

PETROGENESIS OF LUNA 16 ALUMINOUS MARE BASALTS

M.-S. Ma and R. A. Schmitt

Department of Chemistry and the Radiation Center
Oregon State University, Corvallis, OR 97331

R. L. Nielsen*, G. J. Taylor, R. D. Warner and K. Keil

Department of Geology and Institute of Meteoritics
University of New Mexico, Albuquerque, NM 87131

Abstract. Bulk compositions, petrology and mineralogy of > 0.5 mm Luna 16 aluminous mare basalt particles are described. The data rule out any close genetic relationships between Luna 16 and other major types of lunar mare basalts. Compared to high-Ti mare basalts, the Luna 16 basalts contain lower TiO_2 (5.1 wt %) and Ta (\sim 0.8 ppm) and higher Al_2O_3 (13.3 wt %) and REE (\sim 30-70X chondrites) abundances, suggesting that the Luna 16 source rocks crystallized later than (i.e. stratigraphically above) the ilmenite-bearing high-Ti basalt cumulate source rocks. The REE pattern for the Luna 16 basalts requires that the source material from which they were derived crystallized from a light REE enriched magma.

Introduction

Aluminous mare basalts are the dominant lithology at the Luna 16 landing site in Mare Fecunditatis (Vinogradov, 1971; Albee et al., 1972; Keil et al., 1972; Reid et al., 1972; Kurat et al., 1976). The Luna 16 basalts characteristically have high Al_2O_3 contents (> 13 wt %), intermediate TiO_2 contents (\sim 5 wt %), low CaO/ Al_2O_3 (0.8-0.9), and high FeO/MgO (3-4) compared to most other mare basalts, indicating derivation from a perhaps distinctly different source region. The precise nature of the Luna 16 source region has remained uncertain, however, due to a paucity of trace-element and pertinent high-pressure phase equilibria data. This in turn has hampered the formulation of credible models for the petrogenesis of Luna 16 aluminous mare basalts.

In order to shed more light on the nature of the Luna 16 mare basalt source region, we studied 8 hand-picked batches of > 0.5 mm Luna 16 particles. Abundances of major and trace elements were measured by instrumental neutron activation analysis (for experimental techniques see Wakita et al., 1970 and Laul and Schmitt, 1973), and textures and mineral compositions were determined by optical microscopy and electron microprobe analysis of polished thin sections made from the neutron-irradiated samples. The results show that three samples are mare basalts, three are predominantly soil

breccias, and two are impact melts. This paper concerns only the basalts; the soil breccias and impact melts are described by Ma et al. (1979).

Textures and Mineral Compositions

Samples 21013,3 and 21013,8 consist entirely of mare basalt particles. Sample 21003,6 contains \sim 5% agglutinate and soil breccia material, but is predominantly mare basalt. None of the basalt fragments in these samples contains angular clasts or other features that would suggest an origin by impact melting.

The basalts are fine-grained (crystals are smaller than 20 μ m) and have ophitic to subophitic textures. They consist mainly of pyroxene and plagioclase, with smaller amounts of olivine and ilmenite. Microphenocrysts of plagioclase and olivine are rare. Minor phases include Cr-ulvospinel, fayalite, pyroxferroite, silica (probably cristobalite), a phosphate phase, troilite, K-feldspar, and a high-Si-K glass. In general, the order of crystallization appears to have been Cr-ulvospinel followed by olivine, then coprecipitation of ilmenite, pyroxene, and plagioclase.

Compositional zoning trends are similar to those reported previously (Albee et al., 1972; Kurat et al., 1976; Bence et al., 1972; Grieve et al., 1972). Concentrations of Ti, Al and Cr are high in early clinopyroxenes, but decline rapidly with increasing Fe/(Fe+Mg). On the other hand, element ratios such as Ti/(Ti+Cr) (Ma et al., 1979) and Ti/(Al+Cr) (Kurat et al., 1976) are almost constant for all pyroxenes. Olivine compositions range from Fe_{38} to Fe_{68} , with one analysis at Fe_{18} . Plagioclase varies in composition from An_{81} to An_{94} . Fe/(Fe+Mg) in ilmenite ranges from 0.911 to 0.996.

Bulk Compositions

The basalt samples have nearly identical major-element compositions (Table 1). Although minor differences occur, the results are similar to those reported previously for Luna 16 basalts (Vinogradov, 1971; Kurat et al., 1976; Helmke and Haskin, 1972; Philpotts et al., 1972). REE abundances (Fig. 1) are also similar to those reported previously (Helmke and Haskin, 1972; Philpotts et al., 1972); chondrite-normalized abundances are characterized by bow-shaped REE patterns with negative Eu anomalies. Light REE are fractionated less than heavy REE.

*Current address:

Department of Geological Sciences
Southern Methodist University
Dallas, TX 75275

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Table 1. Element abundances in Luna 16 basalts^a

Sample No.	21003,6	21013,3	21013,8
Wt. (mg)	4.6	5.8	4.5
TiO ₂ (%)	5.0	5.3	5.1
Al ₂ O ₃	13.4	13.3	13.3
FeO	18.0	18.6	19.1
MgO	7	6	6
CaO	11.9	11.9	11.7
Na ₂ O	0.513	0.510	0.554
K ₂ O	0.18	0.20	0.21
MnO	0.252	0.260	0.261
Cr ₂ O ₃	0.238	0.217	0.205
Sc ^{2,3} (ppm)	69	69	61
V	89	79	62
Co	17	17	17
Ba	470	290	320
La	20.4	18.3	19.8
Ce	52	51	56
Nd	40	42	48
Sm	12.5	13.4	15.4
Eu	3.26	3.25	3.74
Tb	2.4	2.4	2.8
Dy	15	16	18
Yb	7.2	8.2	9.1
Lu	1.02	1.17	1.28
Hf	11.1	11.0	11.6
Ta	(1.2)	0.6	0.5
Th	2.4	1.5	1.9

^aEstimated errors due to counting statistics are, Al₂O₃, FeO, Na₂O, MnO, Cr₂O₃, Sc, Co, La and Sm, ± 1-5%; TiO₂, CaO, V, Hf, Eu, Yb and Lu, ± 5-10%; MgO, K₂O, Th, Ta, Ba, Ce, Nd, Tb and Dy, ± 10-25%.

Discussion

The uniform compositions of the three basalt fragments suggest that each represents a reasonable average composition for Luna 16 aluminous mare basalts. A few differences with previous

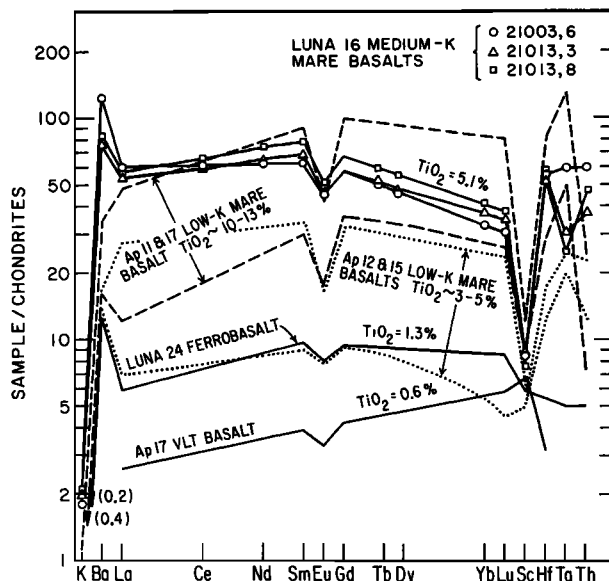


Fig. 1. Trace element abundances in three samples of Luna 16 mare basalts. Fields for other types of mare basalts are shown for comparison.

results appear, but these are minor and are not systematic. We assume that our results reflect the composition of the average mare basalt present at the Luna 16 landing site.

In the following paragraphs we explore the possible relationships, if any, between Luna 16 and other mare basalts. The incompatible trace element patterns of the major types of mare basalts (Fig. 1) and their average chemical compositions compiled by Ma and Schmitt (1979) are used as a basis for the following discussion.

Fractional Crystallization

One possibility is that the Luna 16 basalts are either derived from or are parental to a magma compositionally similar to another type of mare basalt. This can be ruled out unambiguously: no combination of fractionation of major mineral phases produces the observed compositional characteristics of Luna 16 basalts, particularly the combination of intermediate TiO₂, low CaO/Al₂O₃, high Sm/Lu and high total REE.

Partial Melting

Derivation of Luna 16 basalts by partial melting of the same or similar source material that melted to form one of the other types of mare basalts can also be eliminated as a possibility. We outline specific objections below.

The hypothesis that the Apollo 11 and 17 low-K, high-Ti mare basalts formed from a source region similar to that of the Luna 16 basalts, only with higher degrees of partial melting to yield their lower Rb and K₂O contents (~ 3 times lower than in Luna 16 basalts) fails totally because of inconsistencies in the contents of other incompatible trace elements. For example, the REE(Sm-Lu) contents of the high-Ti basalts fall in the range of those in Luna 16 basalt and Ta in the high-Ti basalts is higher by a factor of ~ 2 than in Luna 16 basalt. The less fractionated light REE pattern and the much more fractionated heavy REE pattern of the Luna 16 basalts also demonstrate that these basalts could not have formed from the same source as the high-Ti basalts.

The source region for the Luna 24 VLT mare basalts also cannot be similar to that for the Luna 16 basalts. To produce the factor of almost 10 difference in REE contents (Fig. 1) requires, if the two source regions were similar, approximately a factor of 10 difference in the percentage of partial melting. This is inconsistent with the nearly identical Fe/(Fe+Mg) (~ 0.6) in the two types of basalt.

The unique REE pattern of the Apollo 17 VLT mare basalts, characterized by Sm/Lu of < 1 (Fig. 1), clearly rules out a genetic relationship between these basalts and those from Luna 16. No combination of source mineralogy and melting mode can produce such vastly different magmas by either fractional or batch-equilibrium partial melting.

The low-Ti mare basalts also must have had source material different from that which produced the Luna 16 mare basalts. If the source

rocks are assumed to be similar, comparison of the REE abundances (Fig. 1) indicates that the Luna 16 magmas would have formed at factors of 2-4 times smaller degrees of partial melting than did the low-Ti basaltic magmas. However, such differences in the degree of partial melting would not be expected to produce the factor of 2-3 difference in the abundances of such compatible minor and trace elements as V, Cr, and Co between the Luna 16 and the low-Ti basalts (V = 77 ppm, $\text{Cr}_2\text{O}_3 = 0.22$ wt % and Co = 17 ppm in Luna 16 basalts vs. V = 130-250 ppm, $\text{Cr}_2\text{O}_3 = 0.49-0.56$ wt % and Co = 50 ppm in low-Ti basalts). This is because the bulk partition coefficients for these elements in most of the assumed residual minerals such as olivine, orthopyroxene, and clinopyroxene are greater than or close to unity. Moreover, the similarity in P_2O_5 abundance between the Luna 16 (~ 0.11 wt %) and the low-Ti Apollo 12 and 15 mare basalts (0.05-0.12 wt %) contrasts sharply with the large difference (average factor of ~ 4) observed in the abundances of the incompatible trace elements K and La between the Luna 16 and the low-Ti mare basalts. Again, because of the low partition coefficients of P, K and La in major residual minerals ($D \leq 0.1$), and because accessory P minerals are expected to melt in the earliest stages, these elements will be concentrated in the first partial melt. We therefore conclude that the trace element data support the concept of different source materials for the Luna 16 and the low-Ti basalts.

Nature of the Luna 16 Source

The above considerations show that the Luna 16 magmas were produced from source rocks that differed significantly from the source material that yielded the other mare basalts. However, in spite of the differences, the sources of all mare basalts, except possibly for Apollo 17 VLT mare basalts (Wentworth et al., 1979), had one feature in common: they appear to have crystallized from fractionated (nonchondritic) magmas (Nyquist et al., 1977). The evidence for this derives mostly from the negative slope of the heavy-REE pattern. Luna 16 mare basalts are the extreme case, having the steepest negative slope of any of the mare basalts (Fig. 1).

The mineralogy of the Luna 16 source region is not known because high pressure phase equilibria data is not available for the Luna 16 basalt compositions. We can, however, make a reasonable estimate of the source mineralogy based on the bulk compositions of the Luna 16 basalts. The high Al_2O_3 contents and low $\text{CaO}/\text{Al}_2\text{O}_3$ ratios in the Luna 16 basalts suggests that plagioclase was present in the source rocks (although this is not absolutely essential: see Ridley, 1975). Because plagioclase and clinopyroxene are thought to have coprecipitated in the lunar magma ocean (e.g., Drake, 1976), clinopyroxene was probably also a major constituent of the source. Olivine and orthopyroxene may also have been present, but the REE pattern of the source and the melt derived from it would have been dominated by plagioclase and clinopyroxene.

Assuming a Luna 16 source region composed

predominantly of plagioclase and clinopyroxene with minor amounts of olivine plus orthopyroxene, we calculated the REE pattern expected for such a source. In our calculations we varied the proportions of plagioclase and clinopyroxene (from 5-40 % and 55-25%, respectively) in the hypothetical Luna 16 source rocks. We also investigated two cases for the overall slope of the source's REE pattern: (1) the source rocks crystallized from a magma with unfractionated REE abundances (= initially flat REE pattern); and (2) the source rocks crystallized from a magma with a light-REE enriched pattern (following Nyquist et al. (1977) we chose (La/Lu) c.n. in the initial liquid to be 2). The resulting REE patterns for the source are all bow-shaped and have either positive or negative Eu anomalies, depending on the plagioclase content. However, we found that the pronounced negative slope of the heavy REE's could be produced only if the source minerals had crystallized from a fractionated, heavy-REE depleted magma, in agreement with the observations made by Nyquist et al. (1977).

The degree of partial melting involved in generating the Luna 16 basaltic magmas can be estimated by determining the relative fractionation (F) of Rb from Sr that occurred upon melting of the source rocks to form the magmas. This can be calculated by using equation (2) of Shih et al. (1975) and the Rb-Sr data for Luna 16 basalts reported by Papanastassiou and Wasserburg (1972). The resulting number for the relative fractionation in the Rb/Sr ratio between the Luna 16 basaltic magma and its source is $F = 2.3$, which corresponds to 15-30% partial melting for the source mineralogies discussed above. However, the uncertainty in the Rb/Sr relative fractionation is large (F could be as low as 1.4 or as high as ~ 5), so that the above estimate of the extent of partial melting is poorly constrained.

Conclusion

We conclude that the Luna 16 basalts were derived by $\sim 15-30\%$ partial melting of a cumulate source rich in clinopyroxene and plagioclase. To generate the relatively high abundance of REE in Luna 16 basalts, we estimate that the Luna 16 cumulate source minerals crystallized late in the history of the lunar magma ocean, perhaps after $\sim 99\%$ of it had crystallized. The cumulates may have been laid down above those from which the high-Ti basalts were derived. This conclusion is based on the lower TiO_2 and Ta contents in Luna 16 basalts compared to high-Ti basalts, which can be attributed to removal of these elements from the magma ocean by the crystallization and sinking of ilmenite.

Acknowledgments

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