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Lunar differentiation processes as characterized by trace element abundances

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The pattern of incompatible elements (K, Rb, Ba, r.e.e., Hf etc.) is the same for most samples from the lunar highlands. It is suspected that this pattern of incompatible elements is typical for the whole lunar crust. This seems to be a reasonable assumption as one can show from heat flow data that a large part of the Moon's total U (and consequently other incompatible elements) has to be concentrated in a thin crustal layer, which certainly contributes to the sampled highland rock types. It is supposed that a partial melting process of the major part of the Moon has extracted the trace elements from the interior into the crust. The patterns of incompatible elements of mare basalts are those expected if a second partial melting process were applied to the trace-element-depleted interior.

Some consequences of this model are discussed. A relatively constant Sr and Eu distribution through the whole Moon is inferred, implying a positive Eu-anomaly in the lunar interior.

INTRODUCTION

The discussion will be limited to a certain group of trace elements, the incompatible elements (U, K, Rb, r.e.e., Hf, etc.). These elements are not accepted in lattice sites of normal rock-forming minerals because of their unusual ionic radius and/or ionic charge. They are strongly enriched in liquids formed by small degrees of partial melting or in the late liquid of a fractional crystallization process. The heat-producing elements, U, Th and K, belong to the group of incompatible elements. Therefore heat-flow data can under certain assumptions be used to calculate the bulk abundance of U and other incompatible elements in the Moon. From the increase of temperature with depth within the Moon the distribution of U can be estimated. The trace-element-rich crust, calculated from these data, is thought to have the same incompatible element pattern as KREEP, the dominant trace element component of the lunar highlands. In this way the relative abundance pattern of incompatible elements can be connected to the bulk abundance and distribution of these elements within the Moon.

THE TRACE ELEMENT PATTERN OF THE LUNAR CRUST

Most samples originating from the lunar highlands have the same pattern of incompatible elements. Figure 1 shows the incompatible element patterns for some highland samples. The ratio of two of these elements is always the same, independent of the absolute abundance of these elements. This is most easily explained by the addition of various degrees of a trace-element-rich component ('KREEP'; for K, r.e.e. and P) to lunar highland samples. Exceptions are trace-element-poor anorthosites, which are relatively enriched in K and Ba compared to other incompatible elements (see, for example, 67455 in figure 1) or other rocks of cumulate origin, like 76535 (Haskin *et al.* 1974). These rocks all have low concentrations of incompatible elements (except Sr and Eu) and thus cannot significantly contribute to the total amount of trace elements in the uppermost part of the crust.

Variations of K and Rb of KREEP-rich rocks (61156 of figure 1) can, at least in some cases, be explained by volatilization loss or gain of alkali elements (Palme & Wänke 1975).

The abundances of K and Rb have been multiplied with factors of 30 and 45, respectively. These factors take into account the overall depletion of alkali elements together with the enrichment of refractory lithophile trace elements for the bulk Moon. They were derived from K–La and Rb–U correlations. As only a small fraction of the total amount of W is in the silicate phase a factor of 17 has been taken to correct for the loss of W in an early separated metal phase. This factor is derived from a La–W plot (for details see Palme & Wänke 1975).

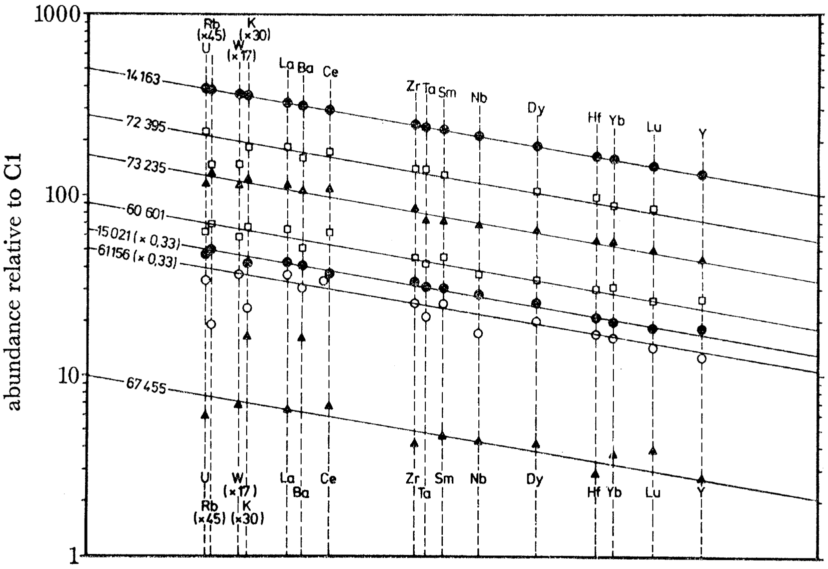

FIGURE 1. The chondrite-normalized incompatible element patterns of highland samples. Sample 14163 is used as a reference sample. Data are from this laboratory, with the exceptions: Rb for 73235 (Hubbard *et al.* 1974), Rb for 60601 (Evensen *et al.* 1973), Rb, Sr, Y, Zr, Nb, Ba for 15021 from Willis *et al.* (1972).

As the KREEP-type trace element pattern of figure 1 is dominant in the lunar highlands, we shall suppose that this type of trace element fractionation is typical for the whole lunar crust on the front side of the Moon. Taylor & Jakeš (1974) have made similar assumptions. They argue that mixing and overturning of crustal material down to some 60 km has homogenized the crust to a certain extent, so that there are no great variations in element abundances within a 60 km crust.

Heat flow data and measurements of thermal conductivities of surface rocks define the temperature increase with increasing depth. Temperatures calculated from these data for a certain depth are unacceptably high (Mizutani & Osako 1974). As a consequence one must assume that the concentration of heat producing elements is steeply decreasing with increasing depth, provided we have a constant heat flow of about 21–29 mJ m^{-2} s^{-1} (0.5–0.7 μcal cm^{-2} s^{-1}) through the surface of the Moon. In fact most thermal models of the Moon assume an exponential decay of the U concentration with depth (see, for example, Hanks & Anderson 1972; Toksöz & Solomon 1973). Considering the fact that the crust was solid some 3.5 Ga ago, to support the mascons, a conservative estimate would be that about half of the Moon's U (and consequently other incompatible elements) are concentrated in a 60 km crust (Palme & Wänke 1975). And in addition within the crust U has to be strongly concentrated towards the surface, assuming the above mentioned heat flow.

It is naturally an open question if the heat flow measured at the Apollo 15 and 17 sites is really representative for a larger part of the Moon, especially for the highlands. But one should keep in mind that a high U concentration for the bulk Moon is not unexpected in view of the enrichment of refractory elements in most samples collected in Apollo and Luna missions. Any simple models based on the correlation of two incompatible elements (both concentrated in the lunar crust, similar to U) like K and La, La being representative for a refractory and K for a non-refractory component, yield U concentrations very similar to those obtained by using heat flow data (Wänke *et al.* 1974).

One might suspect that the low lunar K/La-ratio (70 compared to the chondritic value of 2200) is only the result of a depletion of relatively volatile alkaline elements in the bulk Moon. A correlation of the two incompatible elements Li–La, however, shows that La is also enriched by a factor of 10 relative to the non-refractory Li, which is certainly not volatile (Dreibus *et al.* this volume).

THE TRACE ELEMENT PATTERNS OF MARE BASALTS

The trace element patterns of mare basalts are in a certain sense complementary to the trace element pattern of the crust. In figures 2 and 3 we have plotted the concentrations of the incompatible elements of some mare basalts as a function of the concentrations of the incompatible elements in the crust. Soil sample 14163 serves as a reference sample for KREEP. With the exception of Ta the trace element patterns are relatively smooth curves. This clearly shows that there is some connection between the process, generating the incompatible element pattern of the crust and the process producing the incompatible element pattern of the mare basalts. There is a complementary trend visible for KREEP and the mare basalts from U to Zr in figures 2 and 3. With decreasing enrichment in the crust from U to Zr, the chondrite normalized abundances increase in mare basalts from Apollo 11 and 17. From Sm to Sr, however, the decreasing abundance in KREEP is accompanied by a decrease in abundances of the respective elements in mare basalts.

This relationship can be explained by a two-step partial melting model (Wänke *et al.* 1974; Palme & Wänke 1975). The first step is the generation of KREEK in a partial melting process, affecting most of the Moon. In this process the incompatible elements now concentrated in the crust were extracted from the lunar interior. The KREEP pattern of incompatible elements in the crust has its complement in the residual lunar interior. The order of increasing enrichment factors for the crust from Sr to U (figures 2 and 3) is counterbalanced by an opposite pattern in the interior, the abundances are decreasing from Sr to U. From this trace element depleted lunar interior the mare basalts are produced in second partial melting process.

Assuming 10 × C1 chondritic abundances of refractory trace elements for the bulk Moon (Wänke *et al.* 1975) and an abundance level in KREEP similar to 14163 a series of effective partition coefficients $D_{\text{partial melt/solid}}$ can be defined. These partition coefficients are highest for U and they decrease continuously to Sr. After calculating the incompatible element pattern of the residual interior the above defined partition coefficients are again applied for the generation of the mare basalts. Although the partition coefficients increase from U to Zr, the depletion of these elements after the first partial melting was so large that this depletion dominates the pattern of these elements in the mare basalts (figures 2 and 3). The depletion after the first partial melting was relatively low for the elements from Sm to Sr, thus the decreasing distribution coefficients determine the trace element pattern from Sm to Sr, which is consequently similar to the KREEP pattern. Wänke *et al.* (1974) have shown that a simple formula can be derived, fitting the observed trace element patterns of figures 2 and 3 quite well. The effective distribution coefficients are eliminated in this formula and the degrees of the first and second partial melting X1 and X2 serve as parameters to fit the curves.

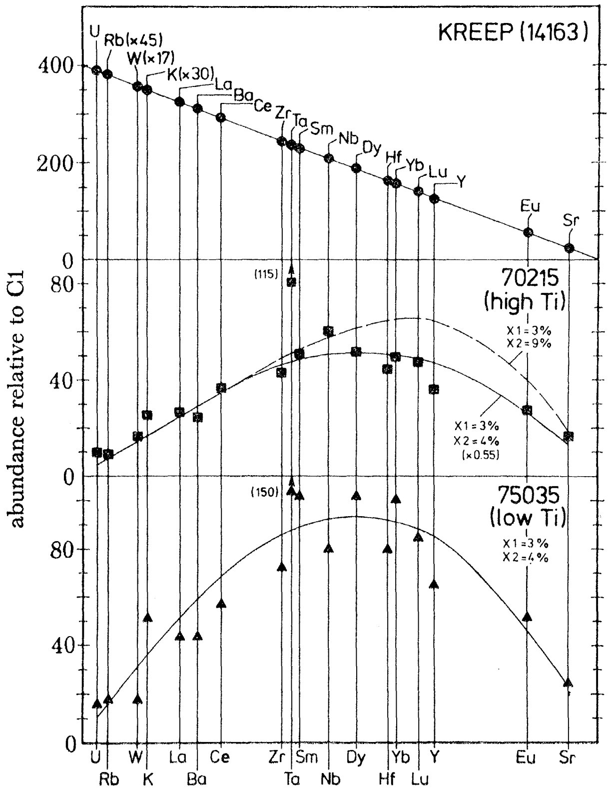

FIGURE 2

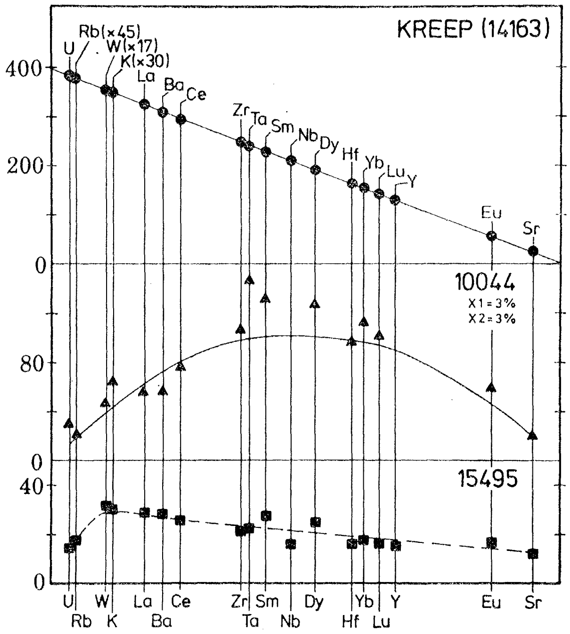

FIGURE 3

FIGURE 2. Enrichment factors relative to chondrites (C1) for incompatible elements in KREEP (14163), a high Ti basalt and a low Ti basalt from Apollo 17. Sources for KREEP and C1 values are given in Palme & Wänke (1975). X1 and X2 are the degrees of partial melting in a two step partial melting model (see text).

FIGURE 3. The same as figure 6 for a low K mare basalt from Apollo 11 and the Apollo 15 rock 15495. The curve of 15495 is not calculated.

As one can see the Apollo 17 low Ti and high Ti rocks can be fitted with the same two parameters X1 and X2. The absolute enrichment of trace elements is about a factor of two lower in 70215 compared to 75035. The low-K Apollo 11 rock has a somewhat different fractionation pattern than the Apollo 17 basalts. The trace element patterns of the Apollo 12 and 15 basalts are less fractionated than those of the Apollo 11 and 17 basalts. They probably originate from a less depleted region than the Apollo 11 or 17 basalts. Furthermore they probably have been produced by a larger degree of partial melting (Ringwood 1975). But nevertheless these rocks are significantly depleted in Rb and U compared to other incompatible elements, as can be seen from a typical Apollo 15 rock 15495 (figure 3). The curve in figure 3 has not been calculated.

In this model KREEP and the mare basalts are produced from the same source region. The main argument against the derivation of KREEP and the mare basalts from the same source region is the higher Mg/Fe-ratio of KREEP-rich highland rocks, compared to the low Mg/Fe-ratio of the mare basalts (Gast 1972; Hubbard *et al.* 1974). According to Wänke *et al.* (1975) the highland rocks can be viewed as mixtures of a primitive lunar plagioclase component, derived from differentiation of an early formed crust, a primary component consisting of unfractionated late accreting material (Mg/Fe ~ 1) and KREEP, the latter being only a minor constituent with respect to the major element chemistry.

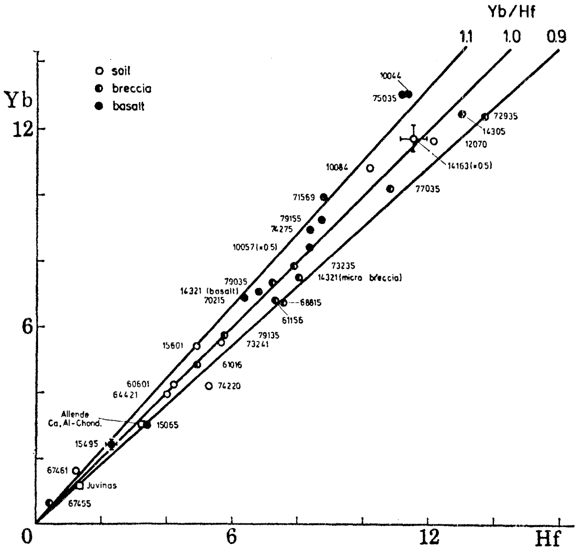

FIGURE 4

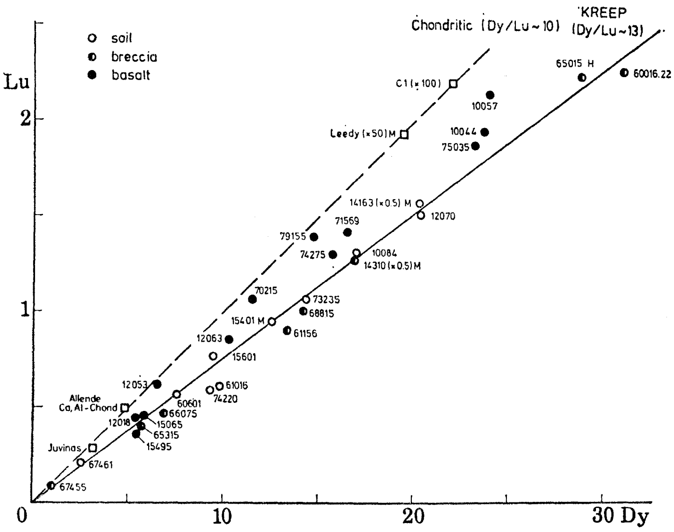

FIGURE 5

FIGURE 4. In spite of the difference in ionic charge Hf and Yb are extremely well correlated in lunar samples (parts/10^6). KREEP-rich samples generally have somewhat lower ratios than 1, while mare basalts tend to have slightly higher Hf/Yb ratios.

FIGURE 5. A Lu-Dy plot (parts/10^6) shows that all lunar samples have a Dy/Lu ratio which is smaller than the chondritic ratio. These relations become clear when looking at figures 2 and 3. Data marked M are from Masuda *et al.* (1972), those marked H are from Hubbard *et al.* (1973).

CORRELATIONS BETWEEN TRACE ELEMENTS OF HIGHLAND SAMPLES AND MARE BASALTS AND SOME CONSEQUENCES

From figures 2 and 3 one can immediately see if two elements are well correlated in mare basalts and KREEP or if their ratio is different for these two groups of lunar rock types. Ytterbium and Hf, e.g. being neighbouring elements in figures 2 and 3 are very well correlated in most lunar samples (figure 4), despite a difference in valency. Figure 5 indicates the constant and chondritic ratio of Ba and La (again two neighbouring elements in figures 2 and 3) in most lunar samples in sharp contrast to the varying Sm/La ratios, two elements having very different enrichment factors for KREEP.

Ba/La ratios are only deviating from chondritic ratios (figure 5), when plagioclase separation is involved or in granitic rocks like the light part of 12013.

As one can see from figure 5 only KREEP-poor highland samples have the high Ba/La ratios. In our model they are derived by crystallization of plagioclase from a totally molten crustal layer of some 40–60 km. The constant ratios of Ba/La in all other samples limits the involvement of plagioclase in the early lunar differentiation processes. It is even difficult to ascribe the Eu anomaly in KREEP and in the mare basalts to separation of plagioclase alone, because that would change the Ba/La ratio in the residual phase (Palme & Wänke 1975).

If our interpretation of figures 2 and 3 is also valid for Eu and Sr we would expect a positive Eu anomaly in the lunar interior. Trivalent r.e. are highly enriched in the crust, while Eu is only rather weakly partitioned into the first partial melt. Furthermore, as the chondrite normalized Eu/Sr-ratio is always larger than 1 (figures 2 and 3) we would expect a complementary ratio in the lunar interior. A similar ratio is Dy/Lu of figure 6. According to figures 2 and 3 the value of this ratio should be larger in KREEP and the mare basalts than the chondritic one of 10. Figure 6 shows indeed that this is the case. Hence, we expect a Dy/Lu ratio smaller than 10 in the lunar interior.

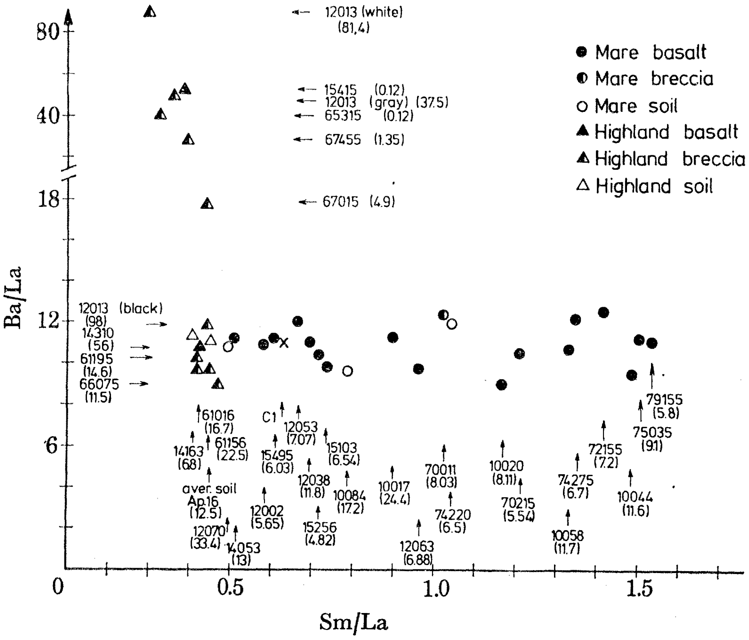

FIGURE 6. The divalent Ba and the trivalent La are much better correlated in lunar samples than the two light r.e.e. Sm and La, their ratios vary by about a factor of 4. The Ba/La ratio is only deviating from the chondritic ratio, when either plagioclase (low absolute abundances of Ba and La) or rare K-feldspars (high absolute abundance of Ba and La) are involved. Data on 12013 are from Hubbard *et al.* (1970), those from 14310 and 14053 from Hubbard *et al.* (1972). (Numbers in parentheses are La, parts/10^6.)

Sm/Eu against Sm plots are sometimes used to show the dependence of the Eu anomaly on the amount of r.e. enrichment. In our opinion, these plots merely reflect the fact that the Eu concentration does not vary much in lunar samples. As a consequence the lunar interior, depleted in trivalent r.e.e., should have a positive Eu anomaly.

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