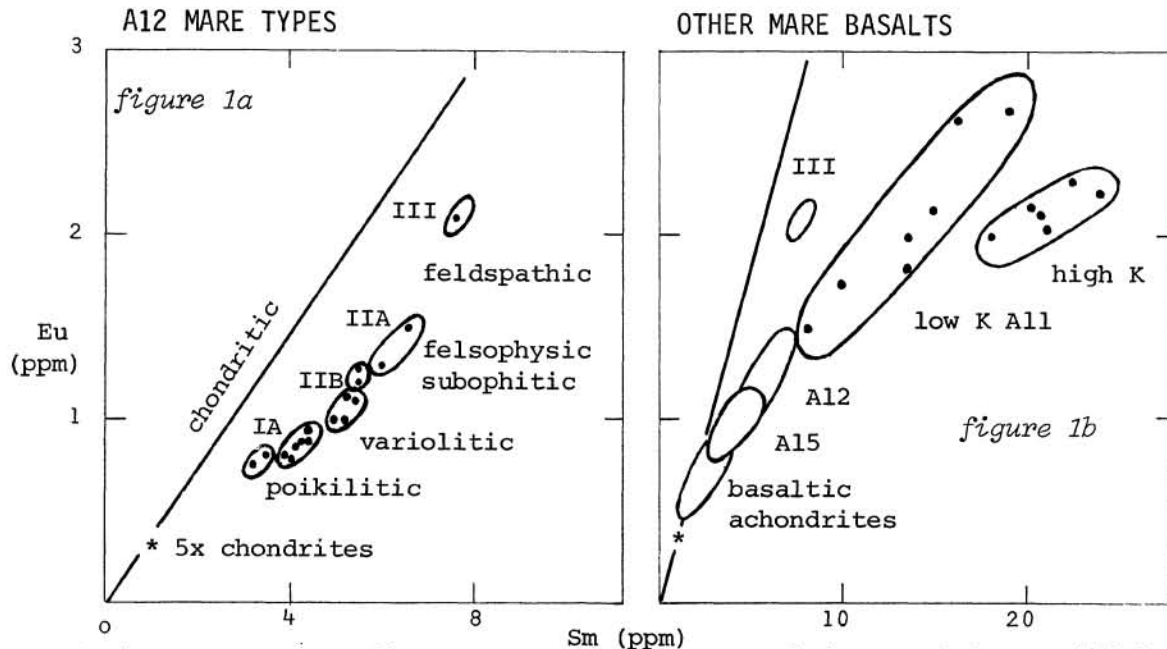REE TRENDS AND RB-SR MODEL AGES IN MARE BASALTS. W. Compston
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Eu anomaly and mare basalt types: The size of the Eu anomaly can be quan-
tified using Eu vs trivalent REE diagrams. Figure 1a shows Eu vs Sm for the
Apollo 12 basalts, in which the Eu anomaly is evident by the location of data
below the chondrite line, with Eu/Sm of the basalts about 0.6 of the chond-
rite values. Figure 1a also emphasizes two points: (A) There is good corres-
pondence between REE contents and textural (1) and petrographic-chemical (2)
classifications of A12 basalts. The A12 subgroups are thought to derive from
separate partial melts from the mantle rather than from one another by low-
or high-pressure crystal fractionation (2). The feldspathic type (12038) has
a smaller Eu anomaly (0.75 chondrites) than the others and may be a plag-
ioclase accumulate. (B) The principal component of REE variation is not
variation in the Eu anomaly but a linear dispersion in abundance along the
"dilution" direction. This trend is accentuated in Figure 1b by the low K
Apollo 11, the Apollo 15 basalts , and basaltic achondrites. It probably
represents a mixing-line between a REE-rich end-member with low Eu/Sm, and
one of low REE content but having Eu/Sm equal to or greater than chondrites.
The A12 feldspathic basalt and A11 high K basalts are seen as special cases.
Point A implies that the REE mixing-line is a property of the lunar mantle.
Both the mixing-line and the Eu anomaly can be well explained using the
Graham-Ringwood model for the mantle and its melting kinetics (3), which
assumes that the average mantle Eu/Sm is chondritic but that trivalent REE
are principally held in accessory mineral phases which selectively enter the
melt, whereas most of the Eu^{2+} is held by Ca-bearing refractory phases. The
REE dispersion between A12 subgroups is probably due to variations of the
modal amount of accessory phases in the mantle, and when the proportion of
melt increases as from the average low K A11 to A15 basalts, the Eu/Sm be-
comes more nearly chondritic. The model has been developed further by Ring-
wood (4) who proposes accessory perovskite for the trivalent REE and refrac-
tory melilite for the Eu.

Origin of old Rb-Sr model ages: Like Eu, the abundance of Sr is depleted
in mare basalts relative to chondrites, presumeably due also to substitution
for Ca^{2+} which will induce correlated changes in Sr, Eu concentrations. There
is fair coherence between Eu and Sr in mare basalts as a whole, much better
coherence within groups, and a clear "Sr anomaly" : evidently the process
which depleted Eu in mare basalts depleted Sr even more strongly. Despite
sampling effects due to the use of tiny rock chips, model Rb-Sr ages of all A
12, A15 and A11 low K mare basalts are close to 4.5 b.y., instead of being
variably younger according to the proportion of Sr retained in the lunar
mantle during the melting process. This observation is difficult to reconcile
with knowledge of partition coefficients for Rb and Sr and with the clear
evidence for the retention of Sr and Eu in the lunar mantle. Three kinds of
hypothesis have been proposed to explain the old model ages: (A) Rb and Sr
were totally extracted (or extracted without change in Rb/Sr) from the mantle
during the (equilibrium) partial melting that formed mare basalts at various
times; the depletion of Eu and Sr in the lunar mantle occurred during an
earlier chemical event at 4.5 b.y. An unsatisfactory feature of this hypoth-
esis is the equal extraction of Rb and Sr: Rb should be enriched in the melt

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A12 MARE TYPES   OTHER MARE BASALTS

figure 1a

III

feldspathic

chondritic

IIA

felsophysic
subophitic

IIB

Eu
(ppm)

IA

variolitic

poikilitic

* 5x chondrites

III

high K

low K A11

A12

A15

basaltic
achondrites

*

figure 1b

o   4   8

Sm (ppm)   10   20

relative to Sr, according to current estimates of the partition coefficients
of these elements.   (B) Rb and its radiogenic ^{87}Sr (plus other low melting-
point components) dating from a 4.5 b.y. chemical event are added to and
dominate the original Rb in various basaltic melts by wall-rock reaction
("contamination"), during the ascent of the magma. The Eu and Sr anomalies
would be relict in the lunar mantle from a 4.5 b.y. event. The classifica-
tion of basalts and the nature of their source in the lunar mantle are
based on major-element chemistry; trace-elements added by contamination
would be irrelevant, at least in terms of describing the mantle source of
mare basalts. However the hypothetical contamination process must add major-
elements as well as trace elements. In documented terrestrial basalts, there
are well-defined correlations of major-elements with alkalais that have
arisen from contamination (5). It is possible that similar correlations are
present in the Apollo 12 basalts, though much less obvious. The A12 pigeon-
ite-basalts (2) have higher SiO_2 relative to TiO_2 than the A12 ilmenite-
bearing basalts; this is matched by their higher Rb/Sr and higher initial
$^{87}Sr/^{86}$. (C) The mare basalts form by non-equilibrium partial melting of a
4.5.b.y. old lunar mantle in which all the Rb and radiogenic Sr are located
in alkali-rich low melting point mineral phases but common Sr in more
refractory phases also. The average mantle has chondritic Eu/Sm but Sm is
concentrated in the low melting-point phases, so that basalts formed by a
low degree of partial melting have a large Eu anomaly. This hypothesis re-
quires that separation between Rb-rich and Sr-rich mineral phases in the
lunar mantle exceeds the diffusion range for Sr, so that radiogenic ^{87}Sr in
the Rb-rich sites does not equilibrate with common Sr. It implies very large
grainsize in the mantle (of the order 1 m) or very low modal abundances of

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the Rb-rich phases and/or Sr-rich phases. It also requires that the melt should be rapidly formed and rapidly removed to avoid Sr isotope equilibration with the refractory Sr-bearing phases in the residue.

The age of the Moon: The ∿4.5.b.y "chemical event" evident from the mare basalts is even more strongly defined by the model ages of some of the soils. It has been widely assumed that this event refers to a period of melting of at least the outer part of the moon that occurred on a global scale. During this period, it has been proposed that plagioclase was floated to form the lunar highlands and to generate the Eu and Sr anomalies in the source regions of the later mare basalts. This is not the only interpretation for the 4.5.b.y. event. It would equally well refer to the pre-lunar chemistry that is registered in chondritic/achondritic material from which the moon accreted. As far as Rb-Sr systematics are concerned, there is no need to melt the moon at 4.5.b.y. to produce old model ages in the mare basalts. Old ages could also be produced from an undifferentiated lunar mantle, and the Eu and Sr anomalies and REE systematics in mare basalts by later non-equilibrium melting. In other words, the time of accretion of the moon is not well constrained by the isotopic data. It will be greater than the oldest mineral ages of rock fragments (∿ 4.2 b.y.?) seen to be derived by post accretion processes (e.g. igneous clasts in impact breccias), but its older limit depends in detail upon theories of lunar origin. If there was an initial period of deep melting on the moon, then this probably occurred at ∿ 4.5 b.y. and accretion was earlier still. On the other hand, accretion would have occurred between the younger limit set by the oldest mineral ages and ∿ 4.5 b.y. as an older limit, in the absence of initial melting.

The low model age of the high K Apollo 11 basalts. The contamination hypothesis (B), easily copes with the high K basalts by assuming wall-rock reaction with a 3.85 b.y. environment. On the Eu vs. Sm plot (figure 1b), the high K basalts lie on a line between low K All basalts and the non-mare KREEP basalts, so that contaminationby KREEP would be a good explanation for their special Eu/Sm and REE concentrations. However, an objection to this is the old model age, 4.4b.y, so far observed for KREEP basalts (6). KREEP-type basalts of model age not greater than 3.85 b.y. are required as the mixing end-member. The non-equilibrium melting hypothesis (C) can also explain the young model age by assuming violation of one or more of its particular constraints. For example, a very low degree of melting may not embrace all the radiogenic Sr that has diffused out of the low-melting phases into nearby Sr-rich phases.

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