

MINOR ELEMENT CHEMISTRY OF MARIA BASALTS
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High pressure-temperature investigations on maria basalts have been used to infer the composition of their source region and conditions of formation (1). It was concluded that maria basalts formed by varying degrees of partial melting of a pyroxenite source region at depths of 200-400 km. The abundances of Ca, Al, and other elements possessing highly involatile oxides, eg. U, Sr, Ba, REE, were believed to be present in the source region at about twice chondritic levels. An acceptable theory of petrogenesis relating maria basalts to their source regions and based upon mineralogy and major element chemistry must also be capable of explaining the minor element chemistry of maria basalts. This objective has been difficult to realize.

The principal minor element characteristics which must be explained are as follows: (A) The abundances of incompatible elements (eg. U, Th, Sr, Ba, REE, Zr, Ta, Li) vary more or less continuously over a tenfold range from 10X chondritic (Apollo 15) to 100X chondritic (Apollo 11, hi K). If Green Glass is included, the total range is twentyfold. (B) Despite this very large range of absolute abundances, the relative abundances within this group rarely deviate from chondritic relative abundances by more than a factor of two. Yet the individual crystal-liquid partition coefficients for elements within this group vary considerably, eg. the coefficients for Yb and U in pyroxene vary by more than 100 (2). (C) Titanium seems to behave as an incompatible element. The Ti/Zr ratios of most maria basalts and Green Glass (except Ap. 17) agree with the chondritic ratio within a factor of two. (D) The magnitude of the Eu (and Sr) anomalies show a general trend to decrease as the absolute abundances of incompatible elements decrease, eg. through the sequence Apollo 11 hi K, Ap. 11 low K, Ap. 14, Ap. 12, Ap. 15, Green Glass. This trend is also one of increasing degree of partial melting (1). (E) Whereas the absolute abundances of most incompatible elements vary by more than tenfold in maria basalts, the abundances of Sr vary only over a threefold range. (F) Many basalts exhibit significant (mostly ≤ 2 fold) depletion of light rare earths relative to intermediate REE. (G) Many maria basalts have Rb/Sr model ages of about 4.5 b.y. whereas their crystallization ages are 3.2 - 3.8 b.y.

Several hypotheses have attempted to explain the above characteristics. One proposes that maria basalts were formed by varying degrees of equilibrium partial melting of a source material containing incompatible elements at several times chondritic levels and in which plagioclase was an important component (eg. 3). This model fails since major element phase equilibria demonstrate that plagioclase was not present in the source region

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of most maria basalts during partial melting (1). Moreover, in view of the very different crystal-liquid partition coefficients for many incompatible elements, it is difficult to explain the small degree of fractionation within this group over a 20-fold total range of absolute abundances. Some previous attempts to achieve this have used doubtful partition coefficients (eg. 4), and postulated mineral assemblages which were not permitted by phase equilibrium data. Finally, the model does not readily explain characteristics C, F and G above.

According to a second hypothesis (eg. 5), maria basalts were formed by equilibrium partial melting of pyroxene-rich cumulates which underlay and were complementary to the highland anorthositic crust. This model can explain the presence of Eu (and Sr) anomalies, the absence of plagioclase on the liquidus of maria basalts, the moderate depletions of the light rare earths and the 4.5 b.y. model ages. There are serious difficulties however. The model does not explain the correlation between the magnitude of the Eu anomaly and the level of abundances of incompatible elements, the inference that the anomaly decreases as the extent of partial melting increases and that for large degrees of partial melting the anomaly almost disappears, implying that the source region of maria basalts did not possess an intrinsic anomaly (1,2). The model also encounters difficulties in explaining characteristics A and B above. It is hard enough to explain these with a single stage of partial melting of relatively primitive material. To propose that patterns A and B above can be explained by partial melting of once-fractionated cumulates is scarcely credible. Moreover, it is difficult to provide acceptable heat sources for melting refractory cumulates. Most of the original U and Th will be in the highland crust, not in the cumulate layer. The high Ti contents of many maria basalts are unexplained since experiments show that Ti is a late-crystallizing component and enters early cumulates only in minor amounts. Other characteristics unexplained by this model are C and E above.

Difficulties with the above bulk equilibrium models suggest exploration of surface or local equilibrium models (2). We propose (a) that the bulk of the incompatible elements in the source region (including Rb, K) are located in accessory minerals. (b) that most of the Eu and common Sr are located initially in a refractory phase and that only limited equilibrium is reached so that most of the radiogenic Sr remains in the low melting accessory Rb, K phase, (c) that during partial melting, the accessory minerals containing the incompatible elements and Sr 87 enter the first increment of liquid in toto. This increment is immediately segregated from the system. With further degrees of

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melting, this liquid is diluted by major elements from the pyroxenite source whilst Eu and Sr are contributed by partial melting of the refractory phase.

An early version of this model proposing that the trivalent REE were contained in accessory phosphates whereas Sr and Eu were partitioned in pyroxenes explained in principle, characteristics A,B,D,E and G above (2). However C was unexplained and this version of the model requires modification. An extended hypothesis is presented below.

We consider that the moon accreted from material which had ultimately formed by fractional condensation from a gas phase of appropriate composition. The essential members of the condensation sequence with falling temperature were perovskite, melilite, forsterite, enstatite, alkali feldspar (6). As the gas cooled over an extended period (> 100 years) large megacrysts (> 1 metre) were formed. Trace elements were partitioned into these phases according to equilibrium condensation and crystal chemical relationships. The following predictions can be made on these grounds: trivalent REE would mainly enter perovskite, most of the Eu and Sr would enter melilite together with an appreciable proportion of light REE, Rb would enter alkali feldspar. The moon accreted from a mixture of these condensates to form a disequilibrium mineral assemblage with a bulk composition similar to that of the pyroxenite source region of maria basalts (1).

After heating deep in the lunar interior, solid state reaction occurred around megacryst boundaries to form an equilibrium pyroxenite (1) containing large unreacted cores of refractory melilite (or its high pressure derivatives) and perovskite. The latter mineral readily forms low melting point liquids when in contact with pyroxenes whereas melilite remains relatively inert. As partial melting commenced, all the perovskite and other low melting phases (eg. alk. feldspar) entered the first liquid which thereby received most of the incompatible elements (except Eu, Sr) present in the source region. This liquid was withdrawn as in the earlier model and diluted by liquids resulting from further degrees of partial melting of the equilibrium pyroxenite. Refractory melilite cores were gradually consumed, thereby supplying relatively constant amounts of Eu and Sr to liquids so produced. It is suggested that this model, in principle, is capable of explaining characteristics A,B,C,D,E,F,G above. REFERENCES: (1) A.E. Ringwood & D. Green, This volume page - . (2) A. Graham & A. Ringwood, Earth Planet. Sci. Lett. 13, 105, 1971. (3) P. Gast et al. Proc. Apollo 11 Lunar Sci. Conf. 2, 1143, 1970. (4) P. Gast The Moon, 5, 1972 (5) Schnetzler & Philpotts, Proc. 2nd Lunar Sci. Conf. 2, 1101, 1971, (6) L. Grossman, Geochim. Cosmochim. Acta. 36, 597, 1972.