3.79	3.06	3.66	3.82	4.59	4.73
Dy	3.98	4.18	4.16	4.32	5.91	5.80	3.61	3.69	3.46	3.41	3.96	3.68
Er	2.03	2.06	2.54	2.18	3.05	3.28	1.82	2.20	1.78	1.64	1.93	1.78
Yb	1.66	1.56	2.31	1.70	—	2.78	1.44	2.10	1.42	1.33	1.50	1.30
Lu	0.244	0.208	0.331	0.235	0.390	0.380	0.199	0.307	0.197	0.192	0.202	0.179
Ba	13.0	177	38.0	187	97.1	31.5	197	185	139	89.6	36.3	89.6
Sr**	93	—	—	—	185	147	411	276	333	104	384	158

* See the text

** Analyzed by H. Hattori

*** Recalculated values on a carbonate- and water-free basis

Table 2,-3

Table 2 (Continued)***

Sample	H 27	H 38	H 40	H 43	H 76*	H 92*	I 19*	I 23*	I 55*	I 66*	I 86	I 108*
La	81.7	9.71	17.9	22.0	2.78	3.73	6.70	12.8	1.93	14.6	9.27	2.49
Ce	191	24.5	47.4	51.1	7.95	10.7	17.0	29.9	5.69	32.7	21.6	7.59
Nd	95.1	16.1	33.7	29.5	7.68	10.1	13.2	20.6	5.55	18.9	14.6	6.90
Sm	16.9	4.26	9.45	7.15	2.97	3.60	3.88	6.02	2.11	4.58	4.03	2.31
Eu	5.42	1.55	3.21	2.51	1.07	1.31	1.48	2.09	0.842	1.50	1.16	1.00
Gd	12.5	—	10.8	7.14	4.03	5.11	4.37	6.78	3.11	4.95	4.53	3.75
Dy	7.43	4.23	10.6	5.43	4.93	6.18	3.94	5.82	3.65	4.48	4.37	4.52
Er	2.72	2.15	—	2.34	2.92	3.70	1.61	2.20	2.09	2.22	2.24	2.41
Yb	1.66	1.41	4.58	1.59	2.81	3.03	1.20	1.44	1.78	1.76	1.68	2.07
Lu	0.211	0.170	0.626	0.204	0.429	0.508	0.175	0.184	0.289	0.270	0.209	0.285
Ba	1604	—	112	626	70.8	17.9	38.3	84.0	11.0	299	66.8	17.8
Sr***	1050	78	—	483	168	68	77	248	27	323	190	69

* See the text

** Analyzed by H. Hattori

*** Recalculated values on a carbonate- and water-free basis

Table 2,-4

Table 2 (Continued)***

Sample	I 113	I 115	I 118	I 121	I 127	I 129	I 136	I 143*	I 145	IB 9	I 34090503
La	2.98	4.37	1.27	0.850	1.28	0.773	1.34	3.05	0.684	1.09	0.421
Ce	8.08	8.34	2.83	2.07	3.48	1.88	4.16	6.58	2.22	3.09	1.32
Nd	7.49	9.80	2.99	2.09	3.24	1.87	4.16	4.81	2.02	2.78	1.48
Sm	2.51	3.18	1.16	0.834	1.22	0.708	1.60	1.61	0.849	1.01	0.631
Eu	0.851	1.21	0.506	0.400	0.655	0.385	0.775	0.599	0.430	0.613	0.273
Gd	3.58	4.09	1.78	1.33	1.83	1.08	2.49	2.30	1.39	—	1.00
Dy	4.22	4.33	2.20	1.66	2.21	1.34	3.05	2.80	1.71	1.78	1.26
Er	2.61	2.50	1.44	1.08	1.46	0.877	2.01	1.67	1.10	1.11	0.797
Yb	2.43	2.15	1.36	1.02	1.39	0.819	1.92	—	1.04	1.02	—
Lu	0.354	0.302	0.201	0.151	0.207	0.120	0.280	0.241	0.155	0.151	0.103
Ba	11.7	14.5	50.8	38.0	13.3	64.3	7.35	9.92	7.35	29.4	—
Sr**	49	65	73	47	106	349	174	104	104	—	—

* See the text

** Analyzed by H. Hattori

*** Recalculated values on a carbonate- and water-free basis

Key to Table 2. (Microscopical observations by M. Adachi, I. Hattori, T. Agata,
H. Hattori and S. Mizutani.)

Hokkaido area (A)

A 4 Plagioclase basalt

Northern Kitakami area (B)

B 36 Amygdaloidal andestic basalt

Southern Kitakami area (C)

C 18 Hornblende diorite

C 58 Basaltic lapilli tuff

C 86 Andesite

C 92 Plagioclase hornblende andesite

C 104 Augite andestic basalt

Abukuma area (D)

D 3 Green schist

Kanto area (E)

E 4 Clinopyroxene andesite

E 20 Micro diorite

E 21 Andesite

E 53 Amygdaloidal basalt

Mino area (F)

F 3 Basic tuff

F 39 Inner core of pillow lava

F 81 Basaltic pillow lava

Tamba area (G)

G 10 Subophitic doleritic basalt

G 29 Fine grained basalt

Kii area (H)

H 2 Amygdaloidal basalt

H 12 Plagioclase variolitic basalt, partly with scoria fragments

H 13 Amygdaloidal basalt

H 15 Ophitic dolerite

H 18 Lapilli tuff with plagioclase and titaniferous augite fragments

H 22 Ophitic doleritic basalt

Key to Table 2 (Continued)

- H 26 Lapilli tuff
- H 27 Titaniferous augite basalt, showing partly variolitic texture
- H 38 Fine grained silisic tuff
- H 40 Basalt
- H 43 Basalt with abundant feldspar phenocrysts
- H 76 Massive pyroxene basalt
- H 92 Basaltic pillow lava

Shikoku area (I)

- I 19 Basaltic pillow lava
- I 23 Amygdaloidal trachy andestic basalt
- I 55 Ophitic basalt
- I 66 Amygdaloidal basalt
- I 86 Porphyritic basalt with plagioclase and clinopyroxene
- I 108 Dolerite
- I 113 Basalt
- I 115 Basalt
- I 118 Clinopyroxene dolerite
- I 121 Clinopyroxene gabbro
- I 127 Brown hornblende clinopyroxene gabbro
- I 129 Clinopyroxene microgabbro
- I 136 Clinopyroxene dolerite
- I 145 Clinopyroxene gabbro
- IB 9 Feldspathic gabbro
- I 34090503 Wehrlite

Mafic minerals of the samples under consideration are often altered to chlorite, actinolite, epidote and calcite. Sericite, leucoxene, prehnite, pumpellyite and stilpnomelane are identified rarely as metamorphic minerals.

Table 3. REE and Ba abundances (ppm) for three groups of pre-Cenozoic geosynclinal basalt in the Japanese Islands *

	REE pattern type		
	liquid-type	modified solid-type	primary solid-type
	(L)	(S ₂)	(S ₁)
La	25.4	7.15	2.14
Ce	55.7	16.8	5.74
Nd	30.5	12.0	5.64
Sm	6.98	3.64	2.04
Eu	2.24	1.34	0.828
Gd	6.79 (1)**	4.45	2.94 (1)**
Dy	5.81	4.37	3.47
Er	2.73 (1)**	2.13	2.06
Yb	2.09 (3)**	1.74 (3)**	1.83
Lu	0.285 (1)**	0.249	0.273
Ba	329	101	26.0
Number of samples	16	8	16

* Tuffaceous rocks were excluded from the calculation of the averages.

** Including interpolations on REE pattern for elements not determined. The figures in parentheses indicate the number of estimates by interpolation.

Appendix:

Chemical compositions and CIPW norms of the Japanese pre-Cenozoic geosynclinal volcanic rocks.

The sample numbers I 113, I 118, I 121, I 127, I 129, I 136 and I 145 here correspond to the sample numbers 2, 7, 9, 15, 17, 22 and 29, respectively, of Suzuki et al. (1971). Major element compositions of these seven samples are from Suzuki et al. (1971), and of IB 9 is from Suzuki et al. (1972).

P "tr" means below 0.01 percent.

following Table provides for small print
(page; App. 2 ~ App. 8)

Sample	A 4	B 36	C 18	C 58	C 86	C 92	C 104
SiO ₂	49.69	51.07	50.09	50.29	55.45	48.36	50.61
TiO ₂	2.74	3.50	1.41	1.95	1.02	1.19	0.72
Al ₂ O ₃	13.85	15.37	19.36	14.95	16.55	16.59	20.05
Fe ₂ O ₃	1.05	8.01	2.05	2.52	1.63	5.42	2.24
FeO	9.53	5.92	9.28	9.93	7.46	4.76	5.84
MnO	0.15	0.13	0.29	0.28	0.19	0.13	0.17
MgO	7.09	3.24	2.44	5.10	4.15	7.11	5.21
CaO	9.36	4.51	10.57	10.58	7.02	11.38	6.39
Na ₂ O	1.93	3.84	2.96	3.22	3.22	1.83	5.62
K ₂ O	2.48	1.86	0.59	0.13	0.90	0.13	0.47
P ₂ O ₅	0.61	0.39	0.20	0.11	0.32	0.06	0.14
H ₂ O +	1.66	1.24	0.90	1.02	1.13	1.96	2.57
H ₂ O -	0.10	0.20	0.11	0.14	0.23	0.12	0.23
CaCO ₃	0.31	0.01	0.69	0.13	0.73	tr	0.67
MgCO ₃	0.02	tr	0.01	0.01	0.02	tr	0.02
Total	100.57	99.29	100.95	100.36	100.02	99.04	100.95
Q	—	8.57	1.63	0.56	9.13	5.61	—
C	—	—	—	—	—	—	—
Or	14.89	11.23	3.49	0.77	5.44	0.77	2.84
Ab	16.58	33.17	25.22	27.50	27.84	15.99	42.98
An	22.12	19.66	38.12	26.20	28.63	37.82	28.81
Ne	—	—	—	—	—	—	3.17
Di	17.14	0.47	11.40	21.60	3.97	15.81	2.30
Hy	17.94	8.03	13.98	15.68	19.85	13.42	—
Ol	3.05	—	—	—	—	—	14.85
Mt	1.55	9.55	3.00	3.68	2.41	8.10	3.33
Il	5.28	6.80	2.70	3.74	1.98	2.34	1.41
Ap	1.44	0.93	0.46	0.25	0.76	0.14	0.32

(continued)

Sample	D 3	E 4	E 20	E 21	E 53	F 3	F 39
SiO ₂	47.20	52.56	49.43	49.55	44.83	45.84	54.48
TiO ₂	0.95	2.61	1.81	2.16	1.67	1.60	1.94
Al ₂ O ₃	15.02	13.47	14.56	16.95	15.11	13.81	12.80
Fe ₂ O ₃	2.61	2.93	2.73	0.03	1.40	2.60	2.68
FeO	7.23	9.00	9.32	10.44	10.44	9.86	6.39
MnO	0.18	0.15	0.17	0.08	0.18	0.14	0.10
MgO	9.32	4.90	4.93	9.94	15.85	10.63	4.68
CaO	12.43	3.17	6.72	1.06	8.54	11.35	2.01
Na ₂ O	1.86	3.74	5.68	2.73	0.83	1.31	4.78
K ₂ O	0.17	0.24	0.05	0.04	0.11	0.03	0.29
P ₂ O ₅	0.06	0.34	0.11	tr	0.11	0.09	0.30
H ₂ O +	1.15	3.69	3.49	5.88	1.10	3.50	3.19
H ₂ O -	0.23	0.56	0.17	0.46	0.20	0.07	0.60
CaCO ₃	0.70	2.94	0.12	0.47	0.27	0.10	4.76
MgCO ₃	0.03	0.13	0.01	0.34	tr	tr	0.22
Total	99.14	100.43	99.30	100.13	100.64	100.93	99.22
Q	—	13.05	—	9.94	—	—	13.49
C	—	2.28	—	11.28	—	—	1.87
Or	1.06	1.54	0.30	0.24	0.65	0.18	1.89
Ab	16.25	34.02	45.00	24.88	7.11	11.42	44.68
An	33.12	14.45	14.73	5.66	37.52	32.60	8.86
Ne	—	—	2.90	—	—	—	—
Di	24.22	—	16.06	—	3.65	20.02	—
Hy	11.74	23.93	—	43.56	24.24	20.92	20.07
Ol	7.74	—	13.00	—	21.34	7.65	—
Mt	3.90	4.57	4.15	0.04	2.04	3.87	4.29
Il	1.86	5.32	3.61	4.41	3.21	3.13	4.06
Ap	0.14	0.86	0.28	—	0.25	0.21	0.76

(continued)

Sample	F 81	G 10	G 29	H 2	H 12	H 13	H 15
SiO ₂	49.31	48.36	46.00	45.99	47.55	46.97	48.04
TiO ₂	1.44	2.54	2.14	1.22	1.21	1.80	0.98
Al ₂ O ₃	13.97	14.49	14.12	17.25	15.22	15.80	15.33
Fe ₂ O ₃	0.27	2.17	0.07	0.81	1.25	2.00	1.95
FeO	6.08	8.86	13.40	9.11	9.33	9.21	8.50
MnO	0.12	0.15	0.18	0.19	0.17	0.13	0.16
MgO	5.30	6.67	7.82	9.34	6.42	7.25	8.23
CaO	7.10	8.84	10.39	9.62	7.92	6.28	8.62
Na ₂ O	4.57	2.86	2.62	3.03	2.84	3.52	2.14
K ₂ O	0.11	0.65	0.41	0.45	0.93	1.37	0.48
P ₂ O ₅	0.16	0.23	0.14	0.13	0.11	0.16	0.12
H ₂ O +	2.42	3.58	2.99	1.30	2.48	3.72	4.00
H ₂ O -	0.22	0.15	0.09	0.33	0.38	0.13	0.56
CaCO ₃	7.68	0.49	0.18	0.39	4.51	1.65	tr
MgCO ₃	0.88	0.02	0.01	0.01	0.10	0.12	tr
Total	99.63	100.06	100.56	99.17	100.42	100.11	99.11
Q	—	—	—	—	—	—	—
C	—	—	—	—	—	—	—
Or	0.71	4.02	2.48	2.72	5.92	8.57	3.00
Ab	43.75	25.22	21.31	21.34	25.85	31.56	19.15
An	19.55	25.87	26.28	33.10	28.00	24.60	32.59
Ne	—	—	0.79	2.74	—	—	—
Di	15.61	14.96	21.41	12.35	11.12	5.95	9.63
Hy	14.28	21.05	—	—	16.61	2.75	30.36
Ol	2.17	0.02	23.12	23.84	7.80	19.51	0.02
Mt	0.45	3.28	0.10	1.20	1.95	3.07	2.99
Il	3.10	5.03	4.18	2.39	2.47	3.61	1.97
Ap	0.42	0.56	0.32	0.30	0.27	0.39	0.30

(continued)

Sample	H 18	H 22	H 26	H 27	H 38	H 40	H 43
SiO ₂	44.61	46.41	43.89	46.63	74.20	47.74	45.35
TiO ₂	1.44	1.51	1.73	2.66	0.72	2.90	2.69
Al ₂ O ₃	13.34	17.66	11.97	17.09	10.49	15.08	19.42
Fe ₂ O ₃	0.89	1.16	3.68	2.00	0.15	1.51	2.95
FeO	10.81	8.77	8.18	8.99	3.36	11.26	10.13
MnO	0.21	0.16	0.19	0.30	0.03	0.25	0.25
MgO	14.39	7.13	12.29	3.85	3.43	5.18	6.96
CaO	7.04	7.35	8.56	6.85	0.34	6.30	2.99
Na ₂ O	1.74	3.86	0.57	3.70	2.02	3.88	3.17
K ₂ O	0.27	1.10	0.28	3.52	1.16	0.38	0.80
P ₂ O ₅	0.16	0.23	0.13	0.98	0.11	0.44	0.44
H ₂ O +	4.03	3.57	5.18	2.58	2.47	4.00	3.55
H ₂ O -	0.80	0.70	1.09	0.30	0.20	0.34	0.78
CaCO ₃	0.30	1.34	1.71	1.23	1.00	0.15	0.34
MgCO ₃	tr	0.03	0.03	0.01	0.08	tr	tr
Total	100.03	100.98	99.48	100.69	99.76	99.41	99.82
Q	—	—	1.68	—	52.35	—	2.90
C	—	—	—	—	5.79	—	9.42
Or	1.69	6.82	1.83	21.54	7.15	2.36	4.97
Ab	15.51	27.79	5.25	21.58	17.77	34.61	28.18
An	29.28	28.96	32.02	20.33	1.02	23.82	12.56
Ne	—	3.50	—	5.87	—	—	—
Di	5.18	6.31	10.80	6.84	—	5.10	—
Hy	18.51	—	38.67	—	14.00	19.22	31.03
Ol	25.17	21.28	—	13.25	—	5.72	—
Mt	1.36	1.76	5.83	3.00	0.23	2.31	4.50
Il	2.88	3.01	3.59	5.23	1.42	5.81	5.37
Ap	0.39	0.56	0.32	2.35	0.25	1.07	1.07

(continued)

Sample	H 76	H 92	I 19	I 23	I 55	I 66	I 86
SiO ₂	48.42	52.06	48.93	44.64	48.94	45.75	49.89
TiO ₂	1.25	1.50	1.88	2.21	1.21	1.56	1.61
Al ₂ O ₃	14.96	14.14	10.81	15.90	13.73	15.38	15.79
Fe ₂ O ₃	1.73	0.07	1.92	0.67	2.98	1.14	2.96
FeO	7.40	9.51	9.63	11.80	7.87	8.26	7.58
MnO	0.17	0.17	—	0.26	0.20	0.19	0.14
MgO	7.62	7.46	11.18	6.58	7.94	7.39	7.51
CaO	10.97	9.65	10.85	2.36	11.05	10.98	6.62
Na ₂ O	3.04	2.39	1.58	1.85	3.10	3.22	4.40
K ₂ O	0.10	0.33	0.14	1.34	0.15	1.01	0.20
P ₂ O ₅	0.09	0.12	0.10	0.29	0.11	0.15	0.25
H ₂ O +	2.23	1.65	2.92	2.62	3.19	1.51	2.32
H ₂ O -	0.23	0.34	0.15	0.74	0.12	0.63	0.17
CaCO ₃	1.05	1.01	0.06	8.96	0.42	1.83	0.65
MgCO ₃	0.03	0.03	tr	0.16	0.01	0.04	0.01
Total	99.29	100.43	100.15	100.38	101.02	99.04	100.10
Q	—	2.94	0.41	7.46	—	—	—
G	—	—	—	8.89	—	—	—
Or	0.59	2.01	0.83	8.98	0.89	6.26	1.24
Ab	26.91	20.73	13.79	17.77	26.99	17.08	38.42
An	28.05	27.62	22.67	11.19	23.74	25.80	23.45
Ne	—	—	—	—	—	6.29	—
Di	22.90	17.06	25.97	—	25.87	24.86	7.07
Hy	7.40	26.33	29.52	39.09	7.58	—	12.26
Ol	8.84	—	—	—	7.89	14.49	9.40
Mt	2.62	0.10	2.89	1.10	4.44	1.74	4.42
Il	2.49	2.92	3.68	4.77	2.36	3.11	3.15
Ap	0.21	0.28	0.23	0.76	0.25	0.37	0.60

(continued)

Sample	I 108	I 113	I 115	I 118	I 121	I 127	I 129
SiO ₂	49.49	50.17	49.42	47.54	50.08	48.45	46.67
TiO ₂	1.63	1.45	1.51	0.71	0.74	1.10	0.59
Al ₂ O ₃	13.44	12.48	11.16	10.94	10.99	15.34	17.35
Fe ₂ O ₃	2.68	2.35	7.70	6.18	2.80	0.24	2.18
FeO	7.51	8.22	6.32	2.67	4.61	8.84	3.58
MnO	0.18	0.16	0.41	0.16	0.15	0.17	0.11
MgO	7.86	8.39	9.04	12.40	11.27	8.37	7.24
CaO	10.14	10.98	7.98	13.91	14.40	11.55	14.79
Na ₂ O	2.17	2.80	3.04	1.41	1.43	2.47	2.21
K ₂ O	0.16	0.04	0.08	0.11	0.04	0.04	0.04
P ₂ O ₅	0.10	0.06	0.09	0.03	0.02	0.05	0.02
H ₂ O +	3.69	2.89	3.63	3.44	3.04	2.86	4.27
H ₂ O -	0.24	0.32	0.46	0.19	0.24	0.21	0.10
CaCO ₃	0.25	0.19	0.13	0.13	tr	tr	0.13
MgCO ₃	0.03	0.02	0.01	0.01	tr	tr	0.01
Total	99.57	100.52	100.98	99.83	99.81	99.69	99.29
Q	4.06	—	4.52	0.63	1.99	—	—
C	—	—	—	—	—	—	—
Or	1.00	0.24	0.47	0.65	0.24	0.24	0.25
Ab	19.29	23.61	26.57	11.93	12.10	20.99	17.96
An	27.71	21.30	17.16	23.28	23.50	30.74	37.62
Ne	—	—	—	—	—	—	0.49
Di	19.70	26.41	18.32	35.45	38.00	21.61	28.82
Hy	20.68	18.71	18.24	14.55	15.37	9.66	—
Ol	—	0.22	—	—	—	11.16	6.08
Mt	4.07	3.39	11.54	7.10	4.06	0.35	3.19
Il	3.25	2.75	2.96	1.35	1.41	2.09	1.14
Ap	0.23	0.14	0.21	0.07	0.05	0.12	0.05

(continued)

Sample	I 136	I 143	I 145	IB 9	I 34090503
SiO ₂	46.74	49.69	47.78	44.84	45.77
TiO ₂	1.68	0.88	0.71	0.90	0.20
Al ₂ O ₃	14.04	12.13	10.34	20.56	3.06
Fe ₂ O ₃	5.87	2.19	0.79	5.20	4.77
FeO	8.13	6.66	6.48	4.24	3.47
MnO	0.20	0.16	0.12	0.14	0.09
MgO	5.50	8.59	13.14	3.95	22.23
CaO	11.51	12.86	14.77	11.86	13.21
Na ₂ O	2.52	2.22	0.87	3.21	0.81
K ₂ O	0.03	0.08	0.03	0.14	0.05
P ₂ O ₅	0.04	0.04	0.02	0.03	0.01
H ₂ O +	2.49	3.18	3.55	3.70	4.16
H ₂ O -	0.18	0.33	0.20	0.16	0.20
CaCO ₃	0.13	tr	0.18	—	tr
MgCO ₃	0.01	tr	0.02	—	tr
Total	99.07	99.01	99.00	98.93	98.03
Q	2.24	0.85	—	—	—
C	—	—	—	—	—
Or	0.20	0.47	0.16	0.89	0.30
Ab	21.49	19.63	7.45	25.57	6.85
An	27.22	24.00	24.54	43.40	4.57
Ne	—	—	—	1.64	—
Di	24.54	34.33	39.61	14.56	47.61
Hy	9.68	15.54	14.95	—	7.02
Ol	—	—	6.93	4.16	20.01
Mt	8.60	3.32	1.16	7.93	6.92
Il	3.23	1.75	1.37	1.80	0.38
Ap	0.09	0.09	0.05	0.07	0.02

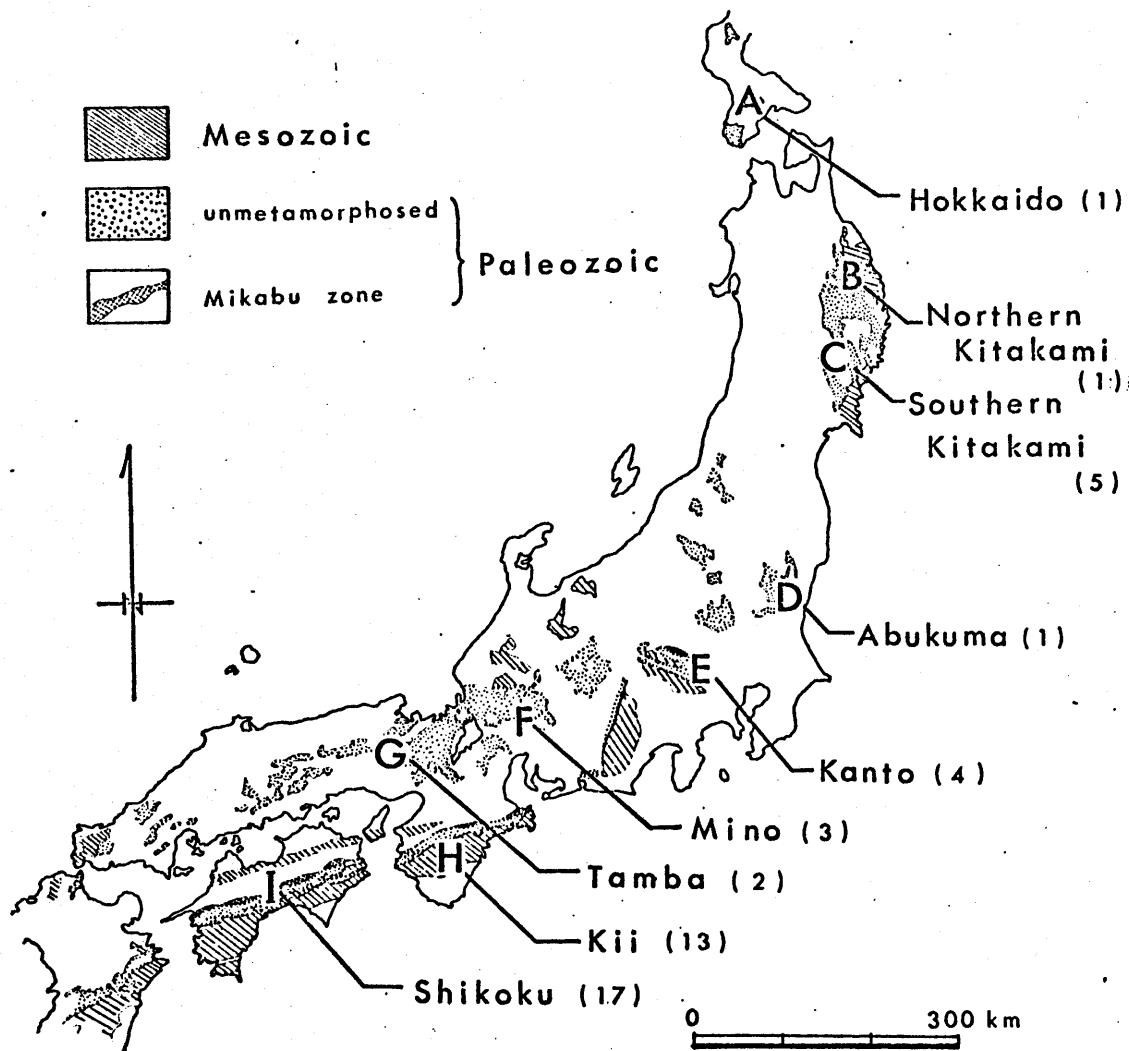


Fig. 1

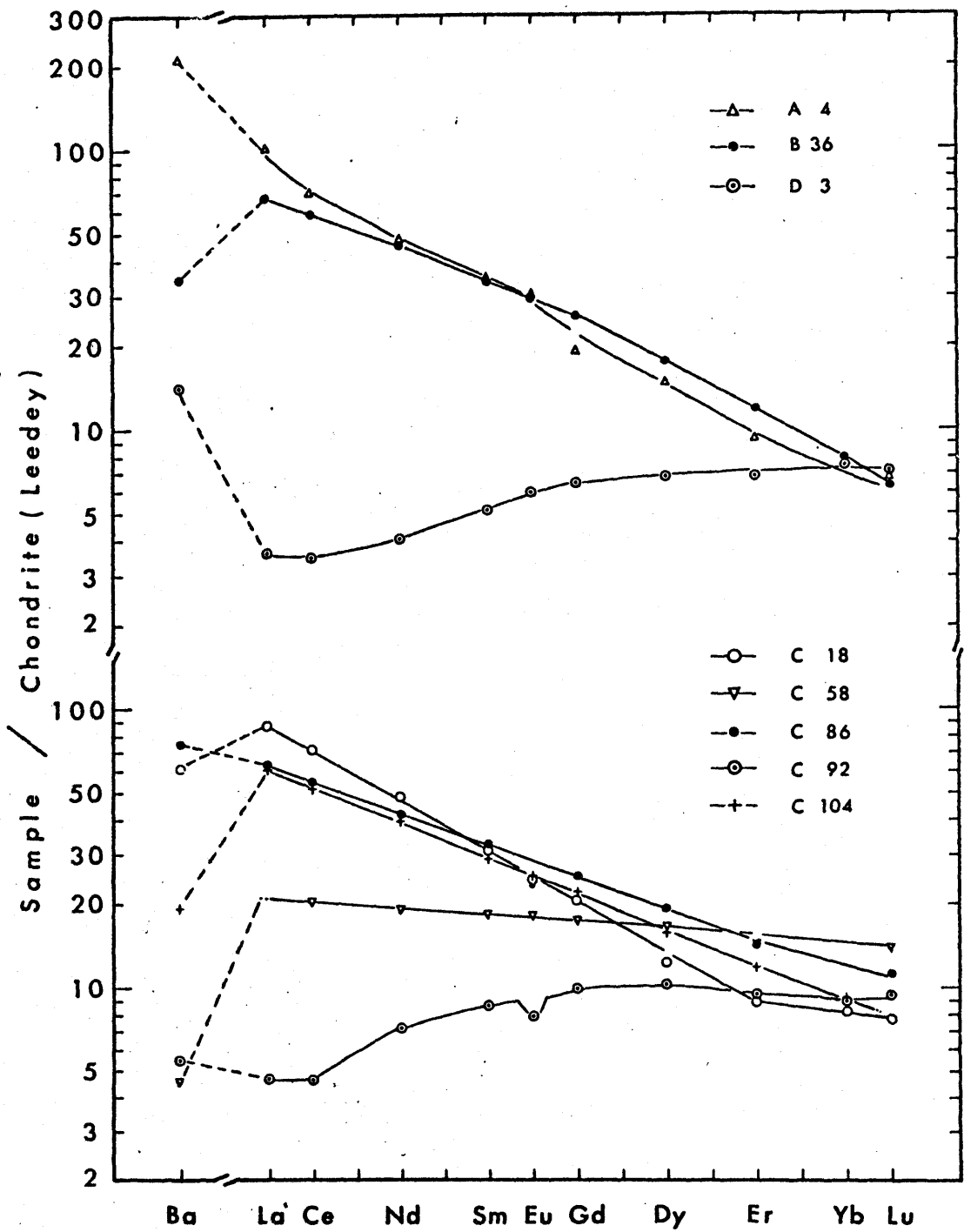


Fig. 2-a

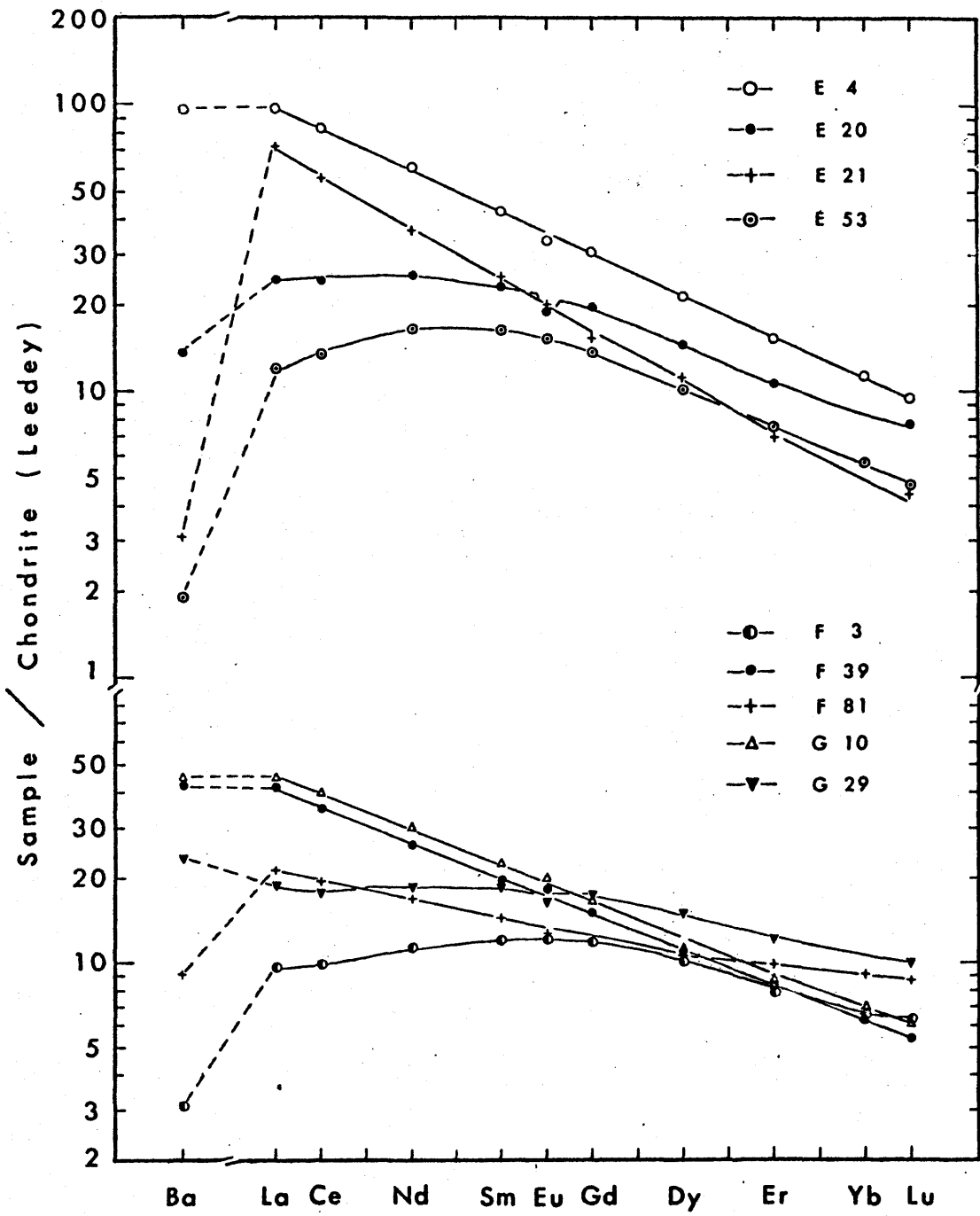


Fig. 2-b

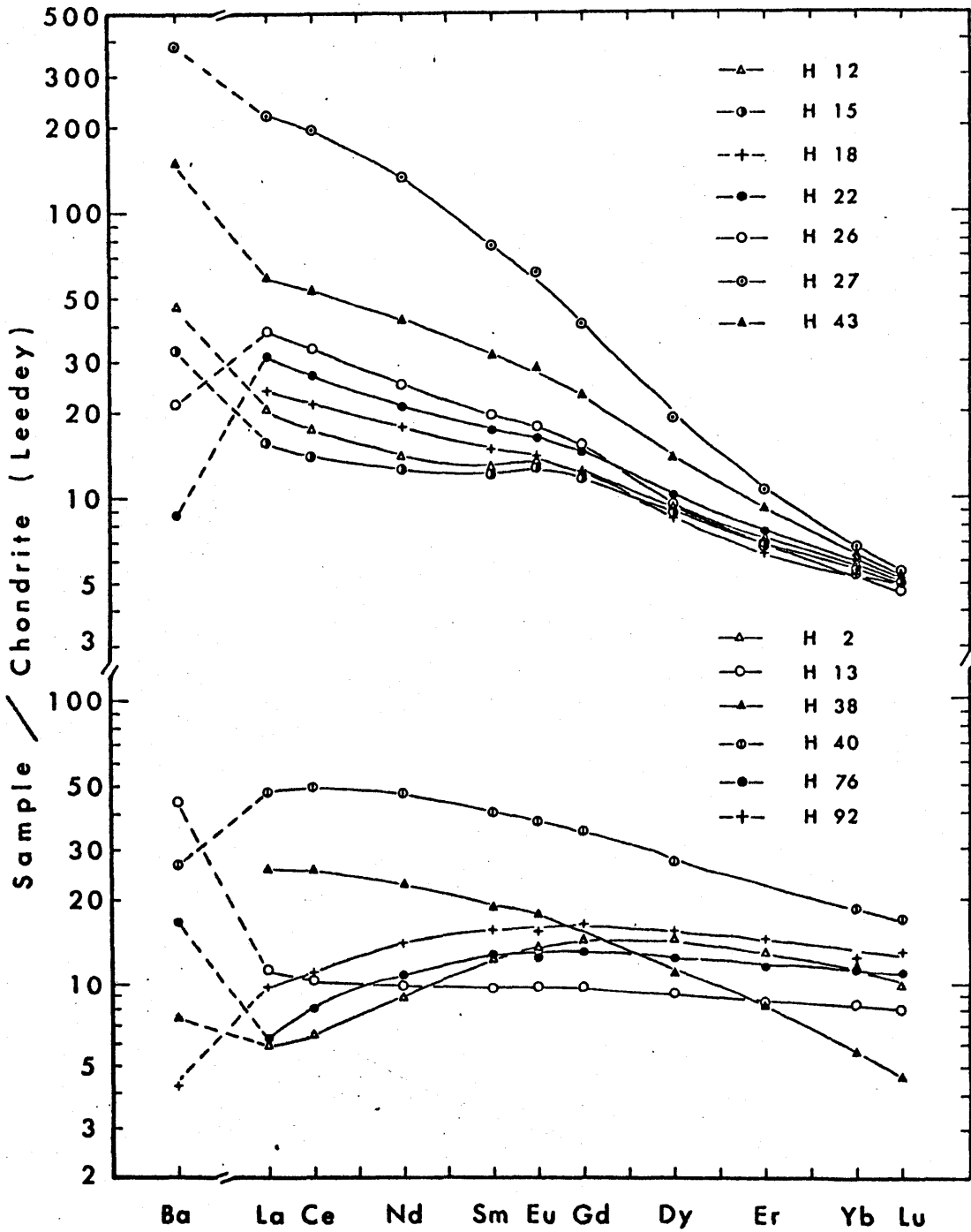


Fig. 2-c

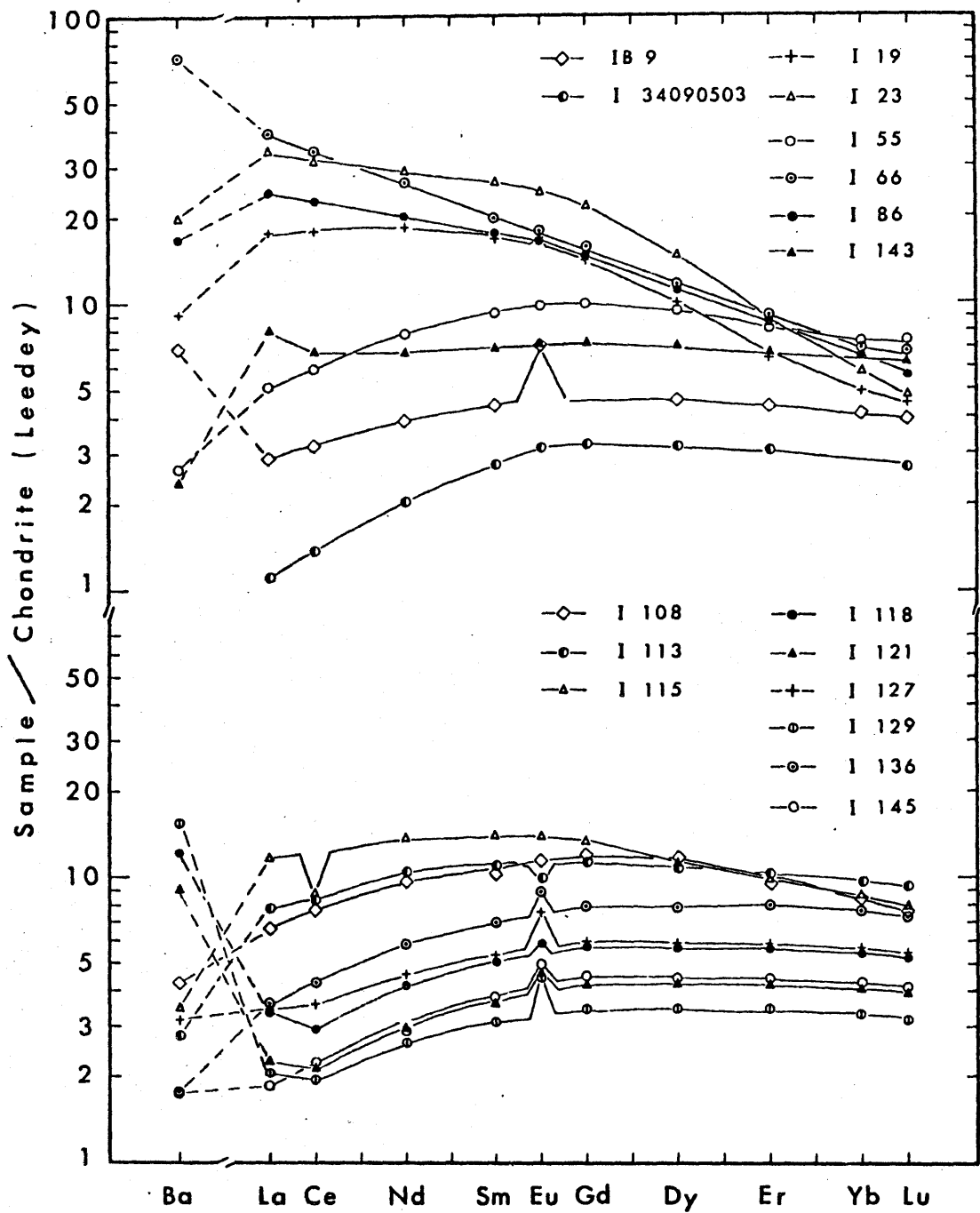
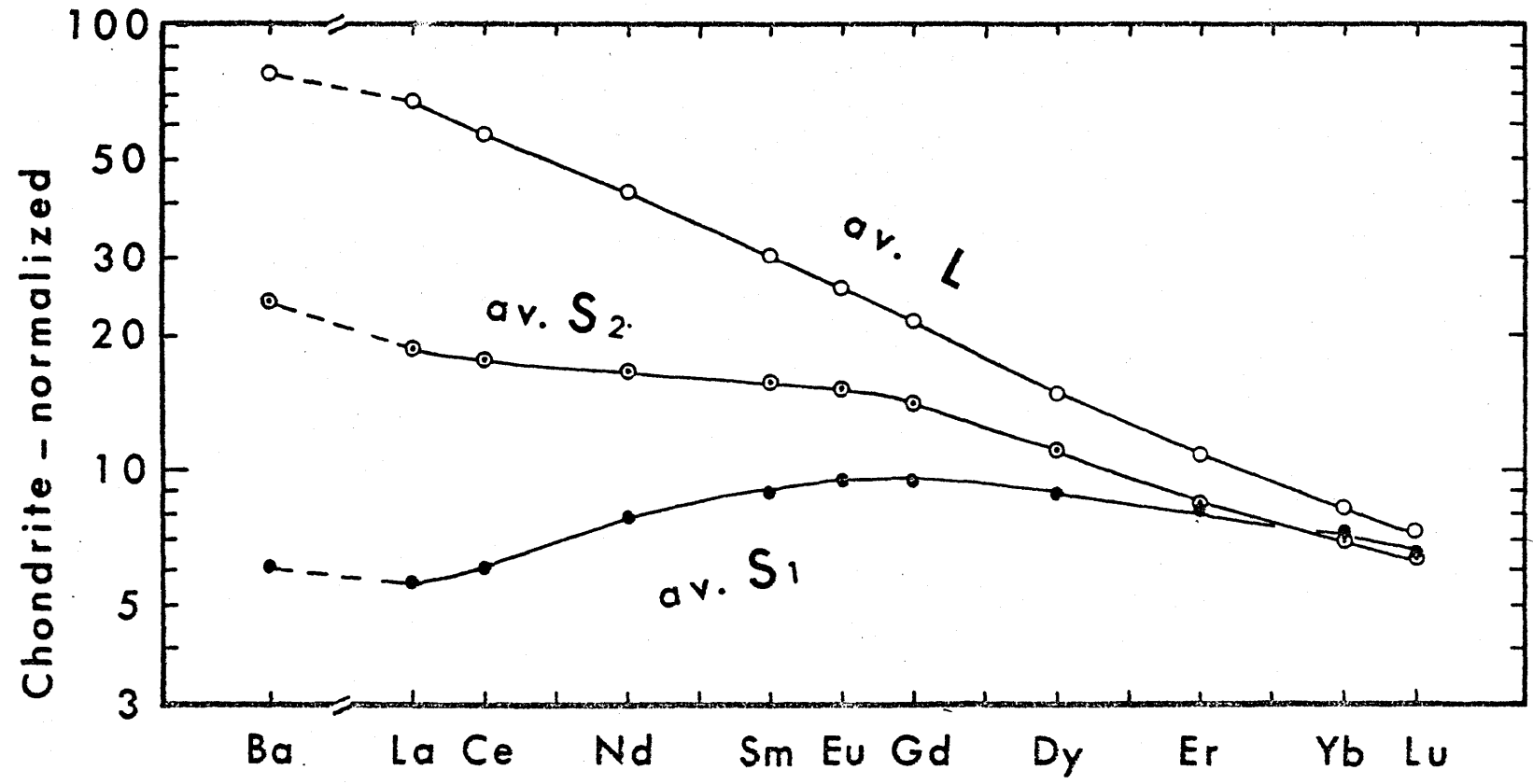


Fig. 2-d

FIG. 3



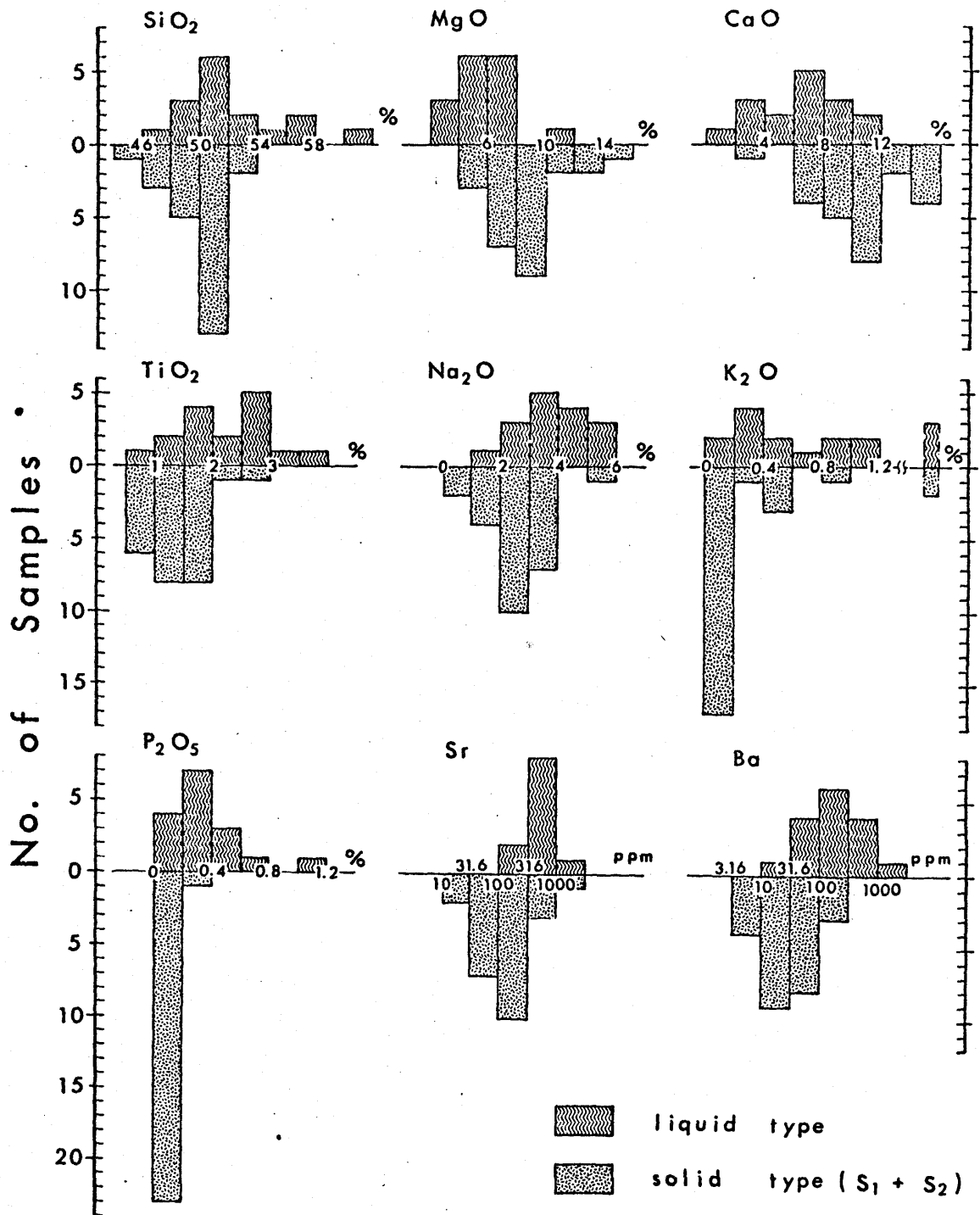


Fig. 4

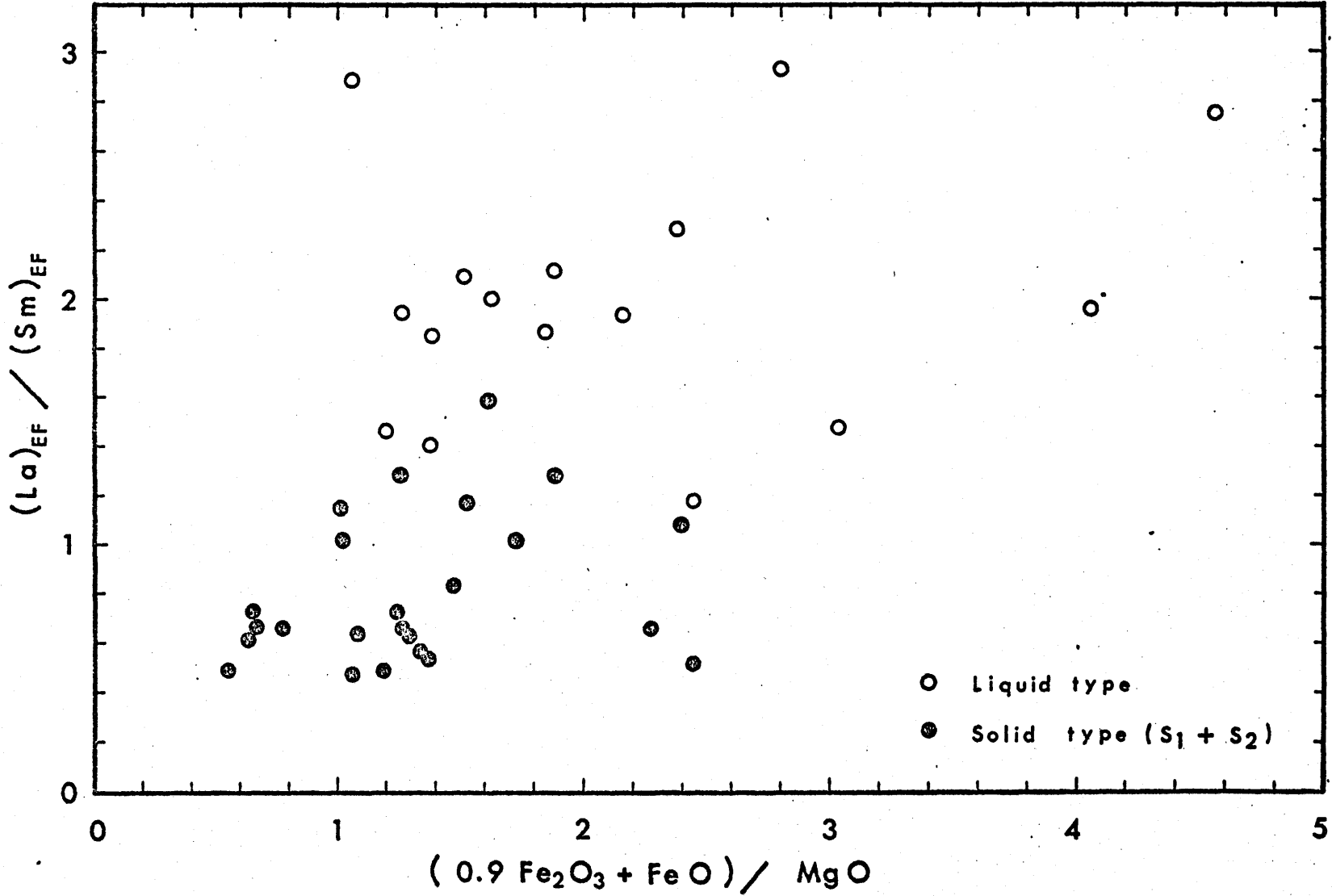


Fig. 5

C

C

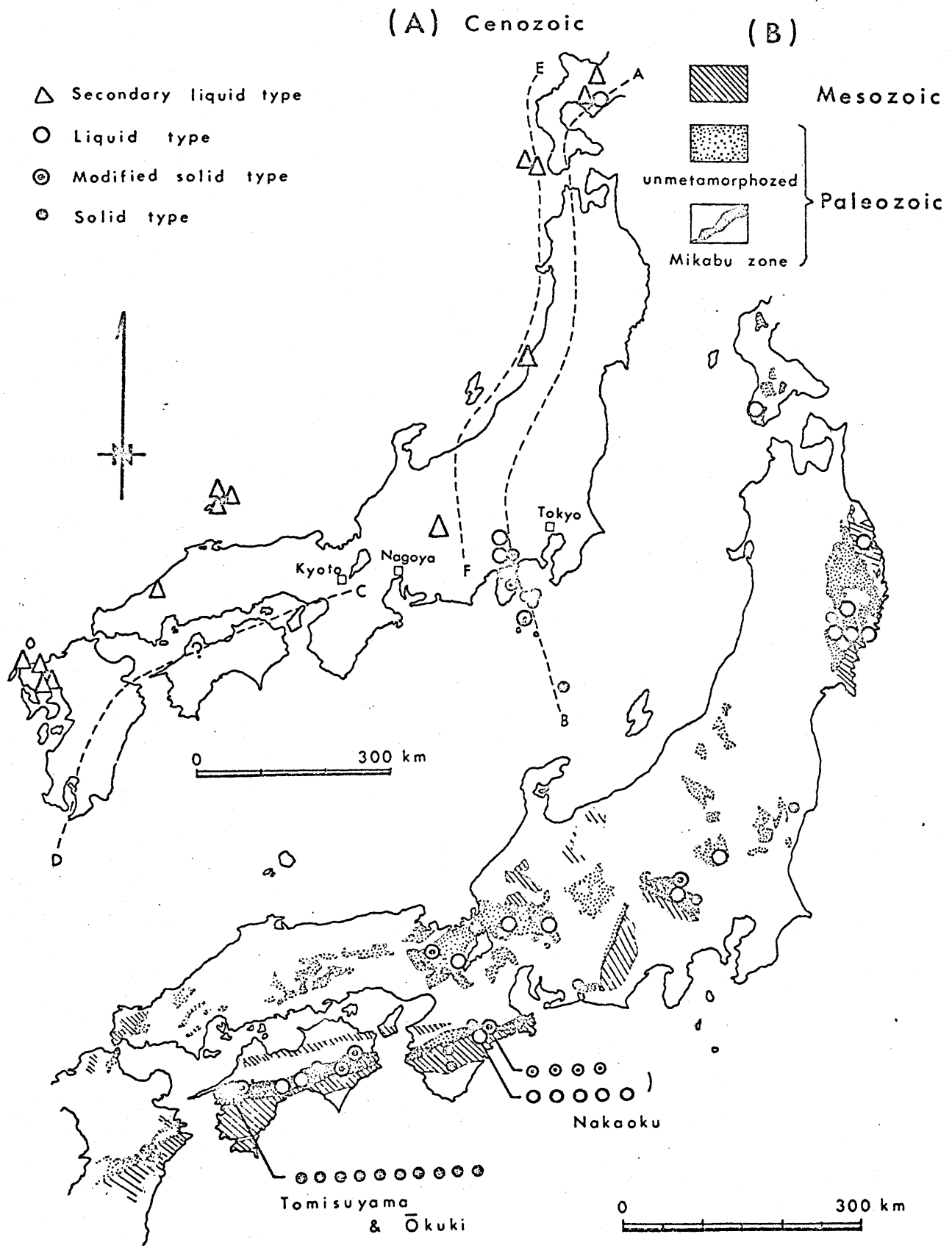


Fig. 6

Fig. 7

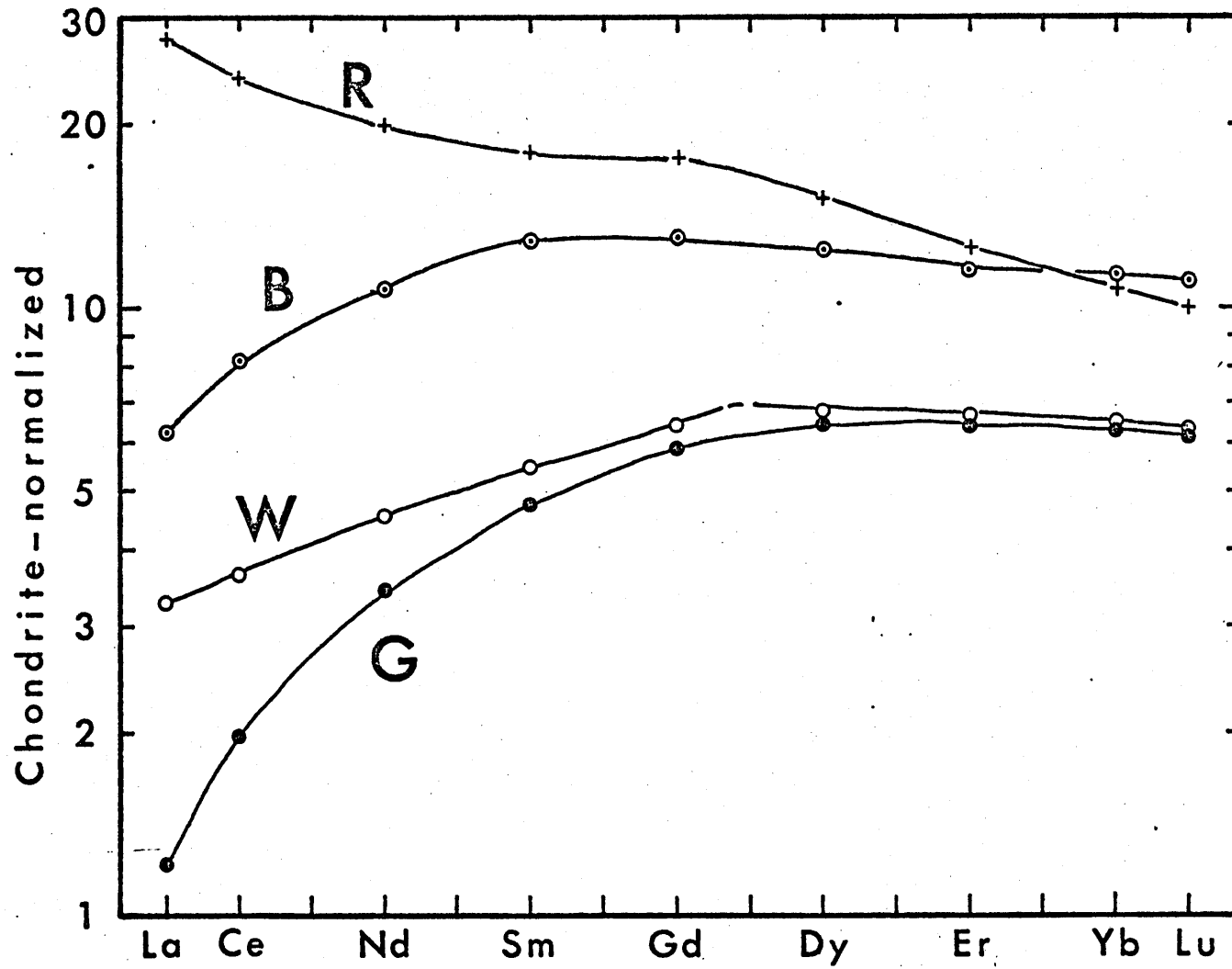


Fig. 8

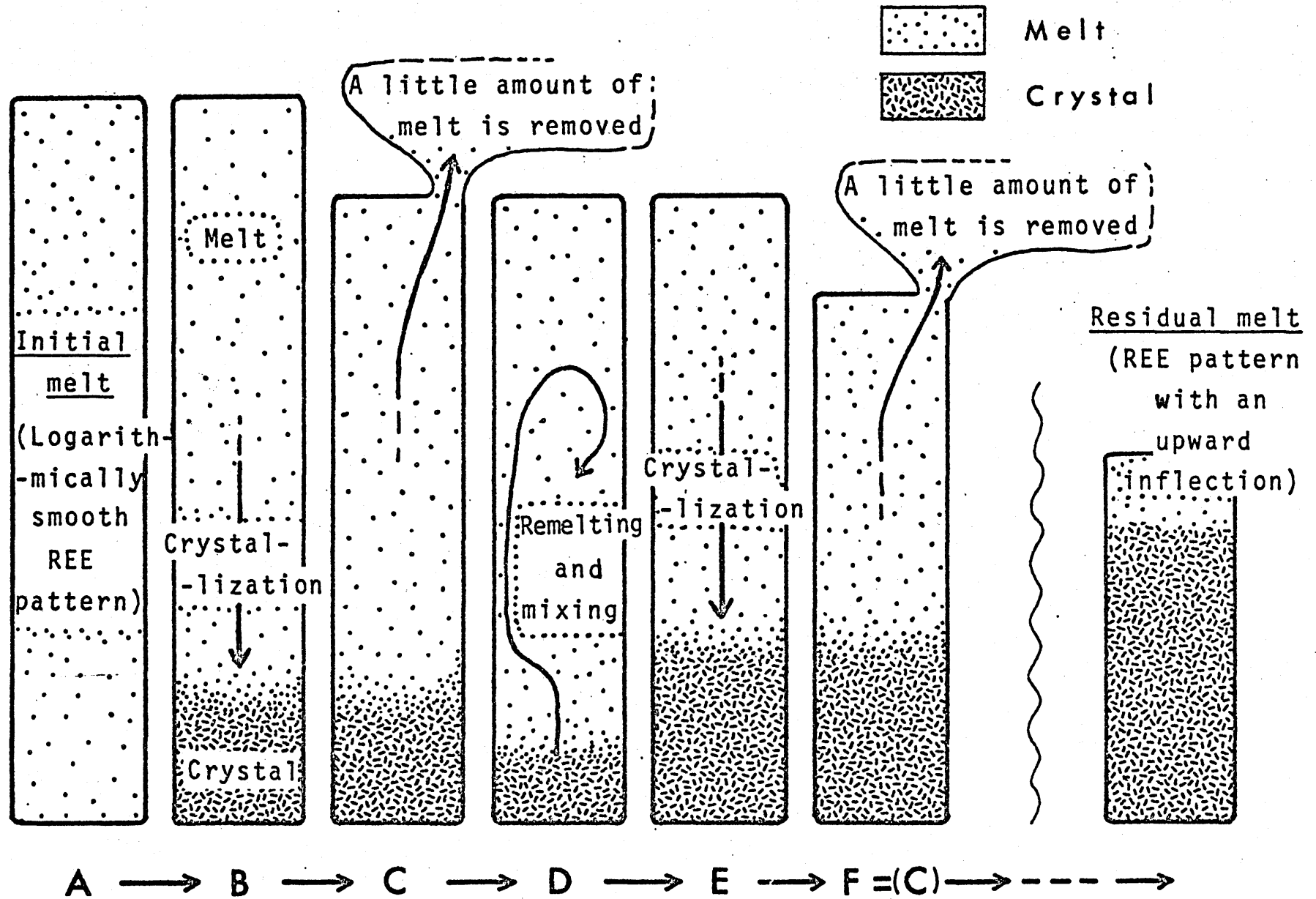
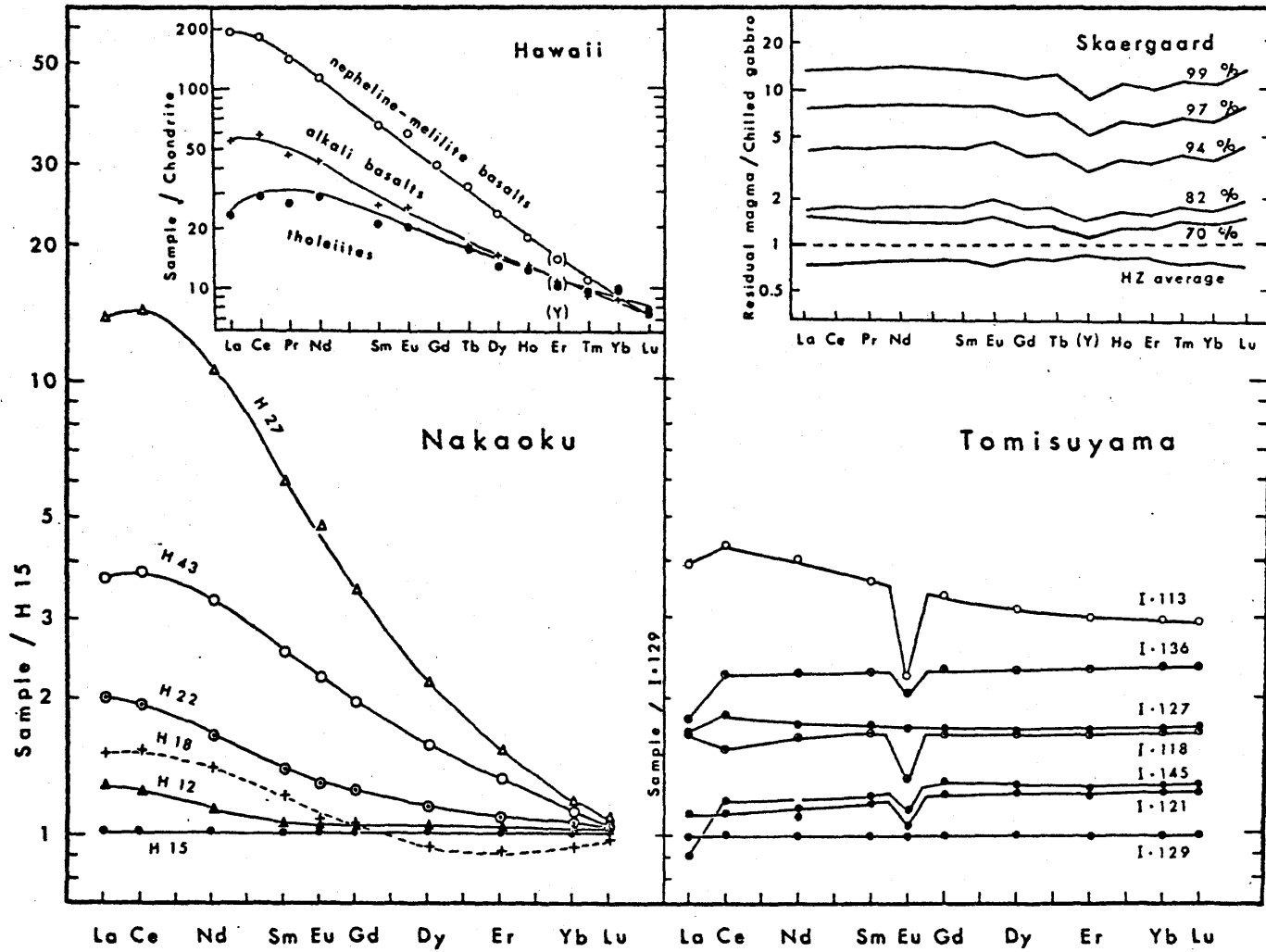


Fig. 9



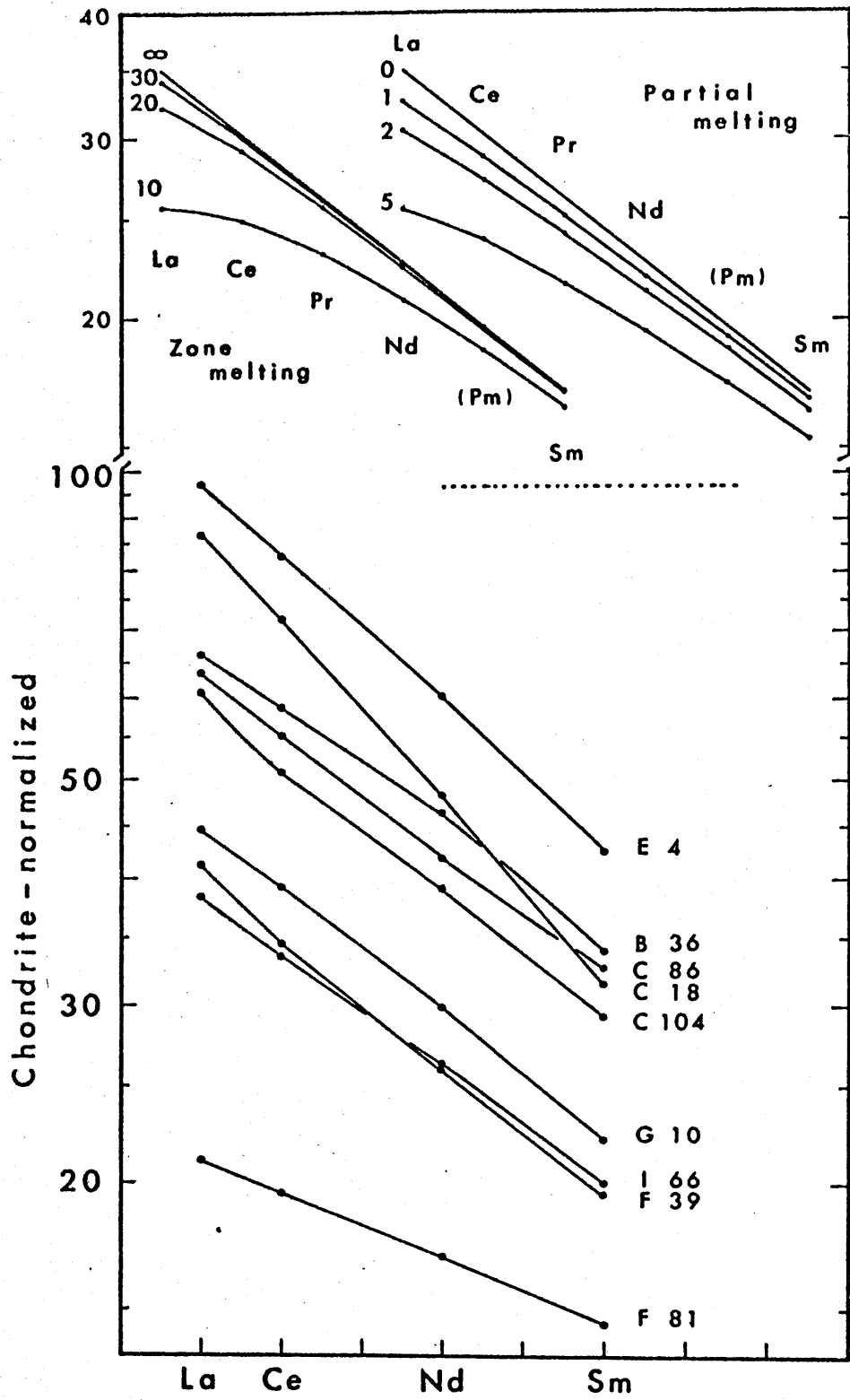


Fig. 10