TITLE

PETROGENESIS OF LUNAR ROCKS: Rb-Sr CONSTRAINTS AND LACK OF H_2O

ARDEN L. ALBEE AND ALEXANDER J. GANCARZ

201

A Preprint of a Manuscript from

THE PROCEEDINGS OF THE SOVIET-AMERICAN CONFERENCE ON THE COSMOCHEMISTRY OF THE MOON AND PLANETS

HELD IN MOSCOW, USSR, ON JUNE 4–8, 1974

(NASA-CR-142007) PETROGENESIS OF LUNAR ROCKS: Rb-Sr CONSTRAINTS AND LACK OF H2O (California Inst. of Tech.) 24 p CSCL 03B
N75-16439
Unclas
G3/90 08530

Distributed by

THE LUNAR SCIENCE INSTITUTE
HOUSTON, TEXAS 77058

TO MAKE THE INFORMATION CONTAINED HEREIN AS WIDELY AND AS RAPIDLY AVAILABLE TO THE SCIENTIFIC COMMUNITY AS POSSIBLE. NASA EXPECTS TO PUBLISH THE ENGLISH-LANGUAGE VERSION OF THE PROCEEDINGS IN LATE 1975. THE FINAL TEXT MAY INCLUDE MINOR EDITORIAL CHANGES IN FORMAT, etc.

JOHN H. POMEROY, NASA HEADQUARTERS
TECHNICAL EDITOR

PETROGENESIS OF LUNAR ROCKS: Rb-Sr CONSTRAINTS AND LACK OF H_2O

Arden L. Albee and Alexander J. Gancarz
Division of Geological and Planetary Sciences*
California Institute of Technology
Pasadena, California 91109, U.S.A.

---

*Contribution number 2474.

ABSTRACT

Rb and Sr isotopic data and other chemical data indicate major lunar differentiation at about 4.6 AE and very limited subsequent differentiation. The constraintsof limited differentiation post 4.6 AE and the apparent lack of H_2O on the moon, when applied to the derivation and petrogenesis of lunar samples, suggest the following: 1) soil samples, breccias, metaclastic rocks, and feldspathic basalts represent mixtures of repeatedly-modified clastic material, which was ultimately derived from materials formed during the ~4.6 AE differentiation; 2) mare basalts crystallized from melts which formed by partial melting and, which developed without equilibration between the melt and crystalline residuum.

I. Introduction

Rb- Sr mineral isochrons currently provide the basic chronology of lunar evolution (Albee et al., 1970a, 1970b, 1974; Papanastassiou et al., 1970; Papanastassiou and Wasserburg, 1970, 1971a, 1971b, 1972a, 1972b, 1972c, 1973; Tera et al., 1974a, 1974b, Wasserburg and Papanastassiou, 1971). Rb/Sr data also impose rigorous constraints on lunar petrogenetic models. This paper will discuss these constraints, emphasize the important role of large scale differentiation which occurred at about 4.6 AE ($AE \equiv 10^9$ years) and show that only limited chemical fractionation occurred during the subsequent evolution of most lunar rocks. Regardless of other types of evidence, no petrogenetic theory for the origin of lunar rocks can invoke extensive fractionation later than about 4.6 AE as a dominant part of the theory. The lack of H_2O on the moon may be the critical physical-chemical factor limiting subsequent fractionation in many processes.

II. Rb-Sr systematics and fractionation factors

Measurements of the isotopic abundance of Rb and Sr in the various mineral phases of a rock provide information not only on the time of crystallization and equilibration (T_x), but also on the fractionation history of the rock prior to this most recent crystallization and equilibration. As illustrated on Figure 1, cogenetic systems, either consanguineous total-rocks or the various minerals in a single rock, attain identical values of $^{87}Sr/^{86}Sr$, but during equilibration at T_x different values of $^{87}Rb/^{86}Sr$. On the Rb-Sr evolution diagram these different compositions subsequently evolve along straight line trajectories with a slope of -1. If the systems were closed to gain or loss of Rb and Sr since T_x, then the cogenetic systems measured at any time form a linear array on the Rb-Sr evolution diagram. An array based on minerals from a single rock is a mineral or internal isochron and one based on cogenetic rocks is a total-rock isochron. The isochron has a slope indicative of the time since equilibration (slope= $\exp(\lambda T_x-1)$) and a $^{87}Sr/^{86}Sr$ intercept, $(^{87}Sr/^{86}Sr)_I$, equal to the Sr isotopic composition at time T_x (Lanphere et al., 1964).

The deviation of $(^{87}Sr/^{86}Sr)_I$ from that assumed to have existed at some time prior to T_x coupled with the $^{87}Rb/^{86}Sr$, provide an integrated measure of the Rb/Sr fractionation history of the rock. This fractionation history can be parametrized by a two-stage model as illustrated in Figure 1. The model assumes that a source material originated at reference time $T_o = 4.6$ AE with the "BABI" value of $^{87}Sr/^{86}Sr$ ($(^{87}Sr/^{86}Sr)_{BABI} = 0.69898$) (Papanastassiou and Wasserburg, 1969). Fractionation at time T_x resulted in three fractions, one enriched in Rb relative to Sr, one unfractionated, and one depleted in Rb relative to Sr. Mineral isochrons on all three rocks would yield identical ages (T_x) and the same $(^{87}Sr/^{86}Sr)_I$. However, they would have different model ages, T_{BABI}, which is the time required for the $^{87}Sr/^{86}Sr$ of the total rock with its measured $^{87}Rb/^{86}Sr$ to evolve from $(^{87}Sr/^{86}Sr)_{BABI}$. The unfractionated rock will have $T_{BABI} = 4.6$ AE, the enriched rock will have $T_{BABI} < 4.6$ AE and the depleted rock will have $T_{BABI} > 4.6$ AE. Thus, any deviation of T_{BABI} from 4.6 AE indicates a fractionation history prior to T_x.

The fractionation factor for this two-stage model is (Papanastassiou and Wasserburg, 1972c):

$$K_D \equiv \frac{(^{87}Rb/^{86}Sr)_2}{(^{87}Rb/^{86}Sr)_1} \cong \frac{T_o - T_x}{T_{BABI} - T_x}$$

This approximation is quite accurate since the decay constant for Rb is small. During the time interval from T_o to T_x numerous episodes of fracitionation could have affected the rock as opposed to the simple two-stage model illustrated. However, $(^{87}Rb/^{86}Sr)_1$ is still the integrated $^{87}Rb/^{86}Sr$ in the interval from T_o to T_x.

As noted previously $T_o = 4.6$ AE and $(^{87}Sr/^{86}Sr)_{T_o} = 0.69898$ are reference values, and the subsequent conclusions drawn in this paper are basically independent of their precise value. In fact, the time of major differentiation is probably not 4.6 AE, but may be as low as 4.5 AE or even 4.4 AE (Tera *et al.*, 1974b).

III. Lunar rock groups

On the basis of petrologic characteristics seven different groups of lunar rocks are recognized. Each of these groups has a distinctive Rb-Sr isotopic pattern. The Rb-Sr data are summarized on Fig. 2, which shows T_x, T_{BABI}, and K_D for representative members of each group. Most of the type examples shown are those on which we have made detailed petrographic and electron probe studies in conjunction with the Rb-Sr isotopic studies of Papanastassiou and Wasserburg. Figure 2 indicates that six of these groups are characterized by T_{BABI} close to 4.6 and $K_D < 2$. The seven groups are as follows:

1) Soils with $T_{BABI} = 4.6 \pm 0.3$ AE

Clots from the soil samples and friable soil-breccia samples, as well as bulk soil samples, have model ages of about 4.6 AE. This group includes samples from all landing sites and has a wide range of Rb/Sr (Papanastassiou and Wasserburg, 1972c). To a large extent many of these model ages are dominated by a small fraction of very high Rb/Sr material with a model age of about 4.6 AE (Papanastassiou and Wasserburg, 1972c).

2) K-rich fragments with T_{BABI} = 4.3 to 4.6 AE

These fragments, the so-called "KREEP" rocks (Hubbard et al., 1971), include glass-rich agglutinates and metaclastic rocks, and have been found in the soils at all landing sites. Most are small fragments such as Luny Rock 1 (Albee and Chodos, 1970), and no internal isochrons have been measured on them. Nyquist et al. (1973), however, showed that by grouping such fragments by chemical composition and location, Rb and Sr data yield linear arrays, which, if interpreted as total-rock isochrons, indicate ages ranging from 4.1 to 4.4 AE. Sample 12013 is the only large sample which we would place in this group. It is a heterogeneous metaclastic rock with K, Th, and U concentration a factor of forty greater than typical mare basalts and a factor of ten greater than Apollo 11 K-rich basalts (Anderson, 1970). Fragments of 12013 have a model age of 4.52 AE and a recrystallization age (T_x) of 4.01 AE (Albee et al., 1970b).

3) Metaclastic rocks with $T_x \approx 3.95$ AE and $T_{BABI} \approx 4.5$ AE

This group includes a large proportion of the Lunar Highlands samples and also constitutes a large proportion of the lithic fragments in soil samples from all landing sites. These clastic rocks, composed predominantly of plagioclase, have been extensively recrystallized by metamorphic and/or partial melting processes (Albee et al., 1973). Typical examples are 65015 and 76055, both of which display isotopic and petrologic evidence for extensive, but not complete equilibration at 3.95 AE (Albee et al., 1973; Papanastassiou and Wasserburg, 1972c; Tera et al., 1974b; Jessberger et al., 1974) Step-wise heating $^{40}Ar-^{39}Ar$ studies on 65015 suggest that the cores of the larger plagioclase clasts have an age greater than 4.46 AE (Jessberger et al., 1974). This is also suggested by Rb-Sr isotopic data (Papanastassiou and Wasserburg, 1972c).

4) Feldspathic basalts with $T_x \approx 3.85$ AE and $T_{BABI} \approx 4.3$ AE

This group includes a number of samples of intersertal, plagioclase-rich basalts from the Apollo 14 and 16 landing sites (e.g., 14310, 14276 and 68415). In addition to the high plagioclase content (60 to 80%) they are characterized by high K, rare earth element, P, Ba, U and Th contents (Gancarz et al., 1972), and a high content of siderophile elements, (Morgan et al., 1972). Even in these rocks, which almost certainly crystallized from a melt, plagioclase grains are present which, on the basis of electron probe data, have not completely equilibrated with the melt (Gancarz et al., 1972). $^{40}Ar-^{39}Ar$ studies also indicate older relict plagioclase and provide evidence for an older event (Huneke et al., 1972b, 1973).

5) Mare basalts with $T_x = 3.16$ to 3.95 AE and $T_{BABI} = 4.1$ to 5.0 AE

This group includes all of the mare basalts with the exception of those in Group 6. Samples from each landing site have similar T_x and T_{BABI}, but $(^{87}Sr/^{86}Sr)_I$ values and trace element concentrations differ for samples from an individual landing site (Papanastassiou and Wasserburg, 1971a, 1973; Tera et al., 1974a, 1974b; Schmitt and Laul, 1973). This suggests derivation of individual samples (and flows) from different sources (Schmitt and Laul, 1973) or differing degrees of assimilation of country rock (Papanastassiou and Wasserburg, 1971a).

Typical well-characterized samples from the various landing sites include:

10044 (Agrell et al., 1970; Albee et al., 1970a; Turner, 1970),

12040 (French et al., 1972; Reid et al., 1973; Papanastassiou and Wasserburg, 1971a),

14053 (Gancarz et al., 1971; Papanastassiou and Wasserburg, 1971b; Turner et al., 1971),

15682 (Dowty et al., 1973; Papanastassiou and Wasserburg, 1973),

75055 (Albee et al., 1973; Tera et al., 1974b; Huneke et al., 1973),

and Luna 16, B-I (Albee et al., 1972; Papanastassiou and Wasserburg, 1972a; Huneke et al., 1972a).

6) Mare basalts with T_x=3.65 AE and T_{BABI}=3.85 AE

Although grossly similar to the Apollo 11 low-K basalts included in Group 5, these samples from the Apollo 11 landing site are higher in K and other incompatible elements, and have much younger model ages. A typical well-characterized example is 10017 (Adler et al., 1970; Albee et al., 1970a; Turner, 1970).

7) "ANT" rocks with T_{BABI} = 4.6 AE

The "ANT" rock suite includes the coarse-grained rocks of the anorthosite-norite-troctolite-dunite suite. In general they display magmatic cumulate textures, but are extensively modified by shock processes. Dunite sample 72417 has both an isochron age and a model age of about 4.6 AE (Albee et al., 1974). No mineral isochron ages have been measured on anorthosite samples such as 15415 (James, 1972; Turner, 1972) or on troctolite samples such as 76535 (Gooley et al., in press). However, low $^{87}Sr/^{86}Sr$ ratios indicate that these rocks cannot have equilibrated and resided in a higher Rb/Sr environment for any extended length of time (Wasserburg and Papanastassiou, 1971; Papanastassiou, personal communication).

IV. Nature of major differentiation at ∿4.6 AE

Many types of chemical, isotopic and physical evidence are consistent with the hypothesis of primitive, large-scale, crustal differentiation (Albee et al., 1970a; Ringwood and Essene, 1970; Smith et al., 1970; Wood et al., 1970). The presence of a "magic component" (Papanastassiou and Wasserburg, 1970) with T_{BABI} of 4.6 AE and a high $^{87}Rb/^{86}Sr$ which dominates the model age of many lunar soil samples indicates that this differentiation occurred at about 4.6 AE and produced rocks with very high Rb/Sr ratios. The existence of high Rb/Sr material with relatively old model ages was confirmed by the discovery of the K-rich rock 12013 (Albee et al., 1970b) and other fragments (Albee and Chodos, 1970; Hubbard et al., 1971). The existence of material complementary to the Rb/Sr rich material is indicated by dunite sample 72417, which has crystallization and model ages of 4.6 AE (Albee et al., 1974).

Rb-Sr data also indicate that, only limited fractionation occurred, subsequent to the primitive differentiation, and furthermore suggest that most of the observed chemical characteristics were produced during the primitive differentiation. That most of the chemical differences observed in the lunar rocks are consistent with primitive differentiation at ∿4.6 AE rather than subsequent fractionation processes is illustrated in Figure 3. Sm/Eu, a parameter sensitive to fractionation, varies by a factor of ∿200, whereas K_D, a measure of fractionation after the differentiation at ∿4.6 AE, varies only by a factor of about 2. The strong fractionation indicated by Sm/Eu must have occurred prior to the time of crystallization. Although neither K_D nor Sm/Eu are particularly sensitive to olivine or Ca-poor pyroxene fractionation, both are extremely sensitive to fractionation of plagioclase or of late stage K-rich material. The large range of Rb/Sr observed between samples, approximately a factor of

1000, is comparable to the range of Sm/Eu. Hence, we conclude that the Sm/Eu differences must have been a characteristic of the source from which the rocks were derived and that most chemical differences in lunar rocks are a result of primitive differentiation at about 4.6 AE.

Regardless of physical details, this primitive differentiation process resulted in a fraction rich in K (Rb, Ba, U, Th, trivalent rare earth elements, a Ca-Al-Si rich fraction (anorthosite and anorthositic gabbro), and a Mg-Fe rich fraction (dunite, troctolite, and norite). Samples of the Ca-Al-Si rich fraction and the Mg-Fe rich fraction have survived subsequent excavation by meteorite impact, but exhibit a wide range of modification. Less-modified samples suggest that these fractions cooled slowly enough to produce rocks with coarse-grained, homogeneous phases. The original nature of the K-rich fraction is not clear as no samples have been recognized which have not been extensively modified.

V. Possible petrogenetic processes involving limited fractionation

The Rb-Sr constraint on the amount of fractionation, as well as constraints imposed by many other kinds of data, are satisfied if we hypothesize that soils, glass-agglutinate fragments, friable breccias, and progenitors of metaclastic rocks and feldspathic basalts (Groups 1-4) are all basically mixtures of clastic material, which have been subsequently modified by a variety of processes, including fragmentation, metamorphism, partial melting and complete melting. Rb and Sr would not be fractionated if the formation of the clastic mixture involved only fragmentation of preexistent rocks from one or many sources; even if fragmentation occurred repeatedly over a long period of time. Consequently, if the source regions of a clastic mixture are primary, unmodified materials formed during the primitive differentiation at∿4.6 AE, or if they themselves are clastic mixtures repeatedly modified either by continued fragmentation and mixing, or by processes characterized below, then Rb and Sr will remain unfractionated and the model age of the mixture will still reflect the time of primitive differentiation.

Preservation of the old model age of such a mixture would be accomplished during subsequent modification by processes with the following characteristics, even if repeated many times:

1) Volatile loss of Rb was in general not significant.

2) Metamorphism, in the absence of H_2O, was strictly controlled by solid-state and grain-surface diffusion and resulted in lithification by sintering at grain boundaries with only short-range migration and limited segregation of elements.

3) Partial melting in the metaclastic rocks of Group 3 and in the K-rich fragments of Group 2, was characterized by extensive reaction between an interstitial melt and larger clastic grains. Lack of Rb-Sr fractionation dictates very limited mobility of the melt and only short-range migration of elements within the melt. These characteristics can be partially attributed to the absence of H_2O and to the fine-scale homogeneity of the fragmental mixture. Local segregation of Rb-rich material and partial Sr equilibration is suggested by the Rb/Sr data of Nyquist et al., (1973) on small chemically-defined groups of samples from single sites. The Rb/Sr data on these samples have been interpreted as total-rock isochrons representing distinct events at times ranging from 4.1 AE to 4.4 AE. These may alternatively be interpreted as the result of local segregation of K-rich, Rb-rich material without total Sr equilibration at 3.95 AE.

4) Impact-produced melts, which formed by nearly total melting of soil,

breccia, or metaclastic rocks, crystallized as the feldspathic basalts of Group 4. Such an origin would preserve the old model age of the source and would satisfy several other geochemical constraints on these rocks, such as the high content of siderophile elements. However, the Rb-Sr constraint could also be satisfied if these rocks formed by partial melting of plagioclase-rich source rocks with the additional restrictions described below for mare basalts.

The Rb-Sr restraint limiting fractionation is satisfied if the ultimate source of the clastic mixture formed during the large-scale differentiation at ∿ 4.6 AE. If the modification process or processes retain the characteristics described above, or if modification is a simple fragmentation process, then fractionation does not basically occur and old model ages are preserved. This is true regardless of either the order or the number of times this clastic mixture is modified.

Mare basalts with near 4.6 AE model ages (Group 5) must also have been derived without substantial fractionation of Rb and Sr, either during formation of the parent magma or during the ascent and crystallization. All other chemical parameters suggestive of a greater degree of fractionation must be a characteristic of the source region. The origin of the mare basalts is further restricted by the $(^{87}Sr/^{86}Sr)_I$ values, which suggest that rocks of the same age were derived from a number of different sources. A magma meeting these requirements could be produced by several mechanisims (Gancarz et al., 1972):

1) Total melting of a source rock which has a Rb-Sr model age of 4.6 AE and also meets all other chemical and isotopic constraints would form a rock satisfying the Rb-Sr constraints. Although total melting is generally regarded as an unlikely terrestrial event, it is possible that, in the absence of H_2O and tectonic activity, instability and separation of a melt from a source region would be delayed until complete melting occurs. Total melting could

also occur as a result of impact processes.

2) Uniform contamination of relatively low Rb/Sr melts by assimilation of Rb-rich crustal material with a model age of 4.6 AE is the mechanism invoked by Papanastassiou and Wasserburg (1971a).

3) Our preferred hypothesis is that, in the absence of H_2O, partial melting occurs by incremental melting of integral volumes of solid phases with little or no equilibration between melt and crystalline residuum. Thus, the low-temperature phases rich in Rb and ^{87}Sr would melt totally and grains of higher-temperature phases would melt peripherally, but the solid residuum would not equilibrate with the melt. As pointed out by Graham and Ringwood (1971), the resulting melt would have the same model age as the source region. Any crystallization and separation of Ca-rich pyroxene and/or plagioclase during the ascent of the melt to the surface would result in Rb-Sr fractionation. However, silicate melt curves typically have a positive slope ($\Delta P/\Delta T > 0$) in the absence of H_2O, and under these circumstances the melt may become superheated as it moves upward, effectively preventing crystallization and consequent Rb-Sr fractionation. Production of a superheated magma is also an important consideration in the contamination hypothesis, since it would facilitate assimilation and homogenization.

The Apollo 11 K-rich mare basalts (Group 6) could also form by this process, but the younger model ages require a greater degree of equilibration between the melt and residuum or of some fractional crystallization before extrusion onto the surface.

VI. Conclusion

An intriguing feature of these explanations for deriving lunar rocks without fractionation Rb and Sr is the linking of this special characteristic to another characteristic lunar feature--the apparent lack of indigenous H_2O. The hypotheses outlined here differ from other models of lunar petrogenesis in that many rock types would be derived by near-surface modification of rocks formed during primitive crustal differentiation. This can be accomplished with energy partially derived from impacting bodies rather than totally from internal heat sources.

Acknowledgments

Most of the Rb-Sr patterns summarized here are based on mineral isochron data from G. J. Wasserburg and D. A. Papanastassiou. Furthermore, many of the arguments incorporated into these hypotheses have been expressed in their published papers and expressed even more vociferously in numerous discussions during the course of our cooperative work since July 1969. Unpublished Sm and Eu data were provided by N.J. Hubbard and by J.A. Philpotts. This paper has been supported by NASA grants NGL-05-002-188 and NGL-05-002-338.

References

Adler I., Walter L.S., Lowman P.D., Glass B.P., French B.M., Philpotts J.A., Heinrich K.J.F. and Goldstein J.I. (1970) Electron microprobe analysis of Apollo 11 lunar samples, Proceedings of the Apollo 11 Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 1, V. 1, p. 87-92.

Agrell S.O., Scoon J.H., Muir I.D., Long J.V.P., McConnell J.D.C. and Peckett A. (1970) Observations on the chemistry, mineralogy and petrology of some Apollo 11 lunar samples, Proceedings of the Apollo 11 Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 1, V. 1, p. 93-128.

Albee A.L. and Chodos A.A. (1970) Microprobe investigations on Apollo 11 samples, Proceedings of the Apollo 11 Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 1, V. 1, p. 135-157.

Albee A.L., Burnett D.S., Chodos A.A., Eugster O.J., Huneke J.C., Papanastassiou D.A., Podosek F.A., Russ G.P. III, Sanz H.G., Tera F. and Wasserburg G.J. (1970a) Ages, irradiation history, and chemical composition of lunar rocks from the Sea of Tranquillity, Science, V. 167, p. 463-466.

Albee A.L., Burnett D.S., Chodos A.A., Haines E.L., Huneke J.C., Papanastassiou D.A., Podosek F.A., Russ G.P. III and Wasserburg G.J. (1970b) Mineralogic and isotopic investigations on lunar rock 12013, Earth and Planetary Science Letters, V. 9, p. 137-163.

Albee A.L., Chodos A.A., Gancarz A.J., Haines E.L., Papanastassiou D.A., Ray L., Tera F., Wasserburg G.J. and Wen T. (1972) Mineralogy, petrology, and chemistry of a Luna 16 basaltic fragment, sample B-1, Earth and Planetary Science Letters, V. 13, p. 353-367.

Albee A.L., Gancarz A.J. and Chodos A.A. (1973) Metamorphism of Apollo 16 and 17 and Luna 20 metaclastic rocks at at about 3.95 AE: Samples 61156, 64423,14-2, 65015, 67483,15-2, 76055, 22006, and 22007, Proceedings of the Fourth Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 4, V. 1, p. 569-595.

Albee A.L., Chodos A.A., Dymek R.F., Gancarz A.J., Goldman D.S., Papanastassiou D.A. and Wasserburg G.J. (1974) Dunite from the Lunar Highlands: Petrography, deformation history, Rb-Sr age, In: Lunar Science V, p. 3-5, The Lunar Science Institute, Houston, Texas.

Anderson D.H. (1970) The preliminary examination and preparation of lunar sample 12013, Earth and Planetary Science Letters, V. 9, p. 94-102.

Brunfelt A.O., Heier K.S., Nilssen B., Sundvoll B. and Steinnes E. (1972) Distribution of elements between different phases of Apollo 14 rocks and soils, Proceedings of the Third Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 3, V. 2, p. 1133-1147.

Dowty E., Prinz M. and Keil K. (1973) Composition, mineralogy, and petrology of 28 mare basalts from Apollo 15 rake samples, Proceedings of the Fourth Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 4, V. 1, p. 423-444.

French B.M., Walter L.S., Heinrich K.F.J., Loman P.D. Jr., Doan A.S. Jr. and Adler I. (1972) Compositions of major and minor minerals in five Apollo 12 crystalline rocks, National Aeronautics and Space Administration SP-306, 142 pp.

Gancarz A.J., Albee A.L. and Chodos A.A. (1971) Petrologic and mineralogic investigation of some crystalline rocks returned by the Apollo 14 mission, Earth and Planetary Science Letters, V. 12, p. 1-18.

Gancarz A.J., Albee A.L. and Chodos A.A. (1972) Comparative petrology of Apollo 16 sample 68415 and Apollo 14 samples 14276 and 14310, Earth and Planetary Science Letters, V. 16, p. 307-330.

Gast P.W., Hubbard N.J. and Wiesmann H. (1970) Chemical composition and petrogenesis of basalts from Tranquillity Base, Proceedings of the Apollo 11 Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 1, V. 2, p. 1143-1163.

Goles G.G., Randle K., Osawa M., Lindstrom D.J., Jérome D.Y., Steinborn T.L., Beyer R.L., Martin M.R. and McKay S.M. (1970) Interpretations and speculations on elemental abundances in lunar samples, Proceedings of the Apollo 11 Lunar Science Conference, Geochimica et Cosmochemica Acta, Supplement 1, V. 2, p. 1177-1194.

Goles G.G., Duncan A.R., Lindstrom D.J., Martin M.R., Beyer R.L., Osawa M., Randle K., Meek L. T., Steinborn T.L. and McKay S.M. (1971) Analyses of Apollo 12 specimens: Compositional variations, differentiation processes, and lunar soil mixing models, Proceedings of the Second Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 2, V. 2, p. 1063-1081.

Gooley R., Brett R., Warner J. and Smyth J.R., Sample 76535, a deep lunar crustal rock, Geochimica et Cosmochimica Acta, in press.

Graham A.L. and Ringwood A.E. (1971) Lunar basalt genesis: The origin of the Europium anomaly, Earth and Planetary Science Letters, V. 13, p. 105-115.

Haskin L.A., Allen R.O., Helmke P.A., Paster T.P., Anderson M.R., Korotev R.L. and Zweifel K.A. (1970) Rare earths and other trace elements in Apollo 11 lunar samples, Proceedings of the Apollo 11 Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 1, V. 2, p. 1213-1231.

Haskin L.A., Helmke P.A., Blanchard D.P., Jacobs J.W. and Telander K. (1973) Major and trace element abundances in samples from the lunar highlands, Proceedings of the Fourth Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 4, V. 2, p. 1275-1296.

Hubbard N.J. and Gast P.W. (1971) Chemical composition and origin of nonmare lunar basalts, Proceedings of the Second Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 2, V. 2, p. 999-1020.

Hubbard N.J., Meyer C. Jr., Gast P.W. and Wiesmann H. (1971) The composition and derivation of Apollo 12 soils, Earth and Planetary Science Letters, V. 10, p. 341-350.

Hubbard N.J., Gast P.W. and Meyer C. Jr. (1972a) Chemical composition of lunar anorthosites and their parent liquids, In: Lunar Science III, p. 404-406, The Lunar Science Institute, Houston, Texas.

Hubbard N.J., Gast P.W., Rhodes J.M., Bansal B.M., Wiesmann H. and Church S.E. (1972b) Nonmare basalts: Part II, Proceedings of the Third Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 3, V. 2, p. 1161-1179.

Huneke J.C., Podosek F.A. and Wasserburg G.J. (1972a) Gas retention and cosmic-ray exposure ages of a basalt fragment from Mare Fecunditatis, Earth and Planetary Science Letters, V. 13, p. 375-383.

Huneke J.C., Podosek F.A. and Wasserburg G.J. (1972b) An argon bouillabaisse including ages from the Luna 20 site, In: Lunar Science IV, p. 403-405, The Lunar Science Institute, Houston, Texas.

Huneke J.C., Jessberger E.K., Podosek F.A. and Wasserburg G.J. (1973) $^{40}Ar/^{39}Ar$ measurements in Apollo 16 and 17 samples and the chronology of metamorphic and volcanic activity in the Taurus-Littrow region, Proceedings of the Fourth Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 4, V. 2, p. 1725-1756.

James O.B. (1972) Lunar anorthosite 15415: Texture, mineralogy, and metamorphic history, Science, V. 175, p. 434-438.

Jessberger E.K., Huneke J.C. and Wasserburg G.J. (1974) Evidence for a ∿4.5 aeon age of plagioclase clasts in a lunar highland breccia, Nature, V. 248, p. 199-202.

Lanphere M.A., Wasserburg G.J.F., Albee A.L. and Tilton G.R. (1964) Redistribution of strontium and rubidium isotopes during metamorphism, World Beater Complex, Panamint Range, California, In: Isotopic and Cosmic Chemistry, eds. H. Craig, S.L. Miller and G. J. Wasserburg (North-Holland, Amsterdam, 1964) 553 pp.

Laul J.C., Wakita H., Showalter D.L., Boynton W.V. and Schmitt R.A. (1972) Bulk, rare earth, and other trace elements in Apollo 14 and 15 and Luna 16 samples, Proceedings of the Third Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 3, V. 2, p. 1181-1200.

Morgan J.W., Laul J.C., Krähenbühl U., Ganapathy R. and Anders E. (1972) Major impacts on the moon: Characterization from trace elements in Apollo 12 and 14 samples, Proceedings of the Third Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 3, V. 2, p. 1377-1395.

Morrison G.H., Gerard J.T., Potter N.M., Gangadharam E.V., Rothenberg A.M. and Burdo R.A. (1971) Elemental abundances of lunar soil and rocks from Apollo 12, Proceedings of the Second Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 2, V. 2, p. 1169-1185.

Nyquist L.E., Hubbard N.J., Gast P.W., Bansal B.M., Wiesmann H. and Jahn B. (1973) Rb-Sr systematics for chemically defined Apollo 15 and 16 materials, Proceedings of the Fourth Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 4, V. 2, p. 1823-1846.

Papanastassiou D.A. and Wasserburg G.J. (1969) Initial strontium isotopic abundances and the resolution of small time differences in the formation of planetary objects, Earth and Planetary Science Letters, V. 5, p. 361-376.

Papanastassiou D.A., Wasserburg G.J. and Burnett D.S. (1970) Rb-Sr ages of lunar rocks form the Sea of Tranquillity, Earth and Planetary Science Letters, V. 8, p. 1-19.

Papanastassiou D.A., and Wasserburg G.J. (1970) Rb-Sr ages from the Ocean of Storms, Earth and Planetary Science Letters, V. 8, p. 269-278.

Papanastassiou D.A. and Wasserburg G.J. (1971a) Lunar chronology and evolution from Rb-Sr studies of Apollo 11 and 12 samples, Earth and Planetary Science Letters, V. 11, p. 37-62.

Papanastassiou D.A. and Wasserburg G.J. (1971b) Rb-Sr ages of igneous rocks from the Apollo 14 mission and the age of the Fra Mauro Formation, Earth and Planetary Science Letters, V. 12, p. 36-48.

Papanastassiou D.A. and Wasserburg G.J. (1972a) Rb-Sr age of a Luna 16 basalt and the model age of lunar soils, Earth and Planetary Science Letters, V. 13, p. 368-374.

Papanastassiou D.A. and Wasserburg G.J. (1972b) The Rb-Sr age of a crystalline rock from Apollo 16, Earth and Planetary Science Letters, V. 16, p. 289-298.

Papanastassiou D.A. and Wasserburg G.J. (1972c) Rb-Sr systematics of Luna 20 and Apollo 16 samples, Earth and Planetary Science Letters, V. 17, p. 52-63.

Papanastassiou D.A. and Wasserburg G.J. (1973) Rb-Sr ages and initial Strontium in basalts from Apollo 15, Earth and Planetary Science Letters, V. 17, p. 324-337.

Philpotts J.A., Schnetzler C.C., Nava D.F., Schumann S., Kouns C.W., Lum R.K.L. and Bickel A.L. (1973) Apollo 16: Large ion lithophile trace element abundances in some fines, a basalt and an anorthosite, In: Lunar Science IV. p. 592-594, The Lunar Science Institute, Houston, Texas

Reid M.J., Gancarz A.J. and Albee A.L. (1973) Constrained least-squares analysis of petrologic problems with an application to lunar sample 12040, Earth and Planetary Science Letters, V. 17, p. 433-445.

Rhodes J.M. and Hubbard N.J. (1973) Chemistry, classification, and petrogenesis of Apollo 15 mare basalts, Proceedings of the Fourth Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 4, V. 2, p. 1127-1148.

Ringwood A.E. and Essene E. (1970) Petrogenesis of Apollo 11 basalts, internal constitution and origin of the moon, Proceedings of the Apollo 11 Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplementl, V. 1, p. 769-799.

Schmitt R.A. and Laul J.C. (1973) A survey of the selenochemistry of major, minor and trace elements, The Moon, V. 8, p. 182-209

Smith J.V., Anderson A.T., Newton R.C., Olsen E.J. and Wyllie P.J. (1970) A petrologic model for the moon based on petrogenesis, experimental petrology, and physical properties, Journal of Geology, V. 78, p. 381-405.

Tera F., Papanastassiou D.A. and Wasserburg G.J. (1974a) The lunar time scale and a summary of isotopic evidence for a terminal lunar cataclysm, In: Lunar Science V. p. 792-794, The Lunar Science Institute, Houston, Texas.

Tera F., Papanastassiou D.A. and Wasserburg G.J. (1974b) Isotopic evidence for a terminal lunar cataclysm, Earth and Planetary Science Letters, V. 22 p. 1-21.

Turner G. (1970) Argon-40/argon-39 dating of lunar rock samples, Proceedings of the Apollo 11 Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 1, V. 2, p. 1665-1684.

Turner, G. (1972) ^{40}Ar-^{39}Ar age and cosmic ray irradiation history of the Apollo 15 anorthosite, 15415, Earth and Planetary Science Letters, V. 14, p. 169-175.

Turner G., Huneke J.C., Podosek F.A. and Wasserburg G.J. (1971) ^{40}Ar-^{39}Ar ages and cosmic ray exposure ages of Apollo 14 samples, Earth and Planetary Science Letters, V. 12, p. 19-35.

Vinogradov A.P. (1971) Preliminary data on lunar ground brought to Earth by automatic probe "Luna-16", Proceedings of the Second Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 2, V. 1, p. 1-16.

Wakita H. and Schmitt R.A. (1970) Elemental abundances in seven fragments from lunar rock 12013, Earth and Planetary Science Letters, V. 9, p. 169-176.

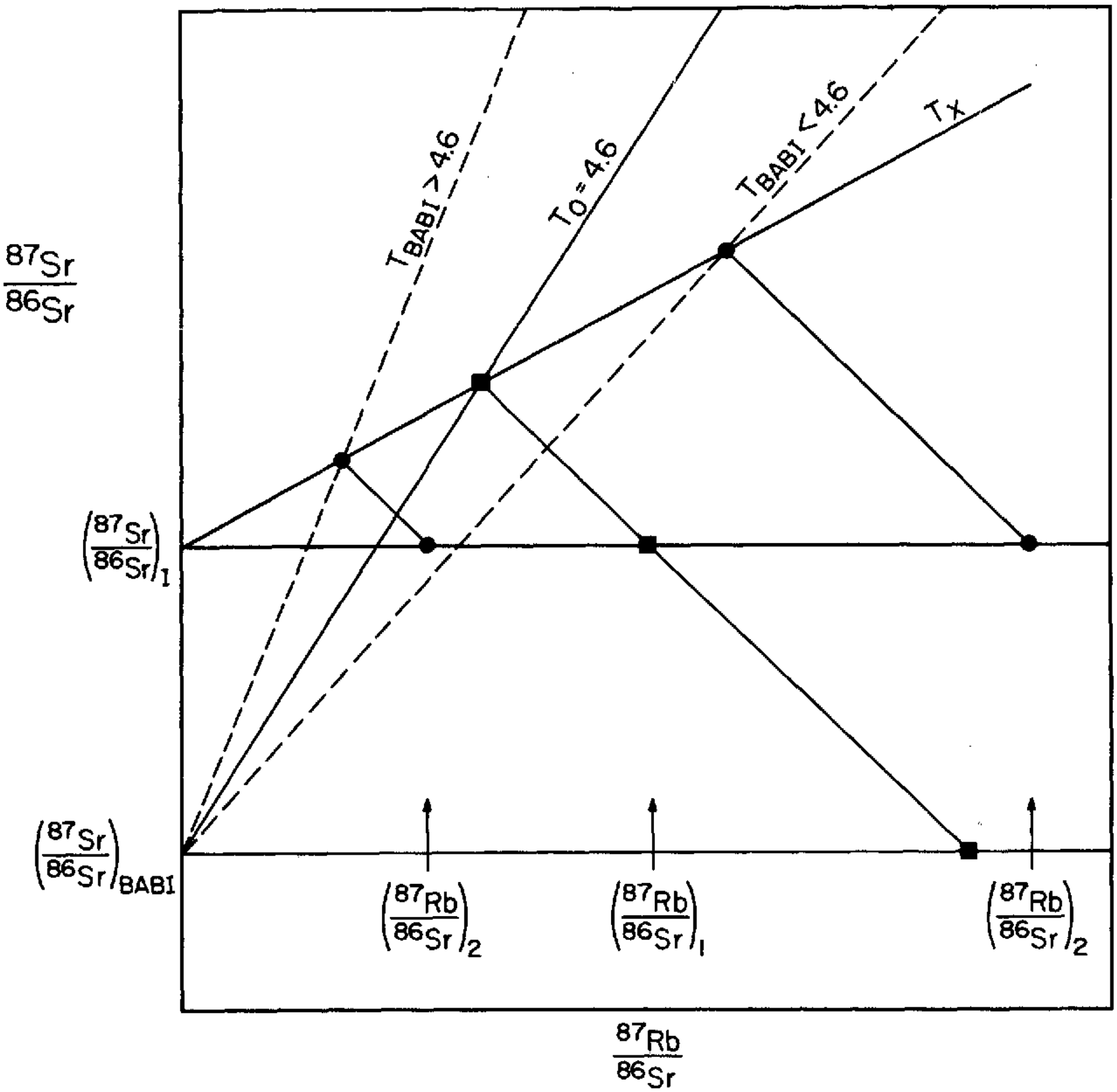
Wasserburg G.J. and Papanastassiou D.A. (1971) Age of an Apollo 15 mare basalt; Lunar crust and mantle evolution, Earth and Planetary Science Letters, V. 13, p. 97-104.

Wood J.A., Dickey J.S. Jr., Marvin U.B. and Powell B.N. (1970) Lunar anorthosites and a geophysical model of the Moon, Proceedings of the Apollo 11 Lunar Science Conference, Geochimica et Cosmochimica Acta, Supplement 1, V. 1, p. 965-988.

Figure 1. Rb-Sr evolution diagram. Material formed at T_o with $(^{87}Sr/^{86}Sr)$ equal to $(^{87}Sr/^{86}Sr)_{BABI}$ is represented by a square. Fractionation at time T_x results in a portion enriched and a portion depleted in Rb relative to Sr (circles) and an unfractionated portion (square), all of which lie along the T_x isochron. The unfractionated portion yeilds a model age, T_{BABI}, equal to T_o, whereas fractionated portions yield model ages different from T_o.

Figure 2. T_{BABI} versus T_x. Despite the variety of rock types represented, nearly all samples indicate less than a factor of 2 fractionation of Rb relative to Sr subsequent to T_o = 4.6 AE. Only the K-rich mare basalts indicate a greater degree of fractionation.

Figure 3. Sm/Eu versus K_D. The large range of Sm/Eu, indicative of extensive fractionation, is not commensurate to the fractionation of Rb relative to Sr as indicated by the small range of K_D. This indicates that the fractionation of Sm and Eu occurred prior to T_x; and, from additional data, most likely occurred during the large-scale lunar differentiation at ∿ 4.6 AE. Sm and Eu data are from the following: Brunfelt et al., (1972), Gast et al., (1970), Goles et al., (1970, 1971), Haskin et al., (1970, 1973), Hubbard and Gast (1971), Hubbard et al., (1971, 1972a, 1972b), Laul et al., (1972), Morrison et al., (1971), Philpotts et al., (1973), Rhodes et al., (1973), Vinogradov et al., and Wakita et al., (1970).



$$K_D = \left(\frac{^{87}Rb}{^{86}Sr}\right)_2 \Big/ \left(\frac{^{87}Rb}{^{86}Sr}\right)_1 \cong \frac{T_O - T_X}{T_{BABI} - T_X}$$

FIGURE 1

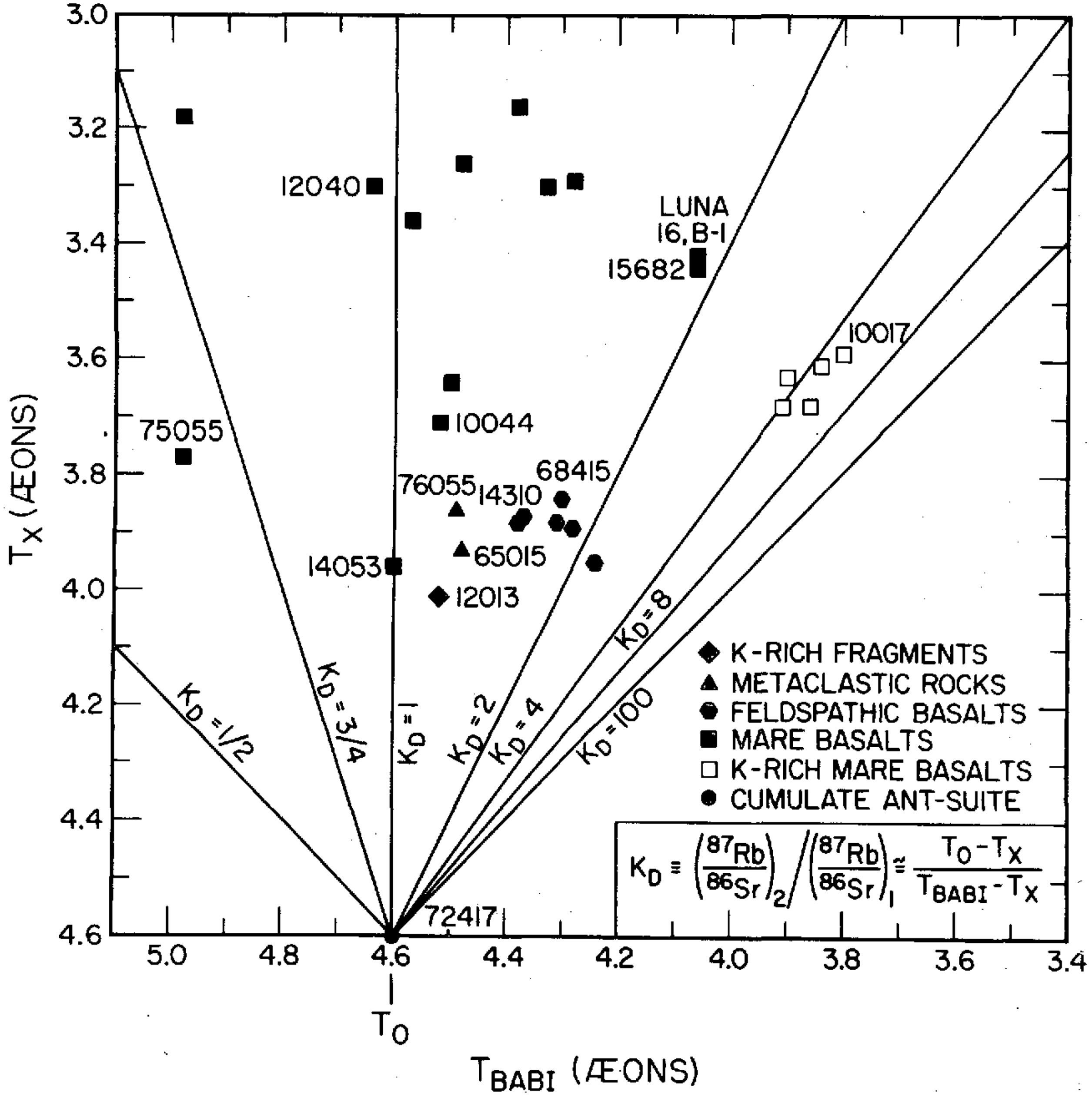
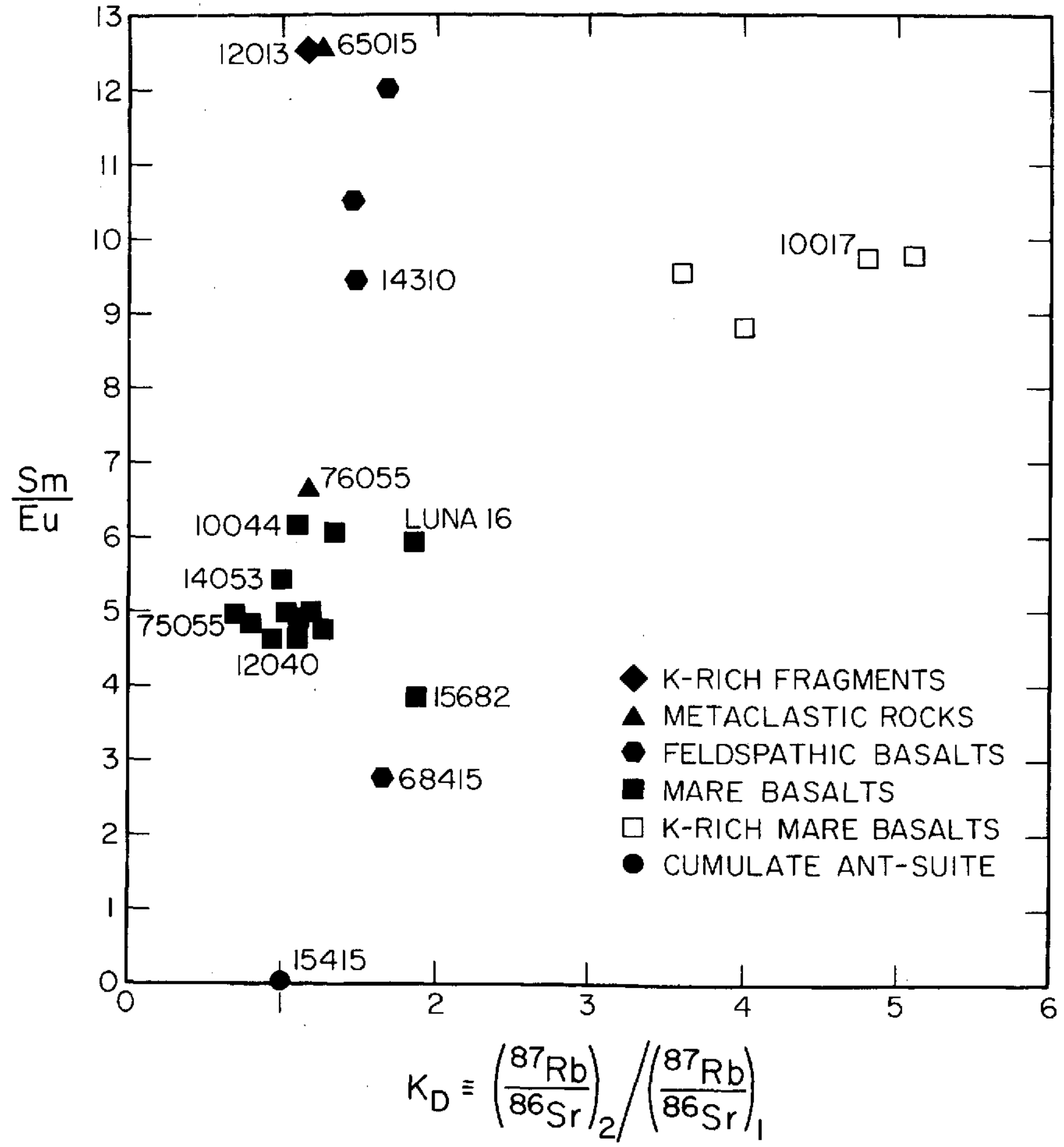

3.0
3.2
3.4
3.6
3.8
4.0
4.2
4.4
4.6
T_X (ÆONS)
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
T_0
T_{BABI} (ÆONS)
12040
LUNA
16, B-1
15682
10017
75055
10044
68415
76055
14310
65015
14053
12013
72417
$K_D = 1/2$
$K_D = 3/4$
$K_D = 1$
$K_D = 2$
$K_D = 4$
$K_D = 8$
$K_D = 100$
◆ K-RICH FRAGMENTS
▲ METACLASTIC ROCKS
⬢ FELDSPATHIC BASALTS
■ MARE BASALTS
□ K-RICH MARE BASALTS
● CUMULATE ANT-SUITE
$K_D \equiv \left(\frac{^{87}Rb}{^{86}Sr}\right)_2 \Big/ \left(\frac{^{87}Rb}{^{86}Sr}\right)_1 \cong \frac{T_0 - T_X}{T_{BABI} - T_X}$

FIGURE 2


Sm/Eu
$K_D \equiv \left(\frac{^{87}Rb}{^{86}Sr}\right)_2 \Big/ \left(\frac{^{87}Rb}{^{86}Sr}\right)_1$
0
1
2
3
4
5
6
7
8
9
10
11
12
13
12013
65015
14310
10017
76055
10044
LUNA 16
14053
75055
12040
15682
68415
15415
◆ K-RICH FRAGMENTS
▲ METACLASTIC ROCKS
⬢ FELDSPATHIC BASALTS
■ MARE BASALTS
□ K-RICH MARE BASALTS
● CUMULATE ANT-SUITE